Green Building Design: Water Quality and Utility Management Considerations

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Green Building Design: Water Quality and Utility Management Considerations

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FOREWORD

The Water Research Foundation (WRF) is a nonprofit corporation dedicated to the development and implementation of scientifically sound research designed to help drinking water utilities respond to regulatory requirements and address high-priority concerns. WRF's research agenda is developed through a process of consultation with WRF subscribers and other drinking water professionals. WRF's Board of Trustees and other professional volunteers help prioritize and select research projects for funding based upon current and future industry needs, applicability, and past work. WRF sponsors research projects through the Focus Area, Emerging Opportunities, and Tailored Collaboration programs, as well as various joint research efforts with organizations such as the U.S. Environmental Protection Agency and the U.S. Bureau of Reclamation.

This publication is a result of a research project fully funded or funded in part by WRF subscribers. WRF's subscription program provides a cost-effective and collaborative method for funding research in the public interest. The research investment that underpins this report will intrinsically increase in value as the findings are applied in communities throughout the world. WRF research projects are managed closely from their inception to the final report by the staff and a large cadre of volunteers who willingly contribute their time and expertise. WRF provides planning, management, and technical oversight and awards contracts to other institutions such as water utilities, universities, and engineering firms to conduct the research.

A broad spectrum of water supply issues is addressed by WRF's research agenda, including resources, treatment and operations, distribution and storage, water quality and analysis, toxicology, economics, and management. The ultimate purpose of the coordinated effort is to assist water suppliers to provide a reliable supply of safe and affordable drinking water to consumers. The true benefits of WRF's research are realized when the results are implemented at the utility level. WRF's staff and Board of Trustees are pleased to offer this publication as a contribution toward that end.

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Finally, we would like thank the building owners and operators of all the buildings we sampled. These people volunteered to participate in this project and their participation increased the success of this project.

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EXECUTIVE SUMMARY

OBJECTIVES

This project is aimed at 1) anticipating green building water conservation features that potentially pose public health and aesthetic concerns, 2) identifying the most common approaches by which green building designs achieve reduced potable water consumption in practice, and 3) evaluating stakeholder satisfaction in regard to those technologies.

BACKGROUND

An increased emphasis on green/sustainable design has created a paradigm shift in water utility operations and customer relations. A few decades of experience with water conservation, water scarcity and droughts in regions not historically prone to such events, and the high cost of developing new water supplies have provided a glimpse into future complexities. For example, reducing water demand can dramatically increase the amount of time it takes to transport water from the treatment plant to the consumer's tap (referred to henceforth as "water age"). This, in turn, can increase chances of microbial re-growth, disinfectant decay, and the likelihood of corrosion (or related) problems in distribution and premise plumbing systems. Recent problems associated with customer satisfaction with reduced flow devices such as waterless urinals, high efficiency toilets, and low flow showerheads have highlighted consumer sensitivity to changes in the quality and aesthetics of their drinking water. The future use of green/sustainable design will further increase the complexity of water quality issues, and a "shared responsibility" model for providing safe and aesthetically pleasing water to consumer taps will be necessary to solve and address these problems, because many are beyond the control of individual stakeholders.

APPROACH

To anticipate problems with green building design features, a thorough literature review was conducted on major issues that occur in premise plumbing, with a focus on factors that could be exacerbated by green building design. A set of three case studies were examined in detail to accompany the thorough literature review. Cases were identified that have a range of green building water conservation features and strategies to reduce water and energy demand. To identify the approaches by which buildings are achieving water conservation, the authors examined a United States Green Building Council (USGBC) database of Leadership in Environmental Engineering Design (LEED) certified buildings under the New Construction v2.2 criteria that logs each certified building and the credits it earned. The analysis examined trends overall and within each United States (U.S.) climate region. Then, an internet survey of all green building stakeholders (designers, plumbers, consumers, etc.) was distributed and analyzed to assess consumer satisfaction with green products. Finally, in-depth interviews were conducted with a subset of green building stakeholders to gain more insight into results obtained in the internet surveys.

RESULTS/CONCLUSIONS

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Key problems associated with health or aesthetics within premise plumbing water systems include loss of disinfectant stability, corrosion of premise plumbing components, scaling, development of taste/odor causing compounds, and microbial (re)growth. One of the most important factors in premise plumbing related to these issues is high water age, which can exacerbate many of these problems. While there are several ways to reduce the water age within buildings, such as limiting the overall volume of the system or regularly flushing the pipes, there are potential downsides to each strategy. Pipe size is often constrained by demand needed for fire protection systems or by the original plumbing design in retrofitted green buildings. It is also currently unclear at this time whether decreasing the pipe size will solve these problems, since smaller pipes increase the surface area to volume ratio and the water velocity within pipes increases. Although reducing pipe size will reduce water age, the higher surface area to volume ratio that results might increase problems with microbial growth and disinfectant decay, and the higher velocities might cause corrosion problems or increase detachment of biofilms. Regularly flushing water at the end of the existing plumbing system is probably the simplest solution to reduce water age for premise plumbing to help maintain chlorine residual and prevent microbial growth, although this practice may seem counterintuitive with respect to water conservation goals. In the one documented case where this was successfully applied, a small increase to existing water demand (~1% of total daily flow) was observed to have dramatic improvements to water quality and were sustained in the long-term.

While water age may be one of the most important factors for maintaining green building water quality, there are many other factors that become increasingly important if large on-site water storage is necessary to achieve conservation goals. For instance, if there is increased water storage for solar or cistern type applications, the higher temperature may make it difficult to maintain good or safe water with low amounts of bacterial growth and that is aesthetically pleasing to drink. . In addition, if alternative water sources such as rainwater are used in buildings, limiting the amount of nutrients from the conveyance system (e.g., organic carbon) may be a fruitful means of preventing bacterial growth. Accordingly, ensuring that systems are well maintained and operating as designed will be important for building staff, especially when the design of the green system is orders of magnitude more complicated within buildings than conventional system counterparts that use utility water.

There are also many conflicts or complications in trying to make sound recommendations on operation and maintenance of premise plumbing systems. For example, the current consensus is that stagnant waters are more likely to promote the growth of microorganisms. While this may be true for overall microbial populations, one direct test of the idea indicated that continuous flow actually facilitates amplification of *Legionella*. There are similar discrepancies in hot water temperature recommendations, such as direct conflicts in safety versus energy savings. To prevent scalding and produce energy savings, many buildings have lowered the temperature of the hot water systems; however, higher temperatures are recommended to control pathogen regrowth potential and prevent odorous bacteria from colonizing the system. The plumbing codes and standards will eventually play an important role in making and promulgating recommendations that balance these complexities. At present, although specific guidelines in several sections of the codes direct designers how to achieve water use reduction, they do not warn against negative effects to consumers that can result from high water age.

The literature also revealed concerns with specific green devices. For instance, metered faucets, which are installed to save water and prevent the spread of germs by eliminating the need to touch the faucet, have been observed to have a higher incidence of opportunistic pathogens than

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their conventional counterparts. Although the precise cause(s) for this problem has not been identified, lower flow rate and pressures as well the materials used in the faucets have been hypothesized to be the primary causes. As more water conservation-specific devices enter the market, despite being NSF/ANSI certified for different health criteria, similar concerns are likely to arise. Fundamental research will be necessary to understand and resolve these problems before such devices can be used with confidence.

Without accepted solutions to maintaining water quality in green buildings, the buildings with more extreme efforts to achieve water and/or energy independence will likely begin taking steps to improve their own water quality by seeking to install disinfection systems in individual buildings. In the literature review, these systems were found to have variable efficacy that was dependent, in many cases, on the source water quality, type of plumbing, and level of maintenance and monitoring. Installation of these systems adds a level of complexity to the maintenance and operation of water systems, which may be beyond the abilities of some building maintenance staff members. In addition, recommendations on how to choose a disinfection system that is compatible with source water quality and the existing plumbing system are not available. The section "Anticipating Issues with In-building Disinfection Systems" in Chapter 3 provides an initial framework to begin thinking about how to make these recommendations.

The three field site case studies provided several important and supporting insights about water quality in green buildings. The first building, a LEED certified outpatient healthcare facility, had increased water age due to large pipe diameters and high number of sinks in each patient exam room coupled with very low use. At this facility, the disinfectant residual was completely absent from each distal tap tested. At one location, it took 80 minutes of flushing to see a residual consistent with the residual in the distribution system. This was accompanied by extremely fast residual decay at the taps, most likely due to a combination of biotic (e.g., nitrification) and abiotic (e.g., reaction with plumbing materials) reactions. At the taps sampled, given how quickly the residual disappeared, there is likely never a chlorine residual at these taps. The lack of residual occurred concurrently with high concentrations of *M. avium*, *Legionella* spp., and opportunistic pathogen host organisms. Due to the complexity of the plumbing system (i.e., there were many branches from the main cold water line), it is possible that flushing in several places would have to be implemented in order to maintain a reasonable disinfectant residual and decrease bacterial concentrations.

The second field site, an experimental house aiming to achieve net-zero energy, uses a solar preheat water tank to decrease the energy requirements of the hot water system. This, in essence, doubles the amount of hot water storage in the house. The solar tank, however, did not recover quickly after being flushed (increasing only 1° C after 1 hour), resulting in lower water temperatures ideal for bacterial growth for extended amounts of time. In addition, with the added storage, the hot water tanks turn over less frequently (complete volume exchange every 2.5 days with the solar tank vs 1.25 days without). This facilitates the decay of the chlorine residual, which was completely absent from all samples taken during periods where water use was being controlled to simulate a family of four. There were again alarmingly high concentrations of *Legionella* spp. and host organisms in stagnant samples compared to well flushed water.

The third field site, a small net-zero and –energy office building, collects rainwater for all its potable and non-potable uses. Although it is advertised as completely off-the-grid, our site visits demonstrated that the water system routinely uses on-the-grid local groundwater resources for maintenance, representing 38-60% of the annual water use associated with the building. At the time of sampling, water quality parameters such as hardness and alkalinity suggest that up to 60%

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of the water present in the cistern was actually from the local ground water sources. In addition, this building would use grid water and grid electricity for firefighting purposes. Although not an issue at this small facility, the utility maintenance associated with maintaining these connections may be a burden to the public utility if such buildings become more commonplace in the future. High levels of OPPPs and host organism *V. vermiformis* were detected in nearly all rainwater samples, despite routine water recirculation that occurs twice daily and semiannual in-building disinfection practices.

A USGBC maintained database for "New Construction" projects proved to be a useful resource to examine trends in water conservation features in green construction. The most common potable water reduction strategies included having no permanent irrigation system, using rainwater for irrigation, high efficiency toilets, and waterless urinals. Some differences by climate region were also observed. These included more frequent use of dual-flush toilets and less frequent use of high efficiency toilets in northwest/marine regions, and more frequent use of high efficiency urinals in hot/dry regions compared to other regions. There were also significant differences in irrigation system selection, with systems in hot/dry regions more likely to only have reduced irrigation whereas mixed humid and cold regions were likely to have no permanent irrigation.

An internet survey of green building stakeholders revealed a high level of satisfaction with the green technologies implemented; however, respondents indicated that some problems were occurring including pipe leaks and clogs (32%), insufficient hot water (31%), premature system failure, complaints about taste, odor, or coloration (29%), and users not using the potable water for consumption (22%). User satisfaction was highest with alternative irrigation techniques and lowest with waterless urinals among the water conserving technologies and practices surveyed.

Telephone interviews identified a number of successes and difficulties associated with water-related innovations in green buildings. Successes cited by interviewees primarily involved green features or devices working as intended. The most common types of difficulties involved owners/maintenance personnel that lacked crucial knowledge necessary to properly operate and maintain innovative water systems. There were also several complaints about inaccurate manufacturer claims. Interviewees were also asked to give advice to the industry. Common themes in the advice included water being undervalued and underpriced, and the desire of many interviewees to shift focus from the water efficiency of specific devices to water recovery and recycling.

APPLICATIONS/RECOMMENDATIONS

Understanding how to reduce water age within buildings is one key factor to eventually maintaining good water quality. More research in this area is needed to identify what water ages are problematic and under what circumstances, as well as the best approaches to reducing water age for different types of green buildings. If it is not possible to reduce water age by normal design and use so that effective disinfectant residuals are maintained and microbial growth is limited, then water flushing is likely to be an effective temporary solution for buildings begin supplied with water that has a disinfectant residual. An advantage to this strategy is that it can be implemented anytime, and the "wasted" water can be recovered and used for non-potable applications. When this solution is not effective, building owners may need to hire consultants to help diagnose and solve more complex problems on a site specific basis.

Reliable recommendations on how to select an in-building disinfection system are needed. Achieving this will require more information on how each different type of in-building disinfection

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system will interact with or affect the existing plumbing material and microbial ecology. This will have to be addressed through detailed small and large scale research in the coming decades.

Code and standard developers, green building designers and practitioners, and the general public need to be aware of the effects of high water age on water quality to develop design guidelines and implement remedial actions. There is a need for communication between these different stakeholders to help solve problems and identify research needs. Research and increased evaluation of green devices are also needed to determine if and how they should be used in green building applications. Common trends in green building water conservation to meet certification goals could lead to climate/region-based techniques that can be more successfully applied. Incorporating information about the effects of high water age into building codes and standards, which also make clear the negative and unintended consequences of ignoring this guidance may be a useful starting point. More monitoring of green buildings is necessary to first identify and then resolve problems as they are encountered.

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CHAPTER 1: HOW TO USE THIS REPORT

The overarching goal of this report is to examine water quality problems that occur in a range of building designs, water qualities, and water use patterns, with an emphasis on changes arising as a result of green building practices. The report is organized into three distinct sections including: a literature review, a summary of selected case histories highlighting possible impacts of green building practices, and a survey of current green building stakeholders. Other products from this research have been published elsewhere and include peer-reviewed articles, online technical reports, and proceedings for national conferences. These include:

Papers/Reports:

Rhoads, W., Pruden, A., Edwards, M. (2013) Anticipating Challenges with In-Building Disinfection for Control of Opportunistic Pathogens.*Water Environment Research, 86(6), 540-549.*

Rhoads, W., Pruden, A., Edwards, M. (2013) Water Conservation Features Create High Water Age and Health Concerns for Potable Water. *To be submitted to Environmental Science and Technology.*

Chambers, B.D., Pearce, Annie R., Edwards, Marc A., Dymond, Randel L., (2013). "Green Building Water Systems: A User Satisfaction Study" (Unpublished)

Chambers, B.D., Pearce, Annie R., Edwards, Marc A., Dymond, Randel L., (2013). "Green Building Water Systems: Innovation Selection and Climate" (Unpublished)

Chambers, B. D., Pearce, Annie R., Edwards, Marc A. (2013). "Green Building Water Efficiency Strategies: An Analysis of LEED 2.2 NC Project Data." US Green Building Council.

Presentations:

W. Rhoads, A. Pruden, M. Edwards. Building Disinfection Strategies to Control Legionella in Premise Plumbing: Anticipating Concerns with the New ASHRAE Standard. Oral Presentation at Water Quality and Technology Conference. Long Beach, CA. November 2013.

W. Rhoads, M. Edwards. Survey of Green Building Water Quality: Identifying Public Health and Aesthetic Concerns, Invited Oral Presentation at American Council for an Energy-Efficient Economy Hot Water Forum. Atlanta, GA. November 2013.

W. Rhoads, M. Edwards. Survey of Green Building Water Quality: Identifying Public Health and Aesthetic Concerns, Invited Oral Presentation at 2nd Annual Meeting. Canadian Advisory Council on Plumbing. Alberta, CA. August 2013.

W. Rhoads, M. Edwards. Survey of Green Building Water Quality: Identifying Public Health and Aesthetic Concerns, Oral Presentation at AEESP 2013. Denver, CO. July, 2013.

W. Rhoads, M. Edwards. Potential Implications of Green Building Design and Standard Practices on Water Quality. Oral Presentation at CaNv-AWWA 2013 Inorganic Contaminants Symposium. Sacramento, CA. Feb, 2013.

W. Rhoads, A. Pruden, M. Edwards. Anticipating Challenges Associated with In-Building Disinfection for Control of Opportunistic Pathogens in Premise Plumbing. Oral Presentation and Conference Proceedings. WEF Disinfection and Public Health Conference. Indianapolis, IN. Feb, 2013

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W. Rhoads, C. Nguyen, C. Elfland, R. Brazeau, A. Pearce, M. Edwards. Water Quality Issues in Green Buildings. Oral Presentation at AWWA Annual Conference and Exposition. Dallas, TX. June, 2012

Chambers, B. D., Pearce, Annie R., (2013). "The sharing of stories about unanticipated consequences in the green building industry." Engineering Sustainability: Innovation and the Triple Bottom Line. Pittsburgh, PA.

The executive summary provides a concise, stand-alone review of knowledge and conclusions derived from the overall project. Detailed information as to how each conclusion was developed is available in Chapters 2-9.

Chapter 2 describes the range of stakeholders involved in premise plumbing problems, emphasizing shared responsibilities in monitoring, prevention of problems, and response to issues. This chapter also outlines possible engineering controls that can be applied at the utility and forecasts some of their limitations in preventing premise plumbing problems.

Chapter 3 proactively anticipates water quality issues in green buildings that are sometimes problematic. Each section provides an introduction, anticipated link to green building plumbing systems, a macroscopic summary of the key issues, and representative remedial strategies to the problems identified.

Chapter 4 provides case examples of waterborne disease outbreaks and/or plumbing failures that highlight the features of green building plumbing system design that contributed to those problems. These case histories provide real-world exemplars of issues with a range of water conservation strategies.

Chapter 5 provides details of field site visits of three green buildings with different types of conservation techniques.

Chapter 6 examines consumer issues with past projects that have been Leadership in Energy and Environmental Design (LEED) certified.

Chapter 7 examines climate-specific tends in the different pathways building designers take to achieve LEED certification.

Chapter 8 provides results from a survey of green building plumbing stakeholders, focusing on types and uses of technologies employed and an initial interpretation of how those technologies are functioning.

Chapter 9 reports on phone interviews with green building stakeholders, focusing on the successes and failures of green technologies that the interviewees have experienced.

Chapter 10 reiterates the key lessons learned from this project.

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CHAPTER 2: INTRODUCTION TO GREEN BUILDING WATER QUALITY, PREMISE PLUMBING STAKEHOLDERS, AND LIMITATION OF UTILITY CONTROL

A paradigm shift in water utility operations and customer relations is taking place due to the increasing emphasis on green/sustainable design and the emergence of premise plumbing pathogens as the primary source of waterborne disease. With a few noteworthy exceptions, such as the Environmental Protection Agency Lead and Copper Rule (U.S. EPA LCR), conventional water treatment, distribution, and building construction practices generally rely on water utilities alone to provide safe and aesthetically pleasing potable water from source to tap. Some customers choose to install in-home devices that could impact health, aesthetics, and corrosion of home plumbing such as filters and water softeners. The range of such devices and their impacts on water quality was once relatively limited. Utility responses to consumer complaints tended to fall into well-defined categories that were amenable to simple "decision tree" type guidance (i.e., control of waterborne disease occurred at the treatment plant and through proper operation of the main distribution system) and rate setting has traditionally been straightforward.

A few decades of experience with water conservation prompted by water scarcity, droughts in regions not historically prone to such events, and the high cost of developing new water supplies have provided a glimpse into future complexities. Reduced water demand can dramatically increase water age, microbial re-growth, and corrosion problems in utility water distribution systems (EPA, 2002). Sudden changes in source water chemistry have sometimes triggered lead corrosion issues and water discoloration problems via reactions with aging plumbing infrastructure (Edwards, 2004; Cotton et al., 2008). Problems associated with reduced flow devices such as waterless urinals, toilets, and showerheads have highlighted consumer sensitivity to change and the law of unintended consequences (Edwards, 2004; Nguyen, et al 2008a and 2008b; Teuber et al., 2008). Furthermore, new rate structures have been required to ensure that utilities remained financially viable in the face of reduced demand (e.g., Burton, 2006).

Mounting use of green/sustainable design and the acknowledged importance of premise plumbing pathogens give rise to an increasing complexity in the range of problems and solutions associated with premise plumbing water systems, necessitating a "shared responsibility" model for provision of safe and aesthetically pleasing water to consumer taps. That is, a range of stakeholders including water utilities, consumers, building designers, plumbers, code setting organizations, and device manufacturers now have critical roles to play in preventing and solving water quality problems in buildings. Water conservation features and use of new water sources (e.g., rainwater, reclaimed water) in buildings can dramatically increase water age and create problems with aesthetics, corrosion, and health (Elfland et al., 2010; Nguyen et al., 2008a, Nguyen et al., 2008b). Further, some "green" hot water systems are more wasteful than their conventional counterparts (Brazeau and Edwards, 2012), leading to consideration of more rational design guidelines, approaches, and visions (Pearce et al., 2011a; Pearce et al., 2011b; Edwards et al., 2009). The following is a partial list of obvious questions that will require answers over the next few decades to address these issues and shared responsibilities:

1) What pipes and fittings are most compatible with very long water age in buildings?

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2) What guidelines, if any, should be given for proper design and sizing of premise plumbing distribution systems to be compatible with lower water use and avoid problems with water age?

3) What corrosion issues will affect the various premise plumbing materials (i.e., leaching of metals and organics, removal of disinfectant residuals, copper pinholes, dezincification of brass, cracking of PEX), and how does selection of each material impact the lifetime of building plumbing infrastructure, pathogen amplification, and aesthetic concerns?

4) What is the role of in-building disinfection (i.e., chlorine, silver/copper ion, heat shock) in controlling problems due to new potable water sources such as rainwater, or to supplement the utilities' secondary disinfectant residual? What unanticipated problems will operation of these disinfectant systems bring to the longevity of premise plumbing infrastructure?

5) When dual potable water sources are used (e.g., rainwater with supplemental/emergency connections to potable water), how does a utility respond to consumer complaints and concerns about aesthetics and corrosion control that potentially arise from multiple sources?

6) What responsibility, if any, should utilities take in providing guidance regarding the impacts from a wave of proprietary "green" devices that will be installed in buildings over the next few decades? Who is responsible for the myriad possible effects of these devices on aesthetics and health?

7) To what extent should utilities provide guidance on hot water system operation including advice on temperature settings, flushing water heaters, and the propensity for problems with premise plumbing pathogens in their particular water?

Developing firm answers to these issues is far beyond the scope of this project, but this work will begin to consider and identify a firm groundwork for a shared responsibility model to help address the emerging water quality concerns.

Above and beyond the primary research goals associated with water quality highlighted above, secondary goals regarding management of green buildings are also subject to change. For instance, off-grid potable water systems frequently utilize an emergency connection to utility supplies. For purposes of this work, we define "partially" off-grid as systems requiring an emergency back-up connection to utility potable water supplies, whereas "fully" off-grid has no utility connection to potable water. Further long-term questions include:

8) What kind of rate structure would fairly compensate utilities for a customer most likely to draw water at the most inopportune times of reduced rainfall or drought, or for maintaining water distribution system infrastructure to serve these customers that is rarely used?

9) What are the increased health risks and aesthetic concerns from nearly permanent dead-ends that will feed such systems, and are there increased concerns about backflow events from building systems operating unconventional grey water and on-site sewage/reclaimed water systems?

10) Can partial off-grid be fairly implemented, given the uncertainty it introduces to revenue and possibility of failure?

11) What role, if any, does a utility have in responding to consumer complaints for fully or partially off grid systems?

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12) How will the plumbing code adapt to have multiple types of water in buildings?

Once again, while developing firm answers to each of these questions is beyond the scope of this project, this research will begin to systematically identify and address concerns of stakeholders in green buildings who are designing, installing, and operating novel water systems.

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CHAPTER 3: POTENTIAL WATER QUALITY PROBLEMS IN GREEN BUILDINGS

This chapter is organized into seven sections highlighting concerns with water quality problems (and possible solutions) in green buildings as follows:

3.1. Rapid loss of disinfectants
3.2 Anticipating issues with in-building disinfection systems
3.3 Corrosion
3.4 Taste and odors
3.5 Rainwater harvesting
3.6 Microbiological contaminants of concern
3.7 Green building assessment and codes

3.1 RAPID LOSS OF DISINFECTANTS

Key words: chlorine, chloramine, rapid decay, chlorine demand, nitrification

3.1.1 Introduction

The presence of a secondary disinfectant residual in the distribution system is a primary barrier against pathogen and bacterial re-growth in water supplied by utilities. Free chlorine (OCl^-, HOCl) and monochloramine (NH_2Cl) are the most common distribution system-wide disinfectants used by U.S. utilities (Siedel et al., 2005). Each disinfectant has advantages and disadvantages, with corresponding public health and building management considerations. One of the most important factors in the success of secondary disinfection is the maintenance of a residual concentration throughout the water distribution and premise plumbing systems. When rapid disinfectant decay occurs and the concentration drops to insufficient levels, a shift in the control of rapid bacterial growth toward factors such as predation by protozoa, toxicity to certain materials, and perhaps nutrient limitations (Nguyen et al, 2011; Zhang and Edwards, 2009; Morton et al., 2005). There are a range of factors that affect the persistence of disinfectant residuals including water quality (chemical, physical, and microbiological), plumbing materials, and system operation. As a result, disinfectant residuals can disappear due to abiotic and biotic reactions taking place in the bulk water and/or at the surfaces (i.e., in biofilms) of plumbing material.

Water age, or water retention time in a building plumbing system, plays a role in many of the plumbing issues discussed in this report. Water age is the amount of time, on average, for water to be used after it enters a building. Water age in a distribution system is most likely affected by a water authority's planning for future needs and fire demands, often resulting in oversizing the system for current water use (U.S. EPA, 2002). While the system as a whole may be oversized, the flow through the system remains relatively constant. In premise plumbing, the largest factor in determining water age is how water is used. Traditionally, potable water is used for bathing, cleaning laundry and dishes, toilet flushing and landscaping, along with human consumption. In green buildings, when alternative water sources are used for toilet flushing and landscaping, all else remaining the same, the amount of total potable water demand decreases and water age within green buildings increase.

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3.1.2 Anticipated link to green buildings

Increased water retention times inherent to plumbing systems focused on water conservation can be expected to exacerbate mechanisms causing loss of disinfection residuals. For example, higher water age can increase the likelihood of nitrification in both main and premise plumbing distribution systems (Zhang et al., 2009). Nitrification not only directly consumes the chlorine-bound ammonia in chloraminated systems via production of nitrite (Zhang and Edwards, 2009; Nguyen et al., 2012), but can also decrease the target pH of the water (Thomas, 1987) and decrease the effectiveness of corrosion inhibitors (Hatch and Rice, 1945; Rompre et al., 1999), both of which can exacerbate the rapid loss of chlorine and chloramine residuals (Nguyen et al., 2012). The stagnant conditions in plumbing systems can also contribute to elevated water temperatures, which increase the abiotic decay of residuals (Hua et al., 1999).

3.1.3 Chlorine and chloramine decay

Chlorine and chloramine decay can occur from both abiotic and biotic reactions. Abiotic reactions include autodecomposition and reactions with pipes or other constituents in the water that consume the chlorine residual. Biotic reactions include any metabolism-driven reaction that consumes disinfectant. Both chlorine and chloramine react with corrosion scale on pipe walls (e.g., LeChevallier et al., 1990; Zhang and Edwards, 2009), but it is generally thought that chlorine reacts much more quickly and indiscriminately than chloramine (especially with iron) when penetrating biofilms or pipe scales, (LeChevellier, 1990). The greater persistence of chloramines is somewhat countered by its reduced effectiveness as a biological disinfectant at the same dose of chlorine, as Cl_2. However, there have been instances when utilities believed they had greater longevity of chlorine than chloramine in distribution systems (Powell, 2004), and recent laboratory work has confirmed this for systems undergoing rapid nitrification (Zhang and Edwards, 2009).

For both disinfectants, there are several key water quality parameters that play a role in the rate of decay reactions that can occur. The elevated temperature of premise plumbing in comparison to the utility distribution network accelerates decay reactions (Gray et al., 1977; Lister, 1956; Adam and Gordon, 1999). Hua et al., (1999), has shown that chlorine decay rates have increased by a factor of two with 10 °C increase in temperature at lower temperature ranges (10-20°C). Greater ionic strength in water has been shown to increase free chlorine decay rates (Adam and Gordon, 1999). In addition, the abiotic autodecomposition rate for chloramines doubled for each 0.7 decrease in pH in one water tested (Thomas, 1987). In reactions with pipe corrosion and scale, the presence of moderate to high levels of natural organic matter (NOM; Ndiongue et al., 2005; Boulay and Edwards, 2001), silica (Davis et al., 2002), and phosphates (Edwards et al., 2002; Schock et al., 2005) can inhibit metal release and promote conversion of pipe scale to a more insoluble solid, thereby preventing or slowing the reaction of pipe scale with disinfectants (Nguyen et al., 2011). However, this also can slow the rate of pipe aging, releasing soluble metallic complexes over a longer time period that may increase the chlorine demand overall depending on exact water chemistry (Edwards et al., 2001).

For chloraminated systems, the effect of corrosion inhibitors such as phosphates is not straightforward when nitrification is occurring in the plumbing system. Nitrification has a two-fold effect on chloramine decay. First, it consumes ~7 mg of $CaCO_3$ alkalinity for every 1 mg of ammonia oxidized, facilitating a reduction of pH concurrent with nitrification (Zhang, 2008), which tends to increase abiotic chloramine decay (Thomas, 1987). Second, when ammonia

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concentrations are low in the bulk water, nitrite produced by nitrifying bacteria consumes chloramines and releases the ammonia as a nutrient source (Margerum et al., 1994). The introduction of phosphates can reduce the concentration of soluble metallic ions in the water by forming a relatively insoluble scale layer on the pipe wall (Schock and Lytle, 1995), thereby preventing their reaction with the disinfectants and slowing this chloramine decay reaction. Phosphate may also reduce soluble copper levels below the 0.09 mg/L that is toxic to nitrifiers (Zhang et al., 2009), so it was speculated that higher levels of phosphate might reduce Cu^{+2} toxicity to nitrifiers especially at higher phosphate doses (Figure 3.1). However, phosphorous is also a nutrient for bacterial growth, and could aid in nitrification growth in some scenarios (Zhang et al. 2008). Therefore, there is some theoretical balance to the benefits and detriments of phosphate addition.

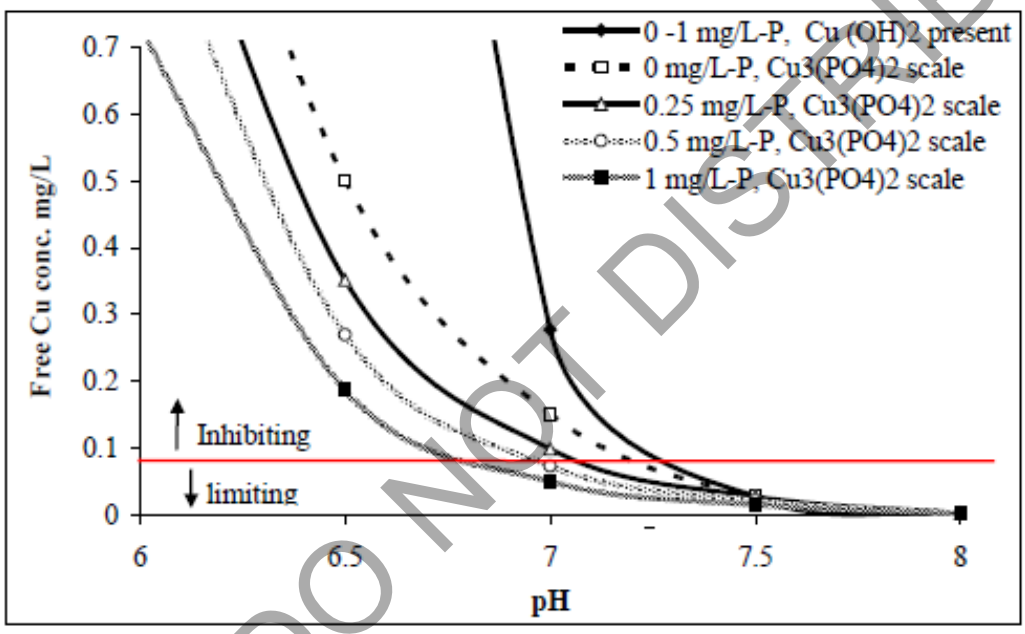

Figure 3.1 Free Cu2+ concentrations present in relation to pH and phosphorus levels (Reproduced from Zhang et al., 2008)

To a lesser extent than the metallic oxides of iron (LeChevallier et al., 1990) and copper (Gray et al., 1977; Zhang and Edwards, 2009) pipe material, other metal catalysts such as nickel, manganese, and colbalt react with chlorine residuals (Ayers and Booth, 1955). In addition, chemical constituents SO_3^{2-}, I^-, Br^-, NO_2^- consume chlorine residuals (Johnson and Margerum, 1991). There is also some evidence that soluble microbial products (Krishna and Sathasivan, 2010) and biofilms (Lu et al., 1999) have at least some level of chlorine demand, although it has not been quantified.

Hallam et al. (2002) found that some pipe surfaces have much more inherent chlorine demand than any of the constituents in the bulk water investigated. Plastic pipes (PVC and MDPE) exhibited a much smaller chlorine demand than cast iron and other metal pipes (0.09 hr^{-1}, 0.05 hr^{-1}, and 0.67 hr^{-1} for PVC, MDPE, and cast iron respectively; Hallam et al., 2002). Pipe material and age also play a role in chlorine demand. Al-Jasser (2007) conducted a study on a variety of pipe materials, diameters, and ages. There were several general trends that seemed to have implications for the overall chlorine demand over the life span of the system. For instance, metallic

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pipes (cast iron and stainless steel) consumed more chlorine as they aged, probably due to the accumulation of corrosion products. The plastic pipes (PVC and MDPE), however, consumed less chlorine as they aged, exerting no demand after about 10 years in service. The diameter of the pipe had an effect on chlorine decay for all pipe materials studied. As the diameter decreased, more chlorine was generally consumed due to the increasing surface area to volume ratio and reactions with the pipe wall. This has a competing effect with designing water age. As pipe diameters are decreased to compensate for the lower overall water demand in green buildings, the reactions with pipe materials may consume more chlorine than the reduction in chlorine decay seen by decreasing the water age. Theoretically, there should be an optimum pipe diameter for a designed water age where an iterative design could minimize disinfectant losses for a given material.

In addition to prolonging direct reactions with pipe materials, water age effects several of the factors mentioned that contribute to decay. Increased nitrification and copper release have been linked to increased water age (Murphy et al., 1997; Zhang et al., 2009). Low water flow rates may also contribute to retarding the aging process for certain plumbing materials (Nguyen et al., 2012), resulting in the continued release of metals and extending the life span of the accelerated residual decay.

3.1.4 Remediation strategies

Several options for maintaining effective levels of disinfection residual in distribution and premise plumbing systems have been suggested. For distribution systems, these include breakpoint chlorination (Harms and Owens, 2003; Odelle et al., 1996; Skadsen, 1993), limiting the use of pipe and in-line product materials and substances with high inherent chlorine-demands (Harrington et al., 2002; Song et al., 1999), increasing the chlorine:ammonia ratio in chloraminated systems (optimal ratio of 5:1; Odell et al, 1996; Wilczak et al., 19996; Karim and LeChevallier, 2006), increasing the concentration of total residual applied, increasing the pH (Harrington et al., 2002; Skadsen, 2002), increasing reservoir turnover (Skadsen, 1993), and flushing the system (Harrington et al., 1996). For premise plumbing systems, little work has been done evaluating the persistence of disinfectant residual in premise after treatments. When, in hospitals and other health care facilities, in-building treatment is desired or required, most case studies simply determine if there is a residual at distal taps after the implementation of the treatment. However, when no residual is present, flushing less than 1% of the total daily water at the end of the premise plumbing distribution system use was effective in one case (Nguyen et al., 2012; See Chapter 4 – OWASA UNC-CH case history). Although all of these techniques have proven successful in certain waters, no one method has worked for all distribution and premise plumbing systems. For buildings with high water ages, simply flushing the system should be implemented if nearby conventionally designed buildings with no special water conservation systems are not having similar issues.

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3.2 ANTICIPATING ISSUES WITH IN-BUILDING DISINFECTION SYSTEMS

Key words: Building disinfection, ASHRAE Standard 188, Unintended consequences
Note: This work was published, in part, in Rhoads et al., 2014

3.2.1 Introduction

A key challenge of water treatment is to ensure that safe potable water produced by utilities will not damage water distribution system infrastructure. It has recently been recognized that the biological and chemical quality of water delivered to buildings often deteriorates within the building's premise plumbing system. Premise plumbing is defined as the portion of the distribution network on the building owner's side of the property line and not completely controlled by utilities. The National Research Council (NRC) has identified premise plumbing as a high priority area for research (NRC, 2006). While the direct focus of most research is to protect public health, any changes must carefully balance corrosion control, scaling, operation/maintenance, energy conservation, scalding, and other considerations along with public health goals (NRC, 2006; Brazeau and Edwards, 2012) given that privately owned plumbing systems represent an asset valued on the order of a trillion dollars (Edwards, 2004).

Opportunistic premise plumbing pathogens (OPPPs) are now the leading cause of water borne disease in developed countries (CDC, 2011). Representative OPPPs include *Legionella* spp. (with emphasis on *L. pneumophila*), *Mycobacterium avium* complex (MAC), *Pseudomonas aeruginosa*, *Acanthamoeba* spp., and *Nagleria fowleri*. Growth of OPPPs generally occurs in the bulk water and biofilms within premise plumbing; however, cooling towers and other systems are also very important sources of these pathogens. Attempts to control OPPPs can include secondary disinfection applied by utilities, but OPPPs are also frequently controlled by treatment within buildings, as is evident in historical treatments within hospitals (e.g., Stout et al., 2007; Srinivasan et al., 2003). Even if the utility employs aggressive levels of disinfectant residuals to control OPPPs, the strategy can be undermined either passively (e.g., normal chlorine decay) or actively (e.g., granular activated carbon treatment that removes chlorine) in buildings. The emerging shared responsibility for control of this public health concern complicates implementation of effective controls, and knowledge regarding their efficacy and secondary impacts on premise plumbing infrastructure is currently incomplete.

Premise plumbing systems can sometimes have low or no secondary chlorine residuals due to long water retention times and/or a high tendency of premise plumbing pipes to form corrosion scale. Corrosion scale and premise plumbing materials consume chlorine (Nguyen et al., 2011; 2012; Zhang et al., 2009). The rate of decay is dependent on various factors, including water chemistry, disinfectant method, plumbing system design, and plumbing system operation. In some situations there is likely little the water utility can do to cost-effectively control OPPPs for the entire range of situations encountered within individual buildings.

In-building disinfection approaches that have demonstrated effectiveness include both remedial (i.e., one-time treatments, usually in response to an outbreak) and continuous disinfection regimes. Remedial techniques include: 1) thermal and 2) chlorine shock. Continuous treatments include: 1) dosing chlorine, 2) chloramine, 3) chlorine dioxide, 4) ozone, 5) copper-silver ionization, 6) ultra-violet light irradiation, 7) peroxide, 8) applying thermal control, and/or 9) proprietary controls sold commercially. Field and case studies have demonstrated, mostly in hospital settings, these methods can be effective for some OPPPs in some situations, but for reasons not currently well understood they are less effective in other situations. To begin to

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address knowledge gaps, a recent report synthesized the current state of knowledge of OPPPs and their control, summarizing several factors required for pathogen growth, routes of exposure, and rates of disease occurrence (Pruden et al., 2012). The inherent complexity and variability in premise plumbing systems often makes it difficult to predict, diagnose, and remediate outbreaks of waterborne disease originating in premise plumbing.

This section of the review is focused on Legionnaires' disease (LD) because it is the most common waterborne disease in the United States (CDC, 2011). *L. pneumophila* is the main causal agent of LD and is illustrative of other OPPPs. Many strategies controlling LD outbreaks and mitigating *L. pneumophila* growth may be applicable to other OPPPs.

3.2.2 Guidelines for control of *Legionella*

Several government and private entities have developed guidelines to follow in the event of a LD outbreak. The most prominent include recommendations of the World Health Organization (WHO) (Bartram et al., 2007), the Florida Department of Health (Florida DoH), Association of Water Technologies (AWT, 2003), the Allegheny County Health Department (ACHD, 1997), the Occupational Safety and Health Administration (OSHA, 1999) and the American Society for Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE, 2000; 2012). The focus of these guidelines, until recently, has been on remedial actions to be taken after an outbreak occurs. These recommendations often cover basic disinfection procedures, requirements for epidemiological studies, and how to maintain a safe plumbing system after disinfection. There has been little focus on preventative measures and none of the guidelines recommend monitoring of target organisms as a long-term preventative or follow-up procedure.

A reluctance to recommend monitoring could be due, in part, to the variation in sampling procedures and sample analysis methods across institutions and research labs. A recently conducted expert workshop identified the difficulty of comparing results between methods and techniques as a research gap for detection and quantification of OPPPs (Pruden et al., 2012). Although there are standard sampling and analysis protocols for culture methods for *Legionella* (Barbaree, 1987), these are fraught with limitations and inconsistencies in results. While molecular-based methods are promising, consensus is still needed in their application. Therefore, while some of the sampling guidelines exclusively support culture methods as an important method of assessing *Legionella* risk, more quantitative measurements would better inform medical health scientists about dose-response relationships related to disease caused by OPPPs. In general, microbiological sampling for *Legionella* is ambiguous because presence, according to culture-based detection of *Legionella* does not necessarily predict the occurrence of disease (Stout et al., 2007). While some guidelines refer to 30% of total samples positive for *L. pneumophila* as a trigger for remedial measures, the guidelines do not recommend where to take samples or how many should be taken. In addition, the accuracy and utility of the 30% action level is questionable. For example, in one building the majority of taps in a building (83%) were positive for *L. pneumophila* serotype 1, but were not associated with disease, while a low number of positive taps in another building (30%) resulted in cases of LD (Stout et al., 2007). Therefore, there is a need to better understand sampling methods, analysis and data interpretation relative to prevention of OPPP outbreaks.

ASHRAE Standard 188 is the most recent and first legally enforceable standard dealing with control of *Legionella*. It is in its third public review at the time of writing. This standard is written in typical code-type language, so that it can be easily adopted by local jurisdictions. Upon

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adoption, it would be enforced by the regulatory structure in place in that jurisdiction. The building owners, therefore, would be subject to meet the requirements set forth by the standard. The basic requirement of ASHRAE 188 is a written Hazard Analysis Critical Control Point (HACCP) plan that addresses all aspects of prevention of, response to, and long-term control of *Legionella* outbreaks. It uses the concept of the HACCP plan to require building owners and operators to have preventative and reactive measures in place before an outbreak occurs.

Overall, ASHRAE 188 is a three-tier standard (Figure 3.2). First, if there are no risk factors associated with a building, then a simple yearly survey is conducted to ensure none have developed.

Second, rather than collecting samples and monitoring *Legionella*, it identifies risk factors for outbreaks (Figure 3.2). If a building meets any risk factors, there must be an HACCP plan in place that meets all the HACCP plan requirements. These include: 1) conducting a hazard analysis, 2) determining the critical controls points, 3) setting critical control limits for the critical control point, 4) establishing a system to monitor control of the critical control points, 5) establishing actions to be taken when monitoring results indicate critical control limits have been violated, 6) establishing procedures to confirm the HACCP plan is working effectively, and 7) establishing documentation for all procedures and records appropriate to the principles and application of the HACCP plan. In order to address water-specific requirements of the HACCP plan, the standard refers to ASHRAE Guideline 12 (2000) to prevent LD. That guideline, in turn, promotes the use of in-building disinfection systems for long-term prevention of LD.

The last tier of ASHRAE 188 is specific to buildings with cooling towers and/or evaporative condensers for the heating, ventilation, and air-conditioning systems as these systems have been linked with LD outbreaks (Cordes et al., 1980; Dondero et al., 1980; Nguyen et al., 2006). Details of this requirement of the standard are beyond the scope of this section.

Although ASHRAE 188 is a step toward assigning enforceable responsibility for preventing disease outbreaks, it is in some ways imperfect and unrealistic. For instance, one risk factor the standard identifies is having an influent chlorine residual below 0.5 mg/L as Cl_2. While it seems easy to measure the influent chlorine residual as a quick and simple check, in practice the residual will vary markedly with system water demand and season. In some systems there may be a residual present only after extensive flushing in the summer, but could be present at all times during the winter due to temperature effects of residual decay. It is unclear how this is addressed in the standard. In addition, although the standard refers to a comprehensive guideline in preventing LD outbreaks (ASHRAE, 2000), neither the standard nor the guideline provide a basic framework for determining which remedial action(s) or continuous disinfection systems are optimal for different water qualities, system design features, or intended uses. While it is important to maintain safe drinking water, some of the in-building techniques suggested in *Legionella* control guidelines and peer-reviewed literature are lacking basic research dealing with how different water chemistries or different premise plumbing materials affect disinfection efficacy. In general, complex premise plumbing networks resulting from water conservation efforts may create unintended consequences for treatments that are not thoroughly understood.

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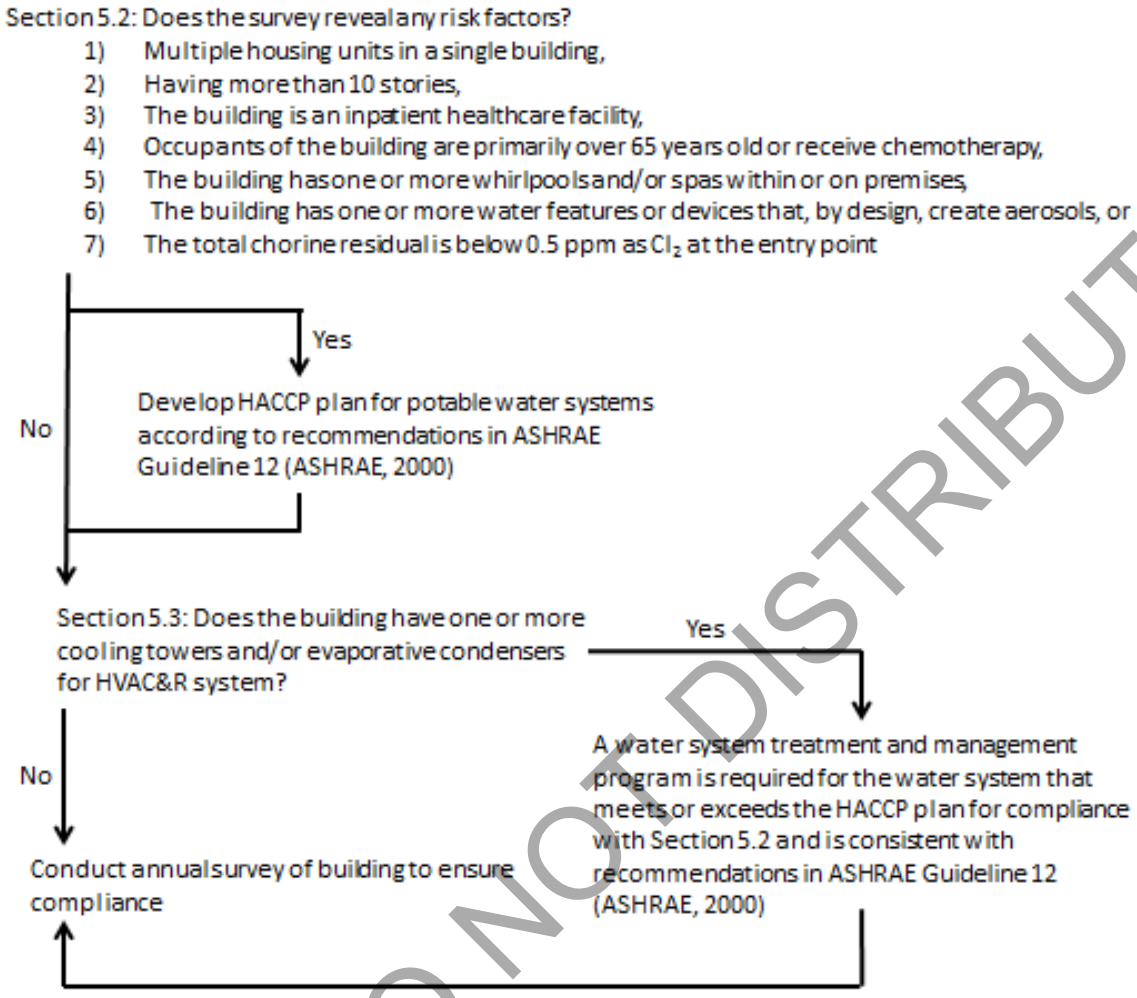

Figure 3.2 ASHRAE Standard 188 flow diagram of requirements (Adapted from Rhoads et al., 2014)

The following sections summarize remedial (i.e., one-time thermal or chemical shock) and long-term (i.e. continuous) disinfectant methods, with a focus on factors influencing site dependency, compatibility with plumbing systems, and knowledge gaps. While most guidelines provide the basic pros and cons of viable treatment options, at present there is no logical framework for holistic decision making. Only WHO includes sections with details on identifying and monitoring control measures based on the intended use of potable water in specific applications (Bartram et al., 2007). For example, a hospital intensive care unit has a much different risk associated with consumer exposure than does a cruise ship residential cabin with respect to the presence of immunosuppressed individuals. When choosing a remedial disinfection method, the intended use and consumers should play a role in the decision-making process.

3.2.3 Review of remediation-based techniques

The goal of remediation is to disinfect a system that is known or suspected to be contaminated with pathogenic bacteria, often in response to an outbreak of waterborne disease.

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Two categories of remediation include thermal and chlorine shock treatments.

3.2.3.1 Thermal shock. For hot water systems, thermal shock is commonly the first choice because temperature inactivation is proven effective. Although guidelines vary slightly as to which temperature should be used and the duration of exposure (Table 3.1), thermal shock generally targets attaining water temperatures above 60˚C for 20-30 minutes while flushing taps, or achieving temperatures greater than 80˚C at least momentarily at all points in the plumbing system. It can be logistically challenging to maintain high enough water temperatures throughout the entire plumbing network to be effective in large systems (Muraca et al., 1990). Plastic pipes used in hot water systems such as chlorinated polyvinyl chloride (CPVC) pipes are rated to withstand temperatures up to 82˚C (180˚F) for continuous use (e.g. Harvel, Gerog Fischer Piping Systems, Easton, PA); however, there has been no research on the effects of continuous or repeated heat exposure on physical integrity or leaching from other types of plastic pipes including PEX and HDPE. In addition, none of the guidelines that recommend thermal shock treatment for *Legionella* remediation warn building owners or operators against the potential for rapid scaling, or the precipitation of calcium carbonate [$CaCO_3$] catalyzed by elevated temperatures in hard waters, a factor discussed later in this section.

3.2.3.2 Chlorine Shock. Dosing a high concentration of free chlorine is another common remediation strategy. The recommended concentration for disinfection varies. The Florida Department of Health (FL DoH) recommends that 20-50 mg/L free chlorine as Cl_2 be maintained in hot water tanks with a minimum concentration of 2 mg/L Cl_2 in the plumbing system for two hours. OSHA recommends 10 mg/L Cl_2 in hot water systems (OSHA, 1999). Others do not recommend a specific exposure time or target concentration, but require that there is no more than 30% reduction of the original concentration over the test period (AWT, 2003; ACHD, 1997).

There is ambiguity about protocols for "passing" shock chlorination recommendations listed above in terms of how and when to take residual measurements. For instance, new copper pipes in some waters will not pass the shock treatment requirements (BOCA, 1997; Edwards et al, 2011; International Code Council, 2000) due to rapid consumption of the chlorine by the pipe wall (Edwards et al., 2011; Nguyen et al., 2011). Even repeated doses may not satisfy the chlorine demand and there are also concerns about initiating non-uniform pitting corrosion (Rushing and Edwards, 2004; Cong and Scully, 2010; Sarver et al., 2011). To counter this effect, pH may be maintained at lower levels (< pH 8) or a corrosion inhibitor may be introduced to reduce copper corrosion, adding further complexity to the method. Maintaining the pH, while a viable strategy, adds the need for the ability to monitor and adjust pH and chlorine levels. This may be beyond the scope of most building maintenance staff personnel. In addition, the surface of high density polyethylene (HDPE) pipes subjected to repeated shock chlorination can be damaged, leading to reduced overall lifetime (Whelton and Dietrich, 2008; Whelton et al., 2011).

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Table 3.1
Summary of thermal-based guidelines for control of Legionellosis (Source: Rhoads et al., 2014)

Entity	Shock Recommendation	Long-term Recommendation	Caution Against Scalding	Caution Against Pipe Damage in Long-Term Recommendations (e.g. scaling)	Recommend Repeated Thermal Shock
Florida DOH	Heat HWHs to 71-77ºC for 24 hr, then flush each tap for 5-20 minutes	Set HWHs to 60ºC; drain periodically to clean; hot-water recirculation pumps run continuously	Yes	No; allude to systems where thermal shock is not possible	Yes; when systems cannot be set at 60ºC because of scalding (retrofit with mixing valves not possible)
OSHA	Heat HWHs to 70ºC for 24 hrs; flush each tap for 20 minutes	Set HWHs to 60ºC with minimum delivery temperature of 50ºC; drain periodically to clean; hot-water recirculation pumps run continuously	Yes	No	No
WHO	No temperature or exposure time recommended for pasteurization; Periodic flushing with waters 50-60ºC	Maintain all water temperatures > 50ºC	Yes	No	No
ASHRAE	Periodically raising HWHs to 66ºC followed by flushing	Store water at 60ºC; Maintain minimum return temperature 51ºC; Where not practical maintain all water temperature above 49ºC	Yes	No	Yes; when long-term temperature maintenance not possible
AWT	Heat HWHs >60ºC; preferably 66ºC; flush for up to 30 minutes	Has no long-term recommendations, but states in review that at 50ºC, there is 90% kill with 2 hour exposure	Yes	No	No

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3.2.4 Review of continuous disinfection practices

After a LD outbreak has occurred and remedial treatments have been implemented, or if a plumbing system is considered conducive to pathogen growth by the new ASHRAE standard, continuous in-building disinfection practices may be considered. These include 1) chlorine, 2) chloramine, 3) chlorine dioxide, 4) ozone, 5) copper-silver ionization, 6) ultra-violet light irradiation, 7) peroxide, 8) thermal control, and 9) proprietary controls. For some of these systems, factors mediating the efficacy towards target pathogens and interaction with plumbing are unclear, especially in relation to application in different water qualities and across different premise plumbing materials.

There may also be regulatory and legal implications to installing additional disinfection practices for in-building applications. For example, the U.S. EPA indicates that any building serving more than 25 individuals dosing a disinfectant is considered a public utility, triggering onerous drinking water standards and associated monitoring requirements. This makes installation of a secondary disinfection system considerably less attractive, or may encourage "unofficial" building-level disinfection systems in some circumstances.

These systems are also difficult to evaluate on a comparative basis. High variability in case study designs, intervention and control measures taken, and application of successive disinfectant patterns makes cross comparison of studies and disinfection methods difficult. Most field studies have been conducted in hospitals or other special care facilities, and application to smaller private homes or small apartment buildings with less maintenance staff are not widely available. The following summarizes literature on each disinfection method, with a focus on implications for premise plumbing.

3.2.4.1 Chlorine and chloramine. While there are over 190 years of experience using chlorine and chloramine as disinfectants (USEPA, 2011), it has only recently been recognized that these disinfectants can sometimes disappear quickly via reactions within premise plumbing systems, even when they are stable in the main distribution network (Zhang et al., 2009; Zhang and Edwards, 2009; Nguyen et al., 2011; 2012). Although both chlorine and chloramine are widely-used for utility distribution system applications (Seidel et al., 2005), dosing of these disinfectants within buildings may have maintenance and corrosion challenges that exceed the capabilities of many building staff. Unfortunately, there is not a large body of research on the application of chlorine and chloramine at the building-level, and it is now known that higher levels of these disinfectants can sometimes cause severe pitting of copper pipe (Sarver et al., 2011; Rushing and Edwards, 2004; Marshall, 2004; Lytle and Schock, 2008).

Chlorine is a strong oxidant that can react with many common plumbing materials including lead, PEX, copper, and brass but apparently not PVC (Sarver et al., 2011; Nguyen et al., 2012; Whelton et al., 2011; Edwards and Dudi, 2004). It can be dosed at the building-level as a powder or liquid targeting concentrations of 1-2 mg/L free chlorine (Muraca et al., 1990). It is well known that certain water chemistries can accelerate or inhibit corrosivity of chlorine towards specific building plumbing materials. For instance, maintenance of a lower pH, presence of natural organic matter, dosing a corrosion inhibitor such as poly- or ortho-phosphate, or natural silica can be effective in limiting the rate of chlorine induced pitting of copper tubing (Rushing and Edwards, 2004; Sarver et al., 2011; Lytle and Schock, 2008). Chlorine can also benefit some copper pipes by converting soluble cupric hydroxide [$Cu(OH)_2$] to tenorite [CuO], reducing aqueous copper and chlorine concentrations markedly (Edwards et al, 1996; Edwards et al., 1999; Hidmi and Edwards,

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1999; Lagos et al., 2001; Patterson et al., 1991; Schock et al., 1995; Nguyen et al., 2011). In some waters without disinfectant residuals the conversion of $Cu(OH)_2$ to CuO or other stable species never occurs, resulting in persistent blue water or blue staining of fixtures until at least a trace of chlorine residual is present (Edwards et al., 2000).

While chloramine has been used at some U.S. utilities since the 1930s (U.S. EPA, 2011), many utilities switched to chloramine as a secondary disinfect in response to the Disinfection Byproduct Rule passed in 2003 (Seidel et al., 2005). Target levels of chloramine are up to 4 mg/L as Cl_2 (U.S. EPA, 2009). Chloramine only reacts weakly with natural organic matter to form disinfection byproducts such as trihalomethanes. For this reason it tends to be more persistent than chlorine in the main distribution system (Neden et al., 1992). However, in premise plumbing with longer stagnation times, greater surface area to volume ratios, more reactive materials, higher levels of microbes, and warmer waters, chloramines can decay rapidly (Nguyen et al., 2012). Nitrifying bacteria, in particular, can cause rapid decay of chloramine via formation of nitrite in premise plumbing (Nguyen et al., 2012; Zhang et al., 2009; Zhang and Edwards, 2009).

3.2.4.2 Chlorine Dioxide. For chlorine dioxide there is a body of literature indicating that it is sometimes effective in hospital applications for prevention and remediation of *Legionella* colonization (Stout and Yu, 2003). However, even relative to the scarce field data on chloramine and chlorine as in-building disinfectants, there is even less research that examines the effects of water chemistry and pipe material on its efficacy, corrosivity, or stability at distal taps. Each of these factors is important in understanding how chlorine dioxide may be utilized most effectively for OPPP control in a given premise plumbing system.

For in-building applications, chlorine dioxide gas is mechanically or electrochemically generated from a sodium chlorite solution. Commercial kits (e.g. Halox Technologies Corporation, San Antonio, Texas) have been developed for small to medium applications and are relatively easy to install and run. Chlorine dioxide is injected based on flow rate to a final concentration not to exceed U.S. EPAs 0.8 mg/L ClO_2 maximum residual disinfectant level(MRDL) (U.S. EPA, 2009). Special consideration must be taken with the formation of chlorite in systems with susceptible hospitalized patients (Bartram et al., 2007). Although limited work has been done in this area, animal and human studies have indicated that individuals susceptible to oxidative hymolysis (e.g., immunocompromised individuals whose red blood cells are Glucose-6-phosphate dehydrogenase (G6PD) deficient), can become anemic when using water treated with chlorine dioxide (Moore et al., 1978; Calabrese, 1978). Some systems using chlorine dioxide have failed to observe these adverse effects (Smith and Willhite, 1990; Ames and Stratton, 1987). However, when exposure to individuals at risk is likely, including anemic young children and fetuses of pregnant women, the residual should be removed by activated carbon or other treatments before use (Srinivasan et al., 2003). Although it sometimes takes several months and continuous application for chlorine dioxide to become effective in OPPP control, it is claimed to completely eliminate *Legionella* spp., even at residuals below U.S. EPA maximum levels (Sidari et al., 2004). At these levels, there is no significant increase in corrosion rates (Srinivasan et al., 2003) and they can be effective for infrequently used branches of the distribution systems (Thomas et al., 2004). One field application study showed that over 17 months, distal taps colonized by *Legionella* were minimized from 45% positive (no in-building control) taps to 4% positive (with chlorine dioxide; Srinivasan et al., 2003). However, there is decreased persistence of the disinfectant residual with higher temperatures, increasing total organic carbon (TOC) concentrations (Zhang et al, 2006 as cited in Zhang et al., 2008), and iron and copper corrosion scale (Zhang et al., 2008).

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Although chlorine dioxide is relatively non-reactive with TOC, reactions with minerals such as goethite, magnetite, and cuprite theoretically would consume residuals (Zhang et al., 2008). In addition to potentially rapid abiotic decay with pipe scales, the effectiveness of chlorine dioxide may be further inhibited because it is not effective in eliminating amoeba hosts in biofilm growth in cool (35˚C) water systems (Thomas et al., 2004). Planktonic *Legionella* was removed in this study, but rapid regrowth occurred in the absence of continual treatment, hypothesized to be due to the host capabilities of amoeba for *Legionella* (Thomas et al., 2004). Some researchers have reported a resistant subpopulation of *L. pneumophila* and *E. coli* in controlled batch experiments (Berg et al., 1988), yet no follow up work has been done to confirm these observations.

3.2.4.3 Ozone. Ozone [O_3] is generated from oxygen [O_2] and dosed based on flow rate to a residual of 1-2 mg/L. It is a very potent biocide and has the capability to inactivate viruses. It has to be produced on-site due to its extremely short half-life. From a practical standpoint, some have reported issues with retrofitting systems with ozone dosing equipment (Muraca et al., 1987). In addition, the systems are technically challenging to maintain and can be very expensive (Muraca et al., 1987). Although ozone requires a short contact time, no disinfectant residual beyond the point of treatment is present. The efficacy is not generally affected by temperature or pH changes in bench-scale studies (Domingue et al., 1988), but some research has shown that ozone reacts more rapidly and less discriminately at higher pHs (>7) (Hoigne and Bader, 1976). Unlike chlorine dioxide, ozone is capable of reducing established biofilms at 0.5 mg/L (Thomas et al., 2004), but controlled studies on the corrosivity of ozone is lacking. It has been shown that there can be 99% reduction of *L. pneumophila* with only a 5 minute reaction period in laboratory, batch-reactor studies (Domingue et al., 1988), but long term efficacy is still unknown (Muraca et al., 1987).

3.2.4.4 Copper-Silver Ionization. Copper and silver ions dosed into water lyse bacteria and protozoa cells and denature their proteins (Lin et al, 1998). The recommended dose of the ions is 0.2-0.4 mg/L copper and 0.02-0.08 mg/L silver, depending on water quality (Cachafeiro et al., 2007). In some systems, these levels of copper can be maintained naturally by corrosion and dissolution from existing copper pipes. The WHO recommends levels up to 2 mg/L copper (WHO, 2008) and 0.1 mg/L silver (WHO, 2008). This concentration of copper exceeds U.S. EPA's action level in cold water, but because hot water is not intended for human consumption this may not have the same health implications. However, the concentrations that would be required to be effective in certain water qualities may conflict with goals of low copper in sewage influent and effluent (Cachafeiro et al., 2007; Boulay and Edwards, 2000). In addition, cooper and silver levels above 0.02-0.04 mg/L may cause discoloration of water or plumbing devices in some waters (Stout et al., 2003). Basic, lab-scale research on its effectiveness is also lacking.

Liu et al. (1998) conducted a case study in a building with a copper-silver ionization system versus a control building with no ionization system. Initially, the test and control buildings had 50% and 20% taps positive for *Legionella*, respectively, before the installation. After four weeks of treatment, 0% of the taps in the test building were colonized and remained at 0% until week 22, six weeks after copper-silver injection had been stopped. The control building fluctuated between 20%-100% positive taps throughout the study, with a mean of 83%. Alternatively, Blanc et al. (2005) observed that before installation of a copper-silver ionization system, 90% of taps in a test building were colonized with *Legionella* while 66% taps in a control building were colonized. After installation and deployment of the ionization system, 93% and 56% of the test and control buildings, respectively, were positive, indicating that the approach was not effective in this water.

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This was attributed to lower concentrations of silver that were used and the higher pH of the water (Blanc et al., 2005). Copper silver ionization is most effective when concentrations can continually be monitored and adjusted (Bartram et al., 2007), requiring special equipment and expertise.

Knowledge of how water quality parameters affect treatment efficacy would be helpful when evaluating treatment options. It is likely that pH, alkalinity, phosphate and other water constituents affect efficacy for controlling OPPPs, as has been observed for other premise plumbing microorganisms (Zhang et al., 2009). Yet, limited work has been done in this area. Although there is no one optimum concentration of copper and silver ions, there is a synergistic effect when they are used at the upper range of the allowable concentrations (Lin et al., 2002). However, there is a large gap in knowledge from aquatic toxicity literature and observational field studies in implementing these systems. In most field studies of copper silver ionization systems the speciation of the metal ions dosed is not measured as it travels throughout the plumbing system (e.g. Stout and Yu, 2003), yet the toxicity literature suggests that speciation is an important factor and highly dependent on pH (Franklin et al., 2000). In some cases the ions can be consumed by the plumbing and background water chemistry (Loret et al., 2005). Some work has been completed in this area, examining the effect of pH and other water quality parameters on the efficacy of silver and copper ions. Lin et al., 2002 determined that at pH 9, copper ions were not effective in eliminating *Legionella* due the speciation of copper ions in the water compared to pH 7. At pH 7, more free copper ions exist in the water than at pH 9, where solids begin to form and do not interact with the bacteria. They determined that there was no such effect with the silver ions. There is also some evidence that copper and silver ions are not able to penetrate established biofilms (Thomas et al., 2004). Lastly, copper ions can also cause severe deposition corrosion of galvanized or steel plumbing systems or components (Kenworthy, 1943; Cruse, 1971), and silver ions might also attack copper pipes and other metals by the same mechanism (Clark et al., 2011).

As of February 1, 2013, copper ionization systems are no longer permitted to be marketed or installed in countries under European Union jurisdiction because “no manufacturer took sufficient action to support the biocidal use of elemental copper during a review period that ended in September 2011” (HSE, 2013).

3.2.4.5 Ultraviolet Light. Ultraviolet (UV) light irradiation at 254 nm damages DNA and disrupts microorganisms ability to replicate, preventing regrowth. For in-building use, there are many commercial systems that range from 3.7 L/min (1 gpm) to 1900 L/min (500 gpm) that require only basic plumbing skills and an electrical outlet, with a wide price range for the initial setup. There is minimal maintenance involved, including replacing the UV bulbs approximately annually and cleaning the quartz sleeve that the water flows through quarterly. The efficacy of UV treatment is dependent on low turbidity water and temperature fluctuations are known to alter the efficiency of treatment (Muraca et al., 1990). There is the opportunity for breakthrough of microbes shielded by small particles or for amoeba present in the protective cyst stage of their life-cycle. Like ozonation, there is no disinfectant residual thus there is no inactivation of microbes that may proliferate downstream of the treatment and no biofilm disinfection. On the basis that necrotrophic growth occurs after short-term thermal disinfection, generation of dead cells might be expected to be problematic with UV treatment as well. If downstream growth is of concern, UV may be most effective in combination with other treatment options (Bartram et al., 2007).

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3.2.4.6 Thermal Disinfection. Perhaps the simplest continuous disinfection method to employ is thermal control. In general, it is thought that bacterial growth is limited in cold water systems below 20˚C (Bartram et al., 2007, AHSRAE, 2000, Florida DOH) and in hot water there is nearly immediate eradication of bacteria above 60˚C (Muraca et al., 1987). The U.S. EPA currently recommends a hot water heater set point of 48 ˚C for domestic systems to reduce the risk of scalding consumers and for the assumed energy savings of cooler water temperature (U.S. EPA, 2004). While 48 ˚C is less likely to scald consumers or foul plumbing systems with scale, it is also less likely to reduce risk of exposure to heat-resistant pathogens (NRC, 2006; Brazeau and Edwards, 2012). In general, there is a major need for practical research aimed at aiding basic decision- and policy-making logic in hot water infrastructure. While certain localities have adopted a tax-credit system for the installation and specific operation of certain hot water systems for in-home and -building applications (Brazeau and Edwards, 2012), there may be long-term, unintended negative consequences associated with these across-the-board recommendations. The new ASHRAE 188 standard for control of *Legionella* growth recommends maintaining water tanks above 60 ˚C and 51 ˚C throughout the entire water network.

Scalding potential must be taken into consideration. It has been estimated that 3,800 injuries and 34 deaths occur from tap water scald burns annually (CPSC, 2005). Young children are especially at risk for scald injuries (NSKC, 2004). Where applicable, mixing values that blend hot and cold water can be used to prevent scalding during treatment. Otherwise, special means to inform occupants of the disinfection should be taken to avoid scalding. Although thermal disinfection can be effective for controlling *Legionella* (Kim et al., 2002; Muraca et al., 1987; Lin et al., 1998b), recent work has demonstrated the potential for *Legionella* regrowth, possibly due to necrotrophic consumption of dead cell biomass resulting from thermal shock (Temmerman et al., 2006).

3.2.4.7 Overall Costs. Few economic evaluations or total life cycle cost estimates have been conducted on the various methods of disinfection. Muraca et al. (1987), included a comparative cost table (Table 3.2) in a broad review of the disinfection methods. This analysis, however, is limited in scope to application in a hospital setting with a fixed number of beds and water heaters. The cost associated with each method has a wide range and are general in consideration. A more precise and up-to-date price comparison that accounts for variation in plumbing materials, implementation, and type of building would be useful. More cross-comparisons of in-building disinfection types are needed with specific focus on the implications and interactions the treatment technique has on the premise plumbing system.

Table 3.2
Representative cost estimates from one case study and status of knowledge regarding corrosion control and scaling (cost estimate data from Muraca et al, 1987)

Disinfection Method	Start Up Costs ($)	Annual Maintenance Costs* ($)	Scaling Implications	Corrosion Implications

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Ozonation	35,000-60,000	6,000-9,000	No	Higher DO
Hyperchlorination	30,000-45,000	5,000-8,000	No	Cl_2 is corrosive
Ultraviolet Light	18,000-35,000	1,000-2,000	No	No
Instantaneous Thermal	15,000-30,000	2,000-4,000	Yes	Plastics degradation concern
Metal Ionization	20,000-35,000	1,500-4,000	Might alter type of scale	Deposition corrosion of Ag, Cu
Continuous Thermal	3,000-5,000	500-800	Yes	Could protect pipe or create non-uniform corrosion
***Normalized for a 500-bed hospital with 13 floors and a recirculating hot water distribution system with two how water tanks**				

3.2.5 Critical evaluation of thermal disinfection

While the U.S. EPA's recommendation of 48 ˚C in water heaters may not be aggressive enough to reduce the risk for certain populations, such as immunocompromised consumers, ASHRAE's recommendation to require maintenance of 51 ˚C throughout the entire system may be unrealistic. For instance, in most premise plumbing systems, flow will remain stagnant long enough for the water in the pipes to cool to ambient room temperature, often very quickly. In order to meet this requirement, the building owners would need to have continuously recirculating systems in place. Some municipalities are mandating these systems for their purported energy/water efficiency of offering tax credits for their installation (MCWD, 2005). Recirculating systems, however, can consume more energy and water than traditional (i.e., standard, conventional) systems (Brazeau and Edwards, 2013). Thus, recirculation to meet AHSRAE recommendations may sometimes conflict with energy and water conservation goals. Even with recirculation, water to distal taps (e.g. from the recirculating loop to a shower head – Figure 3.3) may cool to room temperature. Thus, maintaining water temperatures above 51 ˚C throughout systems may not be practical or possible.

Thermal treatment may also prove ineffective in eliminating some pathogens in certain scenarios. Optimal growth for *Legionella* is between 32-42 ˚C (Yee and Wadowsky, 1982). Evidence of growth has been observed at 51.6˚C (Kusnetsov et al., 1996) and viable *Legionella* have been isolated from water with temperatures up to 66˚C (Dennis et al., 1984). In addition, pathogenic *Legionella* have been shown to survive successive thermal (70 ˚C for 30 minutes) and chemical (hydrogen peroxide) treatments, with the overall biofilm mass intact and the microbial community only temporarily affected (Farhat et al., 2012). Certain bacterial pathogens also have the distinct capability of surviving and replicating within an amoeba host organism, e.g., such as *Legionella* inside *Vermamoeba vermiformis*. This relationship can aid in the survival of the pathogenic bacteria by shielding it from treatment (Greub and Raoult, 2004).

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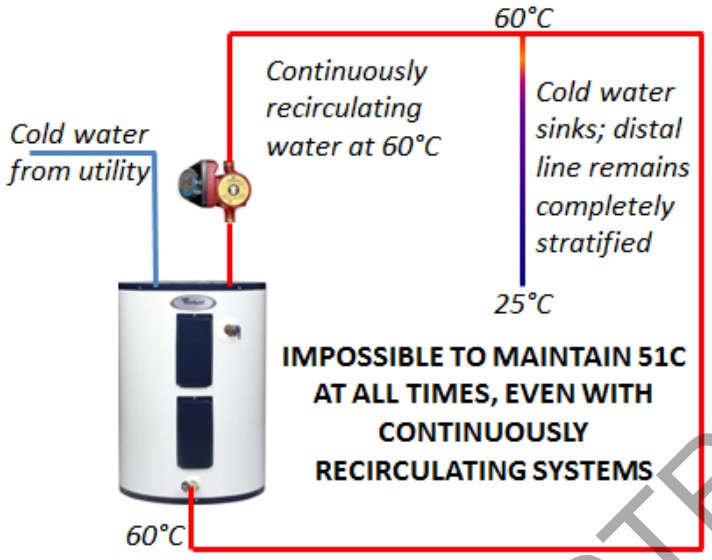

Figure 3.3 Practical scenario demonstrating limitation to maintaining 51 ˚C in continuously recirculating hot water systems

Increasing the water temperature in premise plumbing also increases the propensity of certain water chemistries to rapidly precipitate scale such as calcium carbonate or magnesium silicate. For example, at moderate levels of calcium (80 mg/L) and alkalinity (100 mg/L as $CaCO_3$) concentrations, at pH 7, there is no driving force for precipitation until water temperature rises above 48 °C (Figure 3.4). In a water of this type, at the U.S. EPA's recommended temperature setting, no problems with scaling are likely to occur. However, if the building has an "at risk" plumbing system according to ASHRAE 188 Section 5.2 (Figure 3.2), it is likely the building owner may raise the hot water heater temperature to 60 °C or even higher in an attempt to maintain 51 °C throughout the plumbing system. For the water modeled, 10.7 mg/L of $CaCO_3$ is predicted to precipitate to reach equilibrium. If this water was at higher pH's, precipitation is likely to occur at all temperatures, increasing the likelihood of increased precipitation at higher temperatures.

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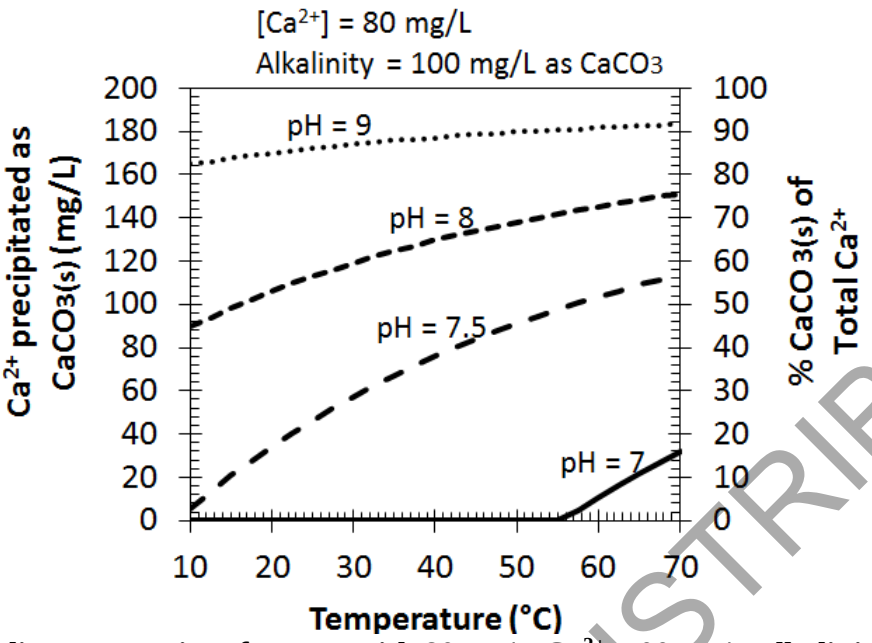

Figure 3.4 Scaling propensity of waters with 80 mg/L Ca^{2+}, 100 mg/L alkalinity as $CaCO_3$, and a pHs 7, 7.5, 8, and 9 (Source: Rhoads et al., 2014)

The precipitation of hard water scales could require increased energy demand in heating and recirculating the water, and cause permanent damage to plumbing systems (Paul et al., 2010). Researchers at the Water Quality Research Council (WQRC) and New Mexico State University found that there was a 30% increase in energy demand associated with hard water after just 14 days in a gas water heater (Isaacs and Stockton, 1981). The Langelier Saturation Index (LSI), while widely discredited for use in determining the relative corrosivity of water and estimating the leaching potential of lead, zinc, and copper from pipes and other premise plumbing materials (AWWARF, 1996; Edwards et al, 1996), is very useful in predicting the potential for certain waters to precipitate scale (Langelier, 1936; Elfil and Hannachi, 2006). The LSI is a calculation based on the calcium ion concentration, pH, and alkalinity of the water in question.

While there are alternatives to the LSI (e.g. Stiff and Davis, 1952; Hissel and Salengros, 2002; van Raalte-Drewes et al., 2004) and even variations on it (Elfil and Hannachi, 2006), each has its own limitation. Two main limitations of calcium carbonate saturation indices for pressurized potable water include (Elfil and Hannachi, 2006): 1) only considering calcite thermodynamics and not less soluble forms of calcium carbonate such as aragonite or monohydrate calcium carbonate; 2) the lack of thermodynamic data to incorporate other solids into the models. Despite these downfalls, the LSI is still commonly and successfully used.

It is important for building owners and operators to take the propensity for the water to scale into account before deciding to employ thermal disinfection to control pathogen growth (Figure 3.5). In some circumstances, it may possible to develop scaling inhibition or softening strategies to avoid scaling. If the water is subject to scaling, and inhibitors are not viable, other disinfection methods should be considered (Figure 3.6).

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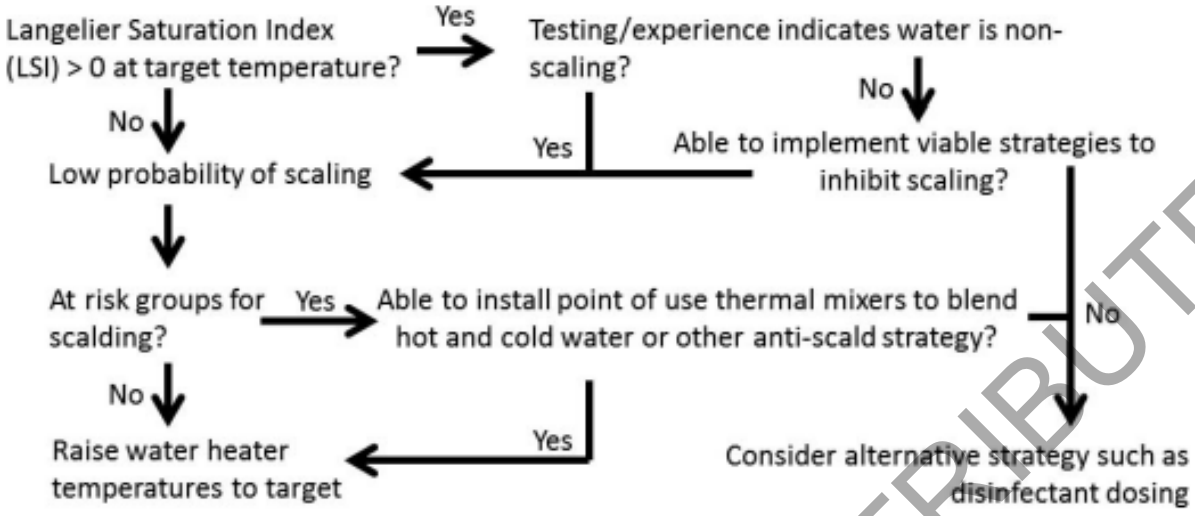

Figure 3.5 Logical framework/decision tree to determine if thermal treatment (shock or continuous) is likely to damage pipes at 60°C (Source: Rhoads et al., 2014)

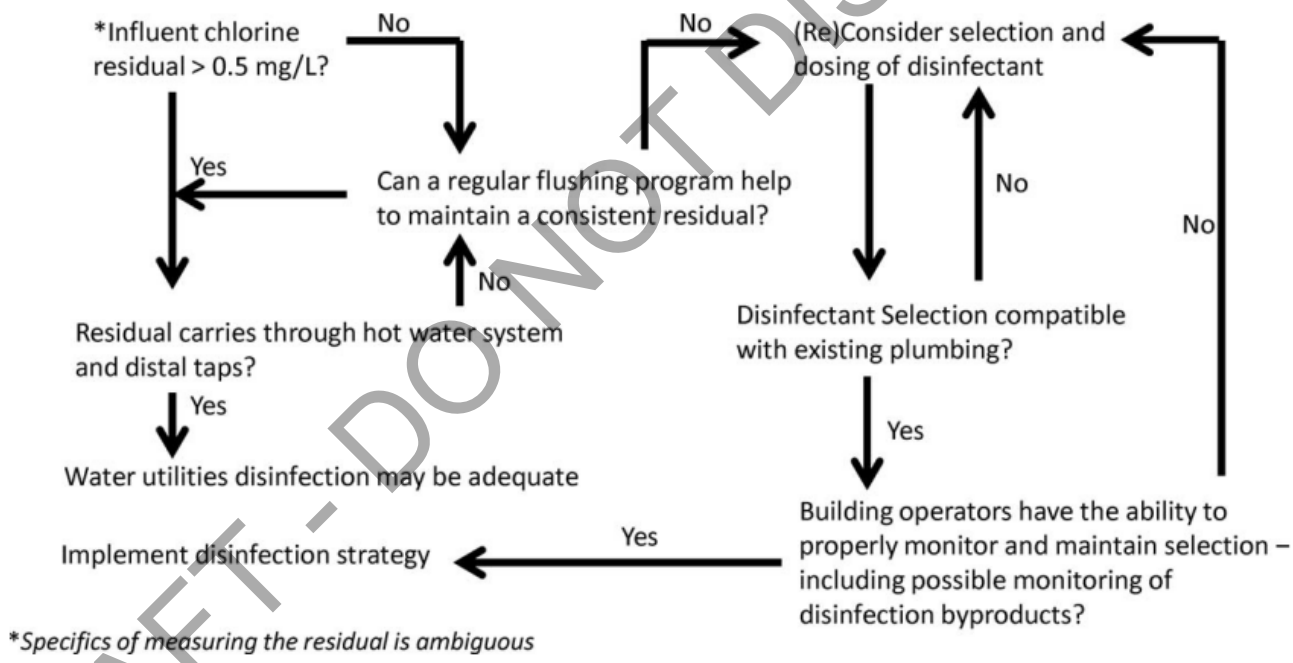

Figure 3.6 Logical framework/decision tree for implementing a treatment technique other than thermal disinfection (Source: Rhoads et al., 2014)

It is important to note that the precipitation potential indices usually do not incorporate the kinetics of the reactions taking place into their calculation. Constituents in the water, the degree of saturation, and other factors will determine if the rate is sufficient to cause damage. In cases where seed crystals of calcium carbonate are not present, precipitation might not initiate. Even when kinetics dictate rapid precipitation of calcite, there are several constituents in water that can slow down the precipitation to negligible rates. For instance, Lin and Singer (2005) demonstrated in lab-scale studies that orthophosphate dramatically inhibited the precipitation of calcium carbonate

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by the adsorption of phosphates on the calcite surfaces. Further, the inhibitory effects were altered by carbonate to calcium ratios and system pH – as each variable decreased, the effectiveness of orthophosphate inhibition of precipitation increased. In addition, the capacity of polyphosphates proved two orders of magnitude more effective than orthophosphate in inhibiting precipitation of calcite (Lin and Singer, 2005; 2006). However, more quantitative research on how water quality parameters and phosphate dosing affect the efficacy of OPPP controls is desired.

Notably, van Raalte-Drewes et al. (2004) has described "new" parameters for calcium carbonate precipitation that can partially account for the kinetics of reactions. In addition to the Calcium Carbonate Precipitation Potential (CCPP) and Saturation Index (SI) indicative of the LSI, this method also uses a Nucleation Index (NI) and Measured Calcium Carbonate Precipitation (MCCP) to predict the kinetics of scaling in untreated hard waters (van Raalte-Drewes et al., 2004). Characteristic values for the CCPP, SI, NI, and MCCP of a range of waters has been explored (Van Raalte-drewes et al., 2004; Table 3.3). There is a notable amount of overlap between the severity of scaling and the values of CCPP and SI for each level of scaling. This illustrates that a water could have a relative high capability to precipitate calcium carbonate (i.e. super saturated CCPP and SI values), yet in practice reactions are taking place at rates that are slow enough such that appreciable problems do not occur (low NI) or the waters do not have the tendency to adhere to surfaces (low MCCP). Obviously, the exact propensity depends on the actual temperature of the water system (see Figure 3.4), which is not addressed through this approach.

Table 3.3
Typical values of parameters to approximate the likelihood of scaling in waters in the Netherlands (data from Van Raalte-drewes et al., 2004)

Severity of Scaling	**CCPP (mM)**	**SI (-)**	**NI (-)**	**MCCP (mM)**
Severe	0.93-1.86	1.09-1.24	0.61-0.76	0.59-1.01
Moderate	0.63-1.11	0.96-1.24	0.53-0.87	0.16-0.51
No Scaling	0.13-0.69	0.52-1.09	0.45-0.73	0.00-0.08

Regardless whether a particular water has the potential to precipitate calcium carbon, magnesium hydroxides, or magnesium silicates, the critical factor is the rate at which the precipitates form. For some waters, even though they are superstaturated and theoretically tend to form scales, the kinetics are slow (Lin and Singer, 2005; 2006), and scaling inhibitors might be explored (Figure 3.5). Although more practical tests that incorporate kinetics to some degree are better than saturation indices, local experiences about problems with scaling at high temperatures can be synthesized on a case-by-case basis. In some circumstances, it may be possible to dose inhibitors or use water softening as strategies to avoid issues. If the water is subject to scaling, and inhibitors are not a viable option, chemical disinfection methods must be considered (Figure 3.6). Current guidelines and standards do not provide a formal decision-making process for how and when to select a certain disinfection procedure. Figures 3 and 4 provide basic information on how to approach this while maintaining the integrity of the plumbing system and safety of consumers.

Other issues that could arise from increased water temperatures include increased corrosion rates of metallic pipes and scalding of consumers. Increased water temperature is known to increase leaching propensity of lead from plumbing devices (Sarver and Edwards, 2011a; 2011b) and increase pinhole corrosion rates in copper tubing (Rushing and Edwards, 2004). Several

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researchers have observed markedly higher corrosion rates at higher temperatures for copper pipes under moderate to continuous flow conditions simulating drinking water systems (Obrecht and Quill 1960a-f). The degradation of the physical attributes of the plumbing system could necessitate using a lower flow rate in premise plumbing hot water systems due to erosion corrosion.

Instead of reducing the temperature of the entire hot water system to avoid scalding, thermostatic mixers can be installed at each tap to blend both hot and cold water to reduce the maximum temperature of dispensed water as per Australian code (Spinks et al., 2003). However, automatic mixing valves in metered and hands-free faucets have been implicated as triggers for OPPP growth (Halabi et al., 2001; Yapicioglu et al., 2011). Similar concerns may emerge with thermal mixing valves installed to reduce scalding potential. In addition, the mixing devices can fail, causing the potential for cross-connections between the hot and cold water lines to develop. There is some work that raises concerns of thermostatic mixing and tempering valves not working properly under all flow conditions observed in premise plumbing (Stephen and Murray, 1993).

3.2.6 Conclusions and research gaps

There is a shared responsibility amongst stakeholders to prevent colonization of OPPPs in in-building potable water systems. ASHRAE 188 is a critical step in this direction, requiring the development of a plan for preventing, responding to, and following up on LD outbreaks. While new research will be necessary to address implementation of the standard, the practical guidance provided herein is a useful starting point for rational design. Explicit information is needed regarding where, how, and when to measure the level of disinfection residual in the plumbing system, and to characterize the overall risk associated with OPPP growth in a system. In addition, relatively little is known about interactions between plumbing materials and in-building disinfectants, and these reactions have important implications for maintaining disinfectant residuals, causing corrosion, and potentially forming harmful disinfection byproducts. Research is needed to determine the background reactions occurring between the disinfectants, water chemistry, and plumbing materials and the effects of these reactions on the efficacy of the treatment. Many systems would be damaged if their temperatures are raised to 60°C due to rapid scaling and increased corrosion, and while the Langelier Saturation Index (LSI) provides a useful starting point for considering whether waters have risk of scaling, more practical tests may also be of value in determining the physical risks associated with the implementation of thermal disinfection. Other strategies to maintain safe water temperature at the point of use in a system with elevated hot water heater temperature, such as thermostatic mixing valves, deserves increased scrutiny. Guidance should be provided in the standards and treatment guidelines that outline the required maintenance and monitoring expertise of the operator to facilitate the selection of an effective disinfection regimen. Guidance is also needed on the relative costs of the design, construction, and operation of the various in-building disinfection techniques. The most thorough work in this area is now well over twenty five years old and does not consider infrastructure and other impacts (e.g. Muraca et al., 1987).

3.3 CORROSION

3.3.1 Blue Water

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Key Words: Blue water, copper, flow, stagnation, pH, orthophosphate, disinfection residual

3.3.1.1 Introduction. Blue water and blue staining is sometimes observed in waters with high soluble and/or particulate copper. While these problems sometimes indicate elevated copper in water, they can also result from reactions between relatively low levels of copper in water and certain household products. Although copper generally does not pose long-term health concerns, it can cause gastrointestinal upset and exacerbate problems associated with nitrate ingestion, especially in children (U.S. EPA, 2003). Most problems can be solved easily using standard approaches, but unusual problems may require external assistance to diagnose and remediate.

3.3.1.2 Anticipated link to green buildings. It is expected that problems associated with blue water and blue staining will be more likely in certain situations with sustainable water or conservation features. Specifically, within conventional distribution systems, blue water and blue staining are often observed in homes experiencing reduced or infrequent flow, at dead ends of distribution systems, or whose plumbing systems have little or no disinfectant residual. The likelihood of these factors playing an important role is increased in many current green building designs.

3.3.1.3 The blue water and blue staining problem. Cases of copper corrosion by-product release can be classified based on whether the released metal is primarily soluble or particulate copper. Problems associated with soluble copper are most common in waters at or below about pH 7.5, often go away by themselves within about a year and can usually be remedied, if necessary, by raising pH. In contrast, the relatively rare problem of blue water due to particulate copper release requires an initiation time before high levels of copper release are observed (Figure 3.7), is not self-correcting, and usually cannot be improved by conventional pH increases (Edwards et al., 2000). Obviously, pipe age plays an important role in the release of copper and is heavily dependent on basic copper solubility and precipitation reactions. A model first conceived at the U.S. EPA and proven to be consistent with extensive field data and laboratory experiments (Schock et al., 1994, 1995a, 1995b; Edwards et al., 1996; Dodrill and Edwards, 1995) indicates that corrosion of new copper tubes is controlled by cupric hydroxide [$Cu(OH)_2$] equilibrium. However, the natural aging process of copper, and subsequent decrease in metal dissolution can be affected by several factors (Figure 3.8).

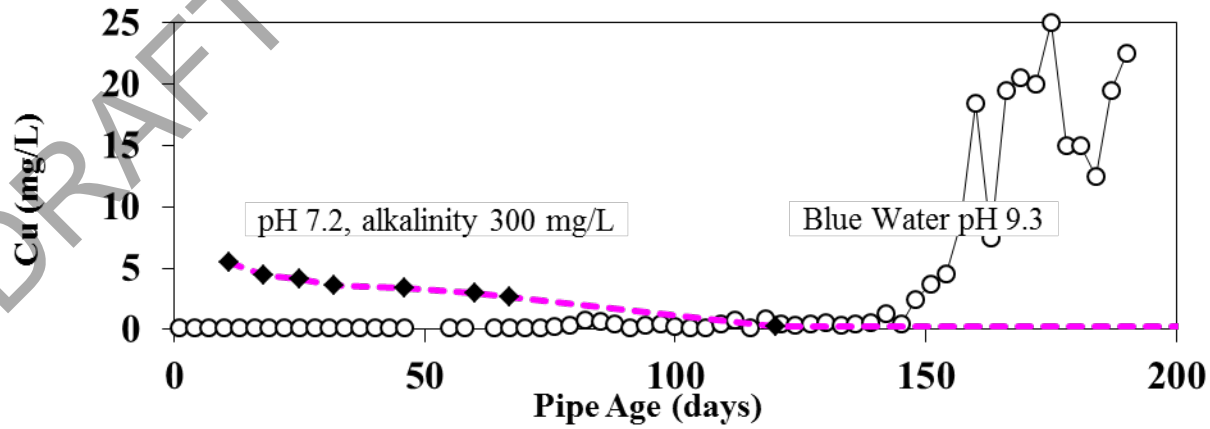

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Figure 3.7 By product release after a fixed stagnation period from pipes in blue water situations worsens with aging, as opposed to conventional behavior in which release lessens with pipe age. (*Source*: Edwards et al., 2000)

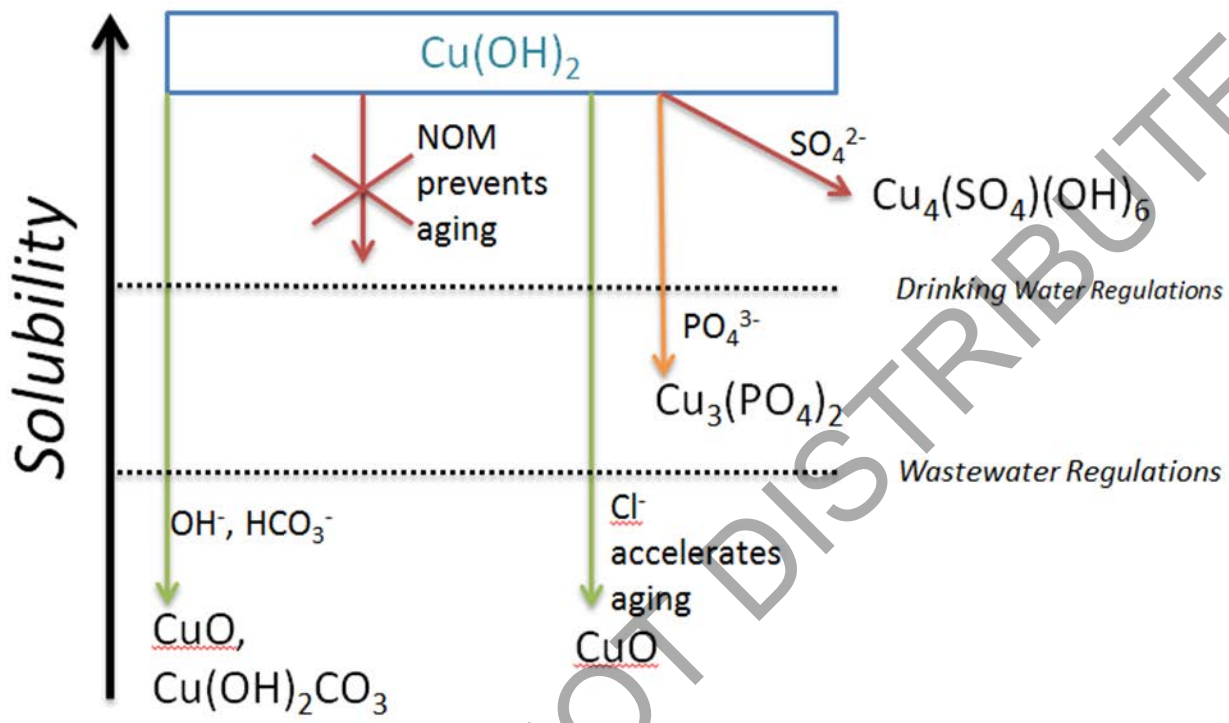

Figure 3.8 Long term simplistic model of equilibrated soluble copper in the presence of various scales

For instance, when sulfate is present at relatively high levels, either from a natural source or as an additive via alum coagulation, it can quickly react to form brochantite [$Cu_4(SO_4)(OH)_6$] (Edwards et al, 2001). Although brochantite is less soluble than cupric hydroxide and its formation can quickly reduce copper concentrations in the short term, it can prevent much less soluble malachite or tenorite from forming, releasing more total copper in the long term. Similarly, the addition of phosphate [PO_4^{3-}] as ortho- or poly-phosphate can quickly form cupric phosphate [$Cu(PO_4)_2$] leading to short term reductions in copper release. However, this also impedes the formation of the less soluble scales, causing more total copper in the long term (Edwards et al, 2001). Natural organic matter (NOM) can also prevent the formation of the less soluble copper scales by acting as a ligand to complex with free copper ions (Korshin et al., 2000) and preventing formation of less soluble solids than $Cu(OH)_2$ (Arnold et al., 2012). Silica, naturally occurring or added as a corrosion inhibitor, can sorb to $Cu(OH)_2$ solids in the water or on pipe surface to reduce the rate of transition of the solid to tenorite (Nguyen et al., 2011). Free chlorine residual can also sometimes act as a catalyst for the conversion of cupric hydroxide to tenorite (Nguyen et al., 2011), which can be beneficial in reducing copper solubility, but potentially results in loss of chlorine and increased microbial growth. The issue of aging, therefore, plays an important role in determining whether the copper corrosion products are mostly soluble or particulate.

Soluble copper can cause blue staining of fixtures, porcelain and shower curtains from specific reactions with water and deposits of soap and other products (Figure 3.9, d). Severe blue

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staining can occur in waters with copper levels well below the 1.3 mg/L U.S. EPA action level of the Lean and Copper Rule (LCR; Scardina et al., 2008; Scardina and Edwards, 2007; Edwards, 2011). For example, it has been demonstrated that copper staining is heavily dependent on consumers' choice of soap and cleaning products (Figure 3.9, c).

Figure 3.9 Blue water and blue water staining: a.) Blue water observed in drinking water (Source: Edwards et al., 2000); b.) Blue water in toilet tank; c.) Blue water staining on shower curtain materials with different soaps and cleaning products applied; d.) blue water staining on a drain plug

Some soap deposits create severe staining when contacted by soluble copper, some caused staining only around the edges of soap deposits, and some soaps produced no staining at all.

Particulate copper, on the other hand, can be visible to the human eye when present at levels exceeding the U.S. EPA action limit. In a few isolated cases particulate copper levels have exceeded 10 or even 100 mg/L (Edwards and Jacobs, 2000). Unfortunately, design of the sampling protocols used for the U.S. EPA LCR calls for monitoring older homes that are most likely to have elevated lead but which are least likely to detect problems with elevated copper. Thus, in some situations extreme problems with blue water can occur in copper pipes of newer homes or remodels, when there is no problem in older homes which are in compliance with the U.S. EPA LCR (Figure 3.9 a, b).

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3.3.1.4 Factors affecting occurrence of blue water. There are myriad factors that copper corroding into drinking water from household plumbing materials including pH, alkalinity, orthophosphate concentration, chlorine residual, water age, flow rate, temperature, and copper pipe age. Raising the pH of the source water can reduce the amount of copper released to water by reducing the solubility of copper and accelerating aging. However, because pH changes with time and from one area of the distribution system to another, pH values at the tap can be outside of those targeted at the treatment plant as optimal for corrosion control (Scardina et al., 2008). Several reactions can cause pH to decrease including nitrification (oxidation of NH_4^+ to NOx^-) in systems with chloramine or ammonia (Zhang et al., 2007). This biological reaction can drive down the pH and can even prevent copper pipes from forming a lower solubility scale layer on the interior of the pipe (Zhang et al., 2009). However, pH can also increase within the distribution and plumbing system due to corrosion reactions, leaching of lime from cementatious pipes (Conroy et al., 1991), or possibly other biological reactions such as denitrification. While there are some exceptions, particulate blue water tends to occur in poorly buffered low, alkalinity waters at higher pHs (Edwards and Jacobs, 2000). Problems with soluble copper tend to be most significant at either low pH and low alkalinity, or low pH and higher alkalinity. As a general rule, most problems with soluble copper occur for situations in which pH is below about 7.6 at the consumers tap. Particulate copper, however, has been observed in higher temperature water (Boulay and Edwards, 2001). In fact, elevated temperature have been shown to aid in developing a stable uniform layer of corrosion products on pipe surfaces (Lytle and Nadagouda, 2010).

Orthophosphate (PO_4) can be added to water as a corrosion inhibitor and it can also reduce cuprosolvency when pH is below 8 (Schock et al., 1995a). It is believed to form an insoluble cupric phosphate precipitate on the surface of the pipe if levels are above about 0.5 mg/L as phosphate (P) and if pH is in the range of 7.2-7.8 (U.S. EPA, 2003; McNeil and Edwards, 2001). However, over the long term, orthophosphate scales are slightly less desirable than naturally formed scales, such as tenorite or malachite, which have lower solubility than cupric phosphate scales (Edwards et al., 2001; Schock and Sandvig, 2009). A confounding factor to the effectiveness of orthophosphate in waters with chloramine is that the ideal pH range for nitrifying bacteria found in drinking water coincides with the effective pH range for orthophosphate, and dosing of phosphate can reduce copper inhibition of nitrifiers and remove nutrient limitations to growth (Zhang et al., 2007). When blue water results from nitrification or other bacteria such as sulfate reducing bacteria, increasing chlorine residuals to the tap via flushing or booster chlorination can be an effective remediation strategy (Edwards and Jacobs, 2000). Higher total chlorine is believed to reduce the activity of nitrifying and other bacteria, which can also help maintain pH control to the tap (Zhang et al., 2009).

3.3.1.5 Remediation strategies. Remedial strategies exist for most blue water and blue staining problems. Passage of time in newer homes, which allows protective scale to form on pipe walls, solves many problems naturally. However, Figure 3.10 outlines common approaches applied by utilities to diagnose and mitigate blue water when it is observed in isolated parts of the water distribution system. Dependent on circumstance, higher pH, orthophosphate or provision of a disinfectant residual can solve many problems. In other cases outside experts should be consulted to solve atypical problems.

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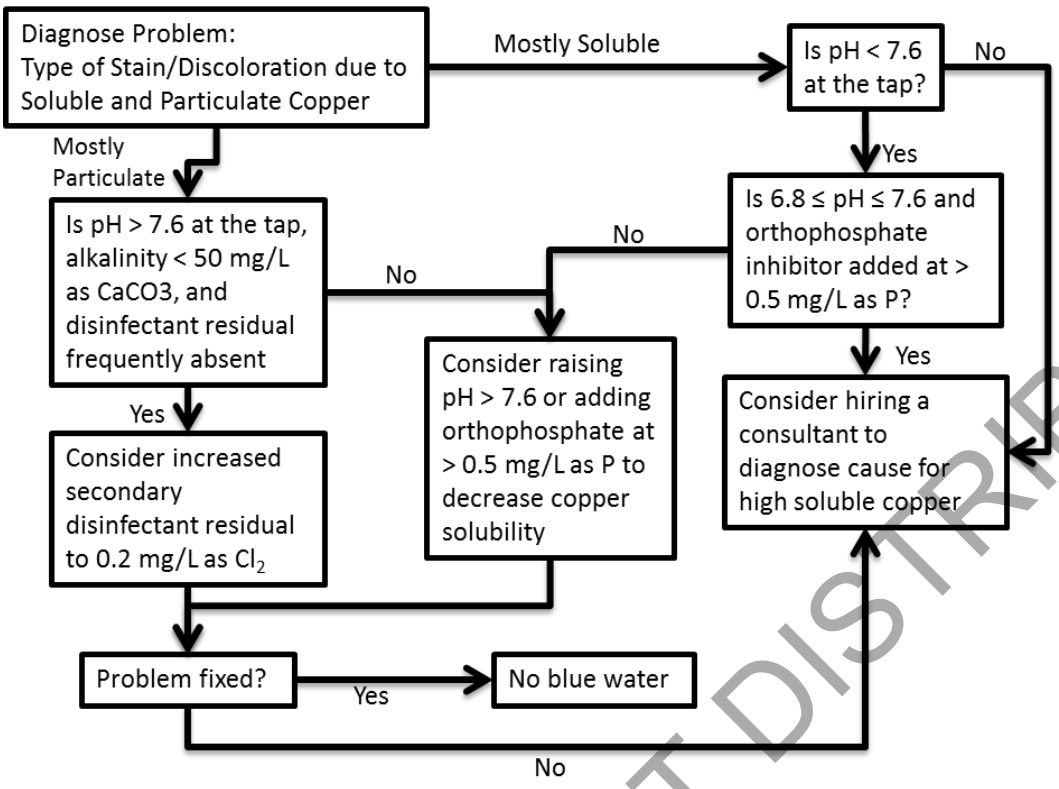

Figure 3.10 Decision Tree for mitigating blue water and blue water staining caused by soluble and particulate

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3.3.2 Pinhole Leaks

Key words: Pitting corrosion, non-uniform corrosion, water age, water velocity

3.3.2.1 Introduction. Copper corrosion failures due to leaks, otherwise known as non-uniform corrosion, pinhole leaks or pitting corrosion, can occur in premise plumbing copper tubes in as little as a few weeks and as long as decades after installation. In some cases, it is strongly believed that accumulation of debris during installation, microbial activity, and frequent stagnation can contribute to problems. Pitting corrosion can compromise an entire plumbing system and require its replacement, the cost of which can be substantial.

3.3.2.2 Anticipated kink to green buildings. Very low flow velocity and low water use can be expected to exacerbate certain types of pitting corrosion, especially those forms attributed to microbial growth and accumulation of debris. Hence, incidence of certain forms of pitting might be expected to increase in green buildings. It is likely that at least some of these problems can be reduced by appropriate installation procedures, including use of approved flux, high rate flushing after plumbing installation during commissioning, and preventing long term periods in which water sits stagnant in pipes including times prior to occupancy.

3.3.2.3 Factors effecting pitting corrosion. Several categories of pitting have been identified in the last decade. "At risk" water chemistries, installation practices, material properties, and microbial activity have also been identified (Table 3.4). Leaks from pinhole corrosion alone cost consumers about $1 billion each year (Scardina et al. 2008; Kleczyk and Bosch, 2008). Like many premise plumbing issues, multiple stakeholders are potentially responsible for identifying, diagnosing, and mitigating problems.

In a systematic study of copper pitting in low alkalinity and high pH waters, Marshall et al. (2006) discovered a synthetic water that showed high propensity for non-uniform pitting in copper tubes (known herein Marshall Pitting Water, or MPW). Tests using MPW have demonstrated that natural organic matter (NOM) and silica increase pitting propensity (Sarver et al., 2011; Custalow, 2009; Lattyak, 2007; Edwards and Parks, 2008). In addition, known corrosion inhibitors like poly- and ortho-phosphate have been proved to reduce pitting in simulated systems (Marshall et al., 2006; Sarver et al., 2011; Lytle and Schock, 2008). Free chlorine was determined to be an important factor to induce pitting in some research, but it does not necessarily need to be in high concentrations like those tested in the MPW (Lytle and Schock, 2008; Edwards et al., 2010).

Other factors beyond the control of the water utility may also contribute to pitting corrosion and result from design and operation including green buildings. For instance, oversizing of pipes relative to demand might increase nitrification in high water age plumbing systems. When one milligram of ammonia is converted to nitrate and nitrite, 8.62 mg of HCO_3^- is consumed (Zhang et al., 2009). Bicarbonate (HCO_3^-) is approximately equal to alkalinity in most drinking waters. To the extent that HCO_3^- is consumed and alkalinity decreases, the propensity for pits to initiate is increased. However, while low flow can exacerbate the effects of nitrification on alkalinity, high flow rate within buildings has also been linked to incidence of pitting when the building water has sediments or particulates that can impact and erode the pipe wall (Custalow, 2009; Lattyak, 2007).

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Table 3.4
Summary of factors that affect non-uniform copper corrosion in premise plumbing (adapted from Sarver et al., 2011)

Parameter	Pitting Considerations	Source(s)
pH	High pH increases severity; pH = 9 found to be worst case	Marshall and Edwards, 2006; Rushing and Edwards, 2004; Cong and Scully, 2010; Sarver et al., 2011, Lytle and Schock, 2008
Free Chlorine	Increased concentrations increases pitting severity	Rushing and Edwards, 2004; Cong and Scully, 2010; Sarver et al., 2011
Chloramines	Not implicated in pitting	Edwards and Parks, 2008; Custalow, 2009
Chloride	Appears necessary for pitting	
Alkalinity	Low alkalinity waters increases pit growth rates	Sarver et al., 2011; Lytle and Schock, 2008
Hardness	Low hardness increased overall growth rates	
Aluminum	Required for pitting	Rushing and Edwards, 2004
Orthophosphate	Dosing orthophosphate inhibits pitting	Sarver et al., 2011; Lytle and Schock, 2008
Silica	Increased silica inhibits pitting	Sarver et al., 2011; Custalow, 2009
NOM	Increased NOM inhibits pitting	Lattyak, 2007; Sarver et al., 2011; Edwards and Parks, 2008
Velocity	Higher water velocity can increase pitting rates	Cong and Scully, 2010; Custalow, 2009; Lattyak, 2007
Flux	Induces pitting	Cohen, 1994
Tube Diameter	Effects water age	
Water age	Possible for pitting corrosion through changes in water chemistry	Zhang et al., 2009; Scardina et al., 2008
Surface anomalies	Suspected to contribute to pitting	Sarver et al., 2011
SRB activity (sulfides)	Pits can develop in micro-anaerobic environements under tubercules.	Scardina et al., 2008

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Sulfate reducing bacteria (SRB) activity has also been linked to pitting corrosion. SRB can be supported in many drinking waters, and are obligate anaerobes that use sulfate as a terminal electron acceptor. They live deep within biofilm or other areas such as copper pits (Figure 3.11). Although no one has ever reproduced the essential features of SRB pitting of copper in the laboratory, it is believed that the lack of oxygen and very high levels of sulfate drawn into pits, are highly conducive to their growth. The sulfides produced by SRB are highly corrosive (Hamilton, 1985; Edwards and Jacobs, 2000; Jacobs et al., 1998). Notably, reactions between iron mains and sulfate reducing bacteria form iron sulfides (e.g. FeS), causing water to appear black.

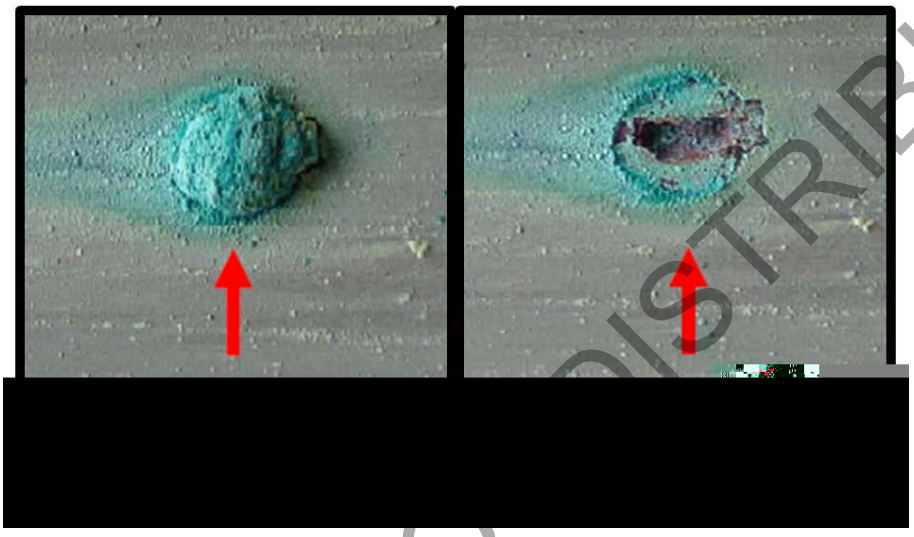

Figure 3.11 Pinhole forming under a tubercle (*Source*: Scardina et al., 2008)

3.3.2.4 Remediation or mitigation. Non-uniform copper corrosion problems can sometimes be controlled by minor water chemistry changes. While diagnosis of such problems requires substantial expertise, solutions that have been effective include increased disinfectant, phosphate and decreased water age. In other cases it may be necessary to replace the plumbing system.

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3.3.3 Lead Leaching

Key Words: Lead, Brass, Leaching,

3.3.3.1 Introduction. Lead (Pb) is a well-known inorganic contaminant in potable water that poses a public health threat. It is a neurotoxin that can cause permanent, irreversible damage when consumed (Bellinger et al., 2003; Canfield et al., 2003), especially in young children. The U.S. EPA regulates the amount of Pb that is allowed in potable water systems and poses an "action limit" of 15 ppb in 90% of sampled buildings according to the Lead and Copper Rule (LCR), for which sampling protocols focus on older homes and buildings. For schools and day-cares – where exposures can be more serious due to the populations using these buildings – the Lead Contamination Control Act of 1988 suggests a limit of 20 ppb in a 250 mL "first-draw" sample from individual taps. This limit, however, is not imposed in the U.S.EPA LCR and is a voluntary standard that schools can choose to meet on their own.

3.3.3.2 Anticipated link to green buildings. While the relative corrosivity of municipal water is a key factor that drives Pb release in building plumbing systems, external factors controlled by the building designer, owner, and operators can also influence Pb leaching within the system. The increased water age of buildings with water conservation features is expected be an important factor in Pb exposure in these buildings, since lead accumulates as water contacts lead bearing plumbing. Moreover, if new water sources are used, such as rainwater without pH adjustment, serious lead problems may be expected since pure water has a high propensity to leach lead (Gardels and Sorg,1989; Abhijeet et al., 2005).

3.3.3.3 Background. Although the use of Pb solder and pure Pb pipes are banned in new construction and renovations, there is still risk of Pb exposure from inline or point-of-use, lead-bearing brass or bronze devices (Boyd et al., 2008; Lytle and Schock, 1997; Birden, 1985; Samuels and Meranger, 1984; Gardels and Sorg, 1989; Dodrill and Edwards, 1995; Edwards and Dudi, 2004; Triantafyllidou and Edwards, 2007). Even NSF 61 and CA Proposition 65 certified brass devices have the potential to leach high amounts of lead (Triantafyllidou and Edwards, 2007, Edwards and Dudi, 2004; Elfland et al., 2010; Triantafyllidou et al., 2012).

Extensive research has been done to identify the water quality parameters and other factors that increase the propensity to leach Pb from inline and endpoint brass devices, as well as leaded solder (Table 3.5). In general, pH below about 8 and low alkalinity (less than ~30 mg/L as $CaCO_3$) waters present the worst case for leaching (Dodrill and Edwards, 1995; Triantafyllidou and Edwards, 2007). If the pH or alkalinity drops during stagnation due to processes such as nitrification or reactions with other corrosion scales, the tendency of Pb leaching increases (Lytle and Schock, 1996; Dodrill and Edwards, 1995; Zhang et al., 2008). Chloramine is often more aggressive than chorine in promoting Pb leaching from brass devices (Edwards and Dudi, 2004; Triantafyllidou and Edwards, 2007) and in some cases Pb solder (Portland, 1983). The presence of natural organic matter (NOM) can increase release of lead in water compared to water without NOM at levels from 0–2 mg/L (Korshin et al., 2000). Additionally, an increase the chloride-to-sulfate mass ratio (CSMR) can cause 1.2–2.7 times more Pb leaching from brass coupons and 2.3–40 times more Pb leaching in lead-tin solder (Edwards and Triantafyllidou, 2007; Nguyen et al., 2010). The CSMR can change due to processes such as anion exchange treatment or switching

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coagulant types with wide-spread implications for Pb leaching. Bench top testing before implementing such a change in the treatment chain of a utility is recommended.

Other factors affecting lead release include brass alloy make-up and dezincification – the rate at which zinc leaches from the alloy. Dezincification is believed to increase Pb release from brass (Kimbrough, 2001; U.S. EPA, 1993) and is correlated with the levels of chloride and bicarbonate in the distribution system water (Sarver et al., 2010). The more Pb an alloy contains, the more Pb it will leach in comparison to alloys with less Pb (Zhang et al., 2009; Lytle and Schock, 1996). Similarly, increasing the zinc content of an alloy can decrease the Pb leaching capabilities at least in the short-term (Zhang et al., 2009). Even manufacturing processes can influence the extent of lead leaching from a given device.

Water age and stagnation also affect the rate at which lead leaches into water. Lead levels often increase exponentially with stagnation time especially in the first 20-24 hours of stagnation (Lytle and Schock, 2000). In a comparison between 24 and 72 hour stagnation times, yellow brass was unaffected (leached the same amount of Pb), but red brass leached 10–25 µg/L more in the 72 hours stagnation time (Lytle and Schock, 1996). At pH 8.5, considerably less Pb was leached overall and no differences between the two stagnation times were observed. A recent practical field study showed that premise plumbing lines in green buildings with relatively low water demand, had very high lead concentrations from end-use and in-line brass devices (Elfland et al., 2010; See Chapter 4 OWASA/UNC-CH case study).

3.3.3.4 Remediation. There are several ways to remediate Pb leaching from brass. Generally, lead levels can decrease with time and elevated lead may therefore be transient (Lytle and Schock, 1996). Regular flushing can also hasten the aging process (Elfland et al., 2010) or improve water chemistry in a manner that reduces microbial growth and lead. For instance, Elfland et al., showed that flushing less than 1% of the total daily water demand of the building from the end of the plumbing system essentially eliminated the elevated Pb. A complicating factor to this strategy is the fact there are usually multiple inline and endpoint brass devices that contain Pb in plumbing systems and flushing may not be effective. Water chemistry adjustments at the water treatment facility have proven to be helpful in mitigating Pb leaching, but pose a large burden on the utility if Pb leaching from premise plumbing is not widespread in the distribution area. Dosing orthophosphates at levels of 1.0 mg/L as P and adjusting the pH above about 8.0 can inhibit Pb release to water. pH adjustment or orthophosphate may be necessary to reduce the corrosivity of novel sources of potable water in green buildings such as rainwater. Replacement of problematic devices with brass devices that meet new NSF regulations for Pb-free devices, which have very low lead (< 0.25%), can also be effective. However, locating the specific devices contributing high Pb to water can be extremely difficult and expensive given difficulties in accessing devices throughout a plumbing system.

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Table 3.5
Summary of water quality parameters that can effect lead release and lead leaching (adapted from Sarver and Edwards, 2011a; 2011b)

Water Quality Parameter	Effect of Lead Leaching	Reference
Increase pH	Generally decrease leaching	Lytle and Schock, 1996
Increase in Free Chlorine	Unknown	
Chloramine	More aggressive than Chlorine	Triantafyllidou and Edwards, 2007; Edwards and Dudi, 20004; Portland, 1983
Increase in Alkalinity	Generally decrease corrosivity to Pb	Dodrill and Edwards, 1995; Zhang et al., 2008
Increase in Hardness	Unknown	
Increase in Chloride:Sulfate	Increase in leaching from Pb-tin solder gavalically coupled to copper and brass coupons	Edwards and Triantafyllidou, 2007; Ngyuen et al., 2010
Increase in Aluminum	Unknown	
Increase in Orthophosphate	Accelerated rate of brass passivation, eventually decreasing lead release	Lytle and Schock, 1996
Increase in NOM	Increased lead leaching	Korshin, 2000
Velocity	No significant effects	Sarver and Edwards, 2011b
Galvanic connection	No significant effects	Sarver and Edwards, 2011b
Increased Water Temperature	Increased Pb leaching	Sarver and Edwards, 2011b
Increased amount of Flux	Can increase lead leaching	Triantafyllidou et al., 2012
Increased No. of surface anomalies	Increased Pb leaching due to heterogeneities in Pb distribution on brass surfaces (e. g. migration of lead to grain boundaries)	
Increased Zinc content	Generally decreased Pb leaching at least in the short term	Zhang, 2009
Increased Lead content	Increased Pb leaching	Zhang, 2009
Nitrification	Increase Soluble Pb Release	Zhang et al, 2008
Increased Stagnation Time	Increases Pb leaching	Lytle and Schock, 1996; 2000; Elfland et al., 2010

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3.4 TASTE AND ODOR ISSUES

Key Words: Taste and odor problems, organoleptic water quality, aesthetic water quality

3.4.1 Introduction

Problems with aesthetic qualities of water including poor taste and odor are often reported to utilities. These problems may arise from seasonal differences in source water and treatment processes (Mallevaille and Suffet, 1987; Suffet et al., 1995), however; taste and odor (T&O) problems can also be generated in the distribution system as influenced by high residence times (water age) and pipe materials (Burlingame and Anselme, 1995; Lin, 1977; Rigal and Danjou, 1999; Tomboulian et al., 2004; Dietrich, 2006; Durand and Dietrich, 2007; Khiari et al., 2002) (Table 3.6). Although most T&O problems do not represent a direct health concern, consumers will often judge their water like any other commodity (Dietrich, 2006), and are often willing to pay more for water they are more certain is safe to drink or aesthetically pleasing (Kolodsiej, 2004). In addition, consumers become acclimated to the quality of water delivered to their homes and work place and can taste subtle changes in the water quality (Lawless and Heymann, 2010; Meilgaard et al., 2007). Consumers are important sentinels of water quality for utilities and building operators (Whelton et al., 2004; Dietrich, 2006; Whelton et al., 2007) and have often helped to locate and identify problems with treatment, the distribution system, and real health concerns. This has been demonstrated in several utilities (Whelton et al., 2007). Consumer assistance in identification of serious problems can also extend to premise plumbing. For example, in one case study in green buildings consumer complaints about T&Os helped identify problems with chronically low disinfectant residual, rampant microbial growth, and high lead (Nguyen et al., 2012).

What most people view as "taste" issues actually represent sensory inputs combined from taste, odor, sight, and touch (or texture, "mouthfeel" in the case of drinking water) (Lin et al., 1977; Rosen, 1970). Here, T&O problems are defined as decreased aesthetic quality in regards to ingestion or use of potable water. T&O problems that arise due to distribution and premise plumbing systems are attributed to one or a combination of three classifications: biological, physical, or chemical reactions undergone during transport to the point of use. There is a diverse range of T&O water quality issues from organic (musty, earthy, moldy) to medicinal and other synthetic odors.

3.4.2 Anticipated linkage to green buildings

Green building plumbing design provides opportunities for very high water age, lower chlorine residuals, higher microbial growth, and prolonged contact with pipe materials which may exacerbate many issues associated with T&O discussed below. In general, the more extreme the conservation features in green buildings, the greater potential for T&O problems unless water age is carefully controlled via plumbing design, or steps are taken to control water age through automated flushing (See Chapter 4 OWASA UNC-CH Case Study). In addition, plumbing materials in the U.S. are evaluated and regulated only on a health effects basis (e.g., ANSI and NSF codes and standards), and not using tests that explore the potential to degrade aesthetics. This means the materials used in building plumbing systems could react with the water and have a detrimental effect on the perceived quality of water by leaching harmless, but odorous compounds.

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Table 3.6
Sources of specific odor wheel organoleptic properties that occur in distribution systems and premise plumbing (adapted from Tomboulian et al., 2004)

Odor Wheel Category	Subdescriptor	Sources/Materials
Medicinal/ Phenolic	1.a. Medicinal/ Phenolic	Acrylic coating in reservoir, styrene butadiene rubber, gaskets and o-rings, pipes and liners, polyethylene, HDPE, PEX, PVC pipe with primer and cement (probably not PVC itself)
	1.b Sweet/Sharp	Dye solvent
Chemical/ hydrocarbon/ miscellaneous	2.a. Solvent, airplane glue, varnish, paint	Polyester resin in water tanks, polyethylene pipes, PVC pipes, epoxy coatings, gaskets (descriptor may be more like "hydrocarbon"), primers, cement liners, solvents; Check source water for contamination and/or PVC and polyethylene pipes for permeation of contaminated soil and/or gasoline (leaking underground storage tanks)
	2.b Kerosene, gasoline;	Rubber gaskets for ductile iron pipes
	2.c. Plastic	PVC pipe, polyethylene pipe (HDPE)
	2.d. Burnt Plastic	PVC pipe, polyethylene pipe (HDPE)
Fruity/ sweet/ flowery/ fragrant/ vegetable	3.a. Vanilla	Degradation product of lignosulfonates, cement/concrete pipes and liners
	3.b Vegetable	Natural decay of vegetation due to bacterial activity
Fishy/ rancid	4.a Rancid	Lubricants used for ductile iron pipes (soapy/rancid)
Mouth feel/nose feel, metallic, astringent, drying, tingling, chalky, oily, pungent	5.a Metallic	Metals – pipe materials, fittings, solder
	5.b Chalky	Cement materials - calcium carbonate
Earth/musty/moldy		Halogenated anisoles; phenols biotransformed by fungi in distribution system. Note: first rule out contribution from natural sources like geosmin and MIB (from cyanobacteria)
Marshy/swampy/septic/sulfurous	7.a rubbery	Primarily rubber: from cement mortar lining, rubber gaskets and o-rings; synthetic rubber covers on storage facilities; rubber coatings and sealants, etc. (If not from decaying vegetation or septic conditions)

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3.4.3 Assessment of T&O problems

To formally assess aesthetic water quality, researchers in the water industry have adapted sensory assessment methods from the food and beverage industry. There are myriad T&O assessment methods that have been developed in the last 50 years. The most applicable and robust methods include those developed by ASTM, Standard Methods, and AwwaRF. The most prominent are ASTM E679-91 Standard Practice for Determination of Odor and Taste Thresholds by a Forced-Choice, Attribute Rating Test, Carolina Biological Supply Odor Test Kit, Flavor Rating Assessment, Flavor Profile Analysis, Threshold Odor Number, and Flavor Threshold Test, 2-of-5 Odor Test, Triangle Test methods. The goals, benefits, and limitations to each of these tests are discussed elsewhere (Dietrich et al., 2006). Selection of an analysis technique depends on costs, materials, lab requirements, time allotment, participation restrictions, amount of training required to administer or participate, complexity of interpretation, and quality assurance measures.

In general, the T&O wheel (Suffet, 1995) is used to classify the taste or smell associated with the water. It attempts to identify typical sources of T&Os in drinking waters to facilitate identification and resolution of issues. Although much work has been done to fill in the wheel more thoroughly, the delivery systems for drinking water are complicated as are the chemical sources of the odors. There are often numerous potential differences in water quality from one part of a distribution system to another, spatially and temporally. Source of problems can be broken into categories (biological, chemical, and physical reactions) as discussed below.

3.4.4 Background of T&O problems in potable water

Biological growth and decay is a function of nutrient and water chemistry conditions. Biological regrowth can be defined as growth of certain microorganisms that are targeted for removal in upstream processes. For certain T&O problems, certain microbes and fungi can produce off-flavors in their biological processes. One common example of this is biomethylation of chemicals (Bruchet, 1999), a reaction that can be promoted by low water velocity and disinfectant residuals, and results in a chemical with a lower odor threshold number (lower concentration at which people can sense it's presence). Perhaps the most commonplace example of this phenomena are sulfate reducing bacteria reducing sulfur in anoxic or anaerobic conditions causing a rotten egg smell associated with sulfur and sulfite.

Chemical reactions can also create or exacerbate T&Os in the distribution system. For example, the T&O compounds that are produced by fungi can be intensified by reactions with disinfectant residual (Nyström et al., 1992). In fact, disinfectant residuals and their byproducts have very well defined threshold levels. Some utilities adjust the amount of disinfectant residual in the effluent water depending on the season or in reaction to an isolated contamination event. Therefore the extent to which the utility is adjusting the disinfectant residual can alter the T&O quality of the water in terms of the threshold values for the disinfectant, their byproducts, and compounds with which they react, such as phenols. Phenols and halophenols (chlorinated, brominated, or iodinated) can cause medicinal odors (eg. water with TOC < 10 µg/L can react with chlorine residual to form 2-chlorophenal; 2,4 di dichlorophenol; and 2,6 dichlorophenol). Phenol can occur in natural waters and pipe materials. When it reacts with chorine and becomes methylated by fungi, phenols can be converted to trichloroanisoles in distribution waters. Amino acids produced by bacteria in biofilm can also react with the disinfectant residual to produce aldehydes and nitriles which also have a medicinal odor (LeCloirec and Martin, 1985).

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Physical reactions include those related to reactions with the pipe materials used in the distribution and plumbing systems and physical characteristics of the water such as temperature. Plastic pipe, coatings, membranes, and epoxy re-linings can leach chemicals into the bulk water system (Durand and Dietrich, 2007; Heim and Dietrich, 2007). Materials have a high potential of producing T&O problems because, in the U.S., new building materials are evaluated on a health risk basis – which does not incorporate an aesthetic scale. Therefore, newer buildings using some plastic or synthetic materials could be compromising "drinkability" for a cheaper or more environmental friendly material that may reduce the number of consumers who will actually consume the tap water. An example of this type of leaching is polyvinyl chloride (PVC) leaching triphenolphosphate (Rigal and Danjou, 1999), which can be one source of medicinal odors. In addition, these reactions are effected by the water residence time and surface area to volume ratios in the pipes. As the reactions have more time and surface area to react with, the extent of the release of leaching odorous products could become worse in green buildings relative to conventional plumbing.

3.4.4.5 Remediation

Solutions to T&O problems can involve conventional treatment of source water (e.g. limiting nutrients, dosing copper sulfate, granular activated carbon filtration), through additional steps at the treatment facility (e.g. advanced oxidation techniques, granular activated carbon filtration), and in distribution or plumbing systems (e.g., designing water age, disinfectant boosters in storage facilities, material replacement). General utility management strategies and approaches are broadly outlined in Table 3.7. Perhaps the simplest prevention of T&O issues that buildings can apply would be to design the water residence times in buildings to be low because most T&O problems have been reported to arise due to reactions occurring in the distribution system (Burlingame and Anselme, 1995; Lin, 1977; Rigal and Danjou, 1999; Tomboulian et al., 2004; Dietrich, 2006; Durand and Dietrich, 2007; Khiari et al., 2002). Premise plumbing systems have many of the same issues as the distribution systems (Suffet et al., 1995) and are, to some extent, more complicated due to the variation in consumer use patterns and material options. By effectively reducing the water age in premise plumbing systems, many taste and odor problems could be avoided. One field study remediated T&O problems that had been isolated to the premise plumbing system by simply flushing 4 gallons per day in the most downstream dead end in the plumbing system, with resulting improvements likely due to higher chlorine residuals and reduced levels of microbes (Nguyen et al., 2012).

Although granular activated carbon filters are effective at removing many T&O-cause compounds, their installation at the point of entry to buildings can only be recommended with extreme caution. Commercial-scale granular activated carbon filters remove the disinfectant residual and are suspected to facilitate increased growth of pathogenic bacteria in buildings and contributing to consumer deaths and waterborne disease (Miami-Dade, 2010; See Chapter 4 Miami Dade case study). Booster chlorine systems can also be considered at the entry point of buildings. In some systems with low disinfectant residuals, these systems serve to reduce microorganism levels and to limit regrowth potential by maintaining a residual through the building plumbing system. However, special expertise is required to operate these systems properly and systems that serve more than 25 individuals or have more than 15 service connections are required to uphold the federal regulations on drinking water quality standards (U.S. EPA, 2013). The latter includes multiple family buildings, hotels, and hospitals that have a treatment system on site. In addition,

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chlorinous T&Os are a leading cause of consumer complaints (Suffet et al., 1995) and could be intensified by boosting disinfectant residual at the head of the building, despite the potential health benefits.

The type of disinfectant employed can even have important implications for T&Os in premise plumbing systems. Chloramines are traditionally thought to be more persistent in distribution systems and can be more effective for inactivation of biofilm bacteria under some circumstances (LeChevallier et al., 1990; Neden et al., 1992). However, there are examples where nitrification has occurred in drinking water systems where chloramines are consumed within only a few hours (Nguyen et al., 2012), leaving no disinfectant residual.

Another approach to mitigating T&O issues in distribution systems and premise plumbing has been to replace or upgrade pipe materials. Some pipe materials inherently cause T&Os and are mitigated by simply replacing the pipes or devices (Table 3.7). For example, chemicals that leach from the PVC pipes can cause a chemical hydrocarbon odor similar to paint or chemical solvent. Leaching of chemicals is already being taken into account in green building design strategies. Some organizations that are sensitive to the aesthetic quality of water in their green buildings are encouraging builders not to use some of these materials, such as PVC. One organization has recently put PVC and materials containing chlorinated polyethylene and chlorosulfonated polyethlene on a "red list" of materials that should not be used in green building construction (International Living Future Institute, 2012).

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Table 3.7
Utility approaches for minimizing distribution and premise plumbing potable water tastes and odors (adapted from Kirmeyer et al., 2000)

Monitoring/Consumers as Sentinels for larger problems	Use customer complaint data to identify areas of distribution system with taste and odor problems Conduct monitoring in areas with frequent taste and odor complaints to identify causes Conduct source water monitoring to determine H_2S levels, microbial conditions, concentrations of iron/manganese Create logical data management techniques to be able to readily process and employ consumer complaints as a tool
Operations	Minimize detention time in pipelines and storage facilities
Maintenance	Conduct routine flushing in areas with excessive detention time, in areas with increased taste and odor complaints Review records showing piping types, age, location, maintenance records
Source Water Treatment	Provide treatment such as GAC filtration, ozonation to remove tastes and odors associated with source water Ensure adequate disinfection and disinfection residual Consider switching to chloramines if chlorinous taste and odors are chronic
Engineering	Consider booster chlorination at lower dosages to maintain a residual Consider taste and odor potential when selecting materials for the distribution and premise plumbing systems Cover storage facilities to limit algal growth Ensure proper application and curing of coating, linings, glues, and primers
Management	Provide information to the public regarding causes of taste and odors Ensure that causes are identified and steps are taken to reduce episodes Train personnel that are in contact with customers to respond to inquiries and to explain actions utility is taking to address issues

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3.5 RAINWATER HARVESTING

Key words: Rainwater, harvesting, runoff

3.5.1 Introduction

The practice of harvesting rainwater for indoor or outdoor use is becoming increasingly popular. Many green rating systems reward the conservation of municipal water. Rainwater harvesting occurs in two basic forms: land-collection and roof-top collection. Land-collection is the practice of pooling and storing rainwater runoff from large portions of a property or directing the rainwater to infiltrate the subsurface to eliminate or reduce runoff hydrographs form storm events. Typical applications include decorative fountains, bioswales, rain gardens, or green roofs as best management practices for storm water mitigation. Land-collected rainwater is not suitable for drinking water without rigorous treatment because of the various materials and contaminants the water accumulates over the large collection area. Beyond decreasing water demand for outdoor uses, and associated increased water age within individual buildings, this practice should not directly impact potable water quality.

Rooftop collection is the practice of collecting water directly from rooftop runoff and treating the water to the quality required for a desired use, including both potable and non-potable applications. Common non-potable uses include toilet/urinal flushing, irrigation, decorative fountains and other aesthetic water features. Use of rainwater for potable water is not currently common in the U.S. In most commercial applications, due to the concern of public health, some water treatment is applied. In these situations, the water is typically treated to nearly potable water quality to address real or imagine risks associated with human exposure to this water.

Commercial systems likely avoid using rainwater as potable water because of the added onerous U.S. EPA regulations the system would be required to meet (U.S. EPA, 2013). If rainwater for potable water use is desired, backup connections to municipal supplies are sometimes required because of the large volume of water required to operate commercial systems (Kniffen, 2010). Household systems, however, are relatively easy to install and maintain, and are not subject to the same federal water quality regulations, although it is wise to target minimum U.S. EPA recommended limits on certain contaminants.

Rainwater harvesting laws vary state-by-state. Some states have no restrictions on the volume or type of system that can be installed and, in fact, encourage rainwater harvesting practices. In other states it is illegal to harvest any and all rainwater. Theoretically, rainwater flows through the watershed or storm water distribution system to a local body of water, which is, in some states, allocated based on water rights laws. By collecting the water before it has the chance to flow downstream to be used by the lawful owner, the rainwater harvesting system can impede the legal rights of the downstream water user. Many states have over-allocated the water in its river ways.

3.5.2 Rainwater Quality

Rainwater has several water characteristics that could negatively impact the quality of potable water produced by rooftop collection systems. One study found that water collected from roof runoff typically had poor microbial quality and total coliforms and enterococci were consistently above U.S. EPA standards for secondary recreational contact water quality standards (Shushter et al., 2013). Rainwater harvesting often has physical debris collected during a rain

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event. While things like twigs, dirt, and animal waste are easily removed using gutter screens and a fist flush flow diverter (a device that allows initial rainfall to be diverted away from the collection tank to avoid these physical contaminants), these contaminants can still contribute unwanted constituents to the water such as total organic carbon (TOC) and heavy metals (e.g. Bailey et al., 1999; Boller, 1997).

Rainwater can also absorb chemicals from the air. One study measured pesticide, herbicides and polycyclic aromatic hydrocarbons (PAHs) in rainwater exceeding EPA limits (Basheer et al., 2003; Polkowska, 2000). Volatile organic compounds (VOCs) from materials on the roof, guttering, or piping can also leach into the rainwater. In one study, copper, zinc, and pH levels did not meet U.S. EPA freshwater quality standards for both raw rainwater and rainwater impacted by rooftop collection systems (Chang et al., 2004). The pH of rainwater is typically low (~5.5), and has virtually no hardness or alkalinity. Low pH, hardness, and alkalinity waters are known to be very corrosive to metals located within the plumbing system, sometimes leaching lead levels over the U.S. EPA action limits (Sarver et al., 2011a; Lytle and Schock, 2008; Gardels and Sorg, 1989), even when the individual devices are ANSI/NSF certified (Edwards and Dudi, 2004; Triantafyllidou and Edwards, 2007).

Microbiological contaminants associated with rainwater are less understood. In general, rampant microbial growth should be avoided to avoid foul odors in anaerobic or septic tanks and plugging of small-pore treatment filters. These problems can usually be avoided by best management practices for maintenance. For harmful biological contaminants, monitoring indicator (fecal-derived pathogens and enterococci) and heterotrophic organism plate counts are typically recommended for assuring rainwater harvesting water quality (e.g. TWDB, 2005). However, one rainwater harvesting study reported no link between fecal and enterococci indicators and other pathogens such as *Legionella pneumophila*, suggesting that using indicators for monitoring the safety of rainwater is not robust (Ahmed et al., 2008). Similar reasoning has been used for municipal water systems when opportunistic pathogens colonize plumbing systems.

Other factors that have significant influences on the levels and type of contamination include the amount of time between rain events (Yaziz et al., 1989), season (Jones and Harrison, 2004), the age of the roof (Chang et al., 2004), land use of the surrounding area (Bucheli et al., 1998), roof directional orientation (Evans et al., 2006), and slope and length of the roof (Kingett Mitchell Ltd., 2003). For many situations, especially for retrofit buildings, the user has little control of these factors.

3.5.3 Implementation Strategies

While there are limited resources on the treatment of rainwater for specific contaminants, there are several best management practices for the production of potable water. It is important that ANSI/NSF certified processes and products are used. These standards include levels of disinfectants to be used (NSF 60), standard practices for UV treatment systems (NSF 55), certified drinking water components (NSF 61), and certified plastic materials for transporting and storing the water (NSF 14).

Maintenance of the system is probably the next most important factor in high quality water. Even a good system can fail if not properly maintained. Much of this can be done by the homeowner/building operator or can be contracted out to the installation/designer companies for rainwater harvesting systems.

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Monitoring is also critically important; however, a recent survey of individuals representing approximately 2,700 rainwater systems indicated only 12% of homeowners and 3% of contracted maintenance personnel monitored microbial water quality quarterly (Thomas et al., 2013). Typical water quality testing includes heterotrophic plate counts, coliform bacteria, turbidity, and in some instances inorganic contaminants such as lead and copper. In a report titled Rainwater Harvesting Potential and Guidelines for Texas, the Texas Water Development Board (TWDB), a widely respected authority on rainwater harvesting implementation, has put forth specific recommendations (Table 3.8).

Table 3.8
Minimum water quality guidelines for indoor use of rainwater (reproduced from TWDB, 2006)

Category of Use	Rainwater Quality for Non-Potable Indoor Use	Rainwater Quality for Potable Use
Household/Residential	Total Coliform <500 CFU/100 mL Fecal Coliform <100 CFU/100 mL Water testing **recommended** annually	Total Coliform - 0 Fecal Coliform – 0 Protazoan Cysts – 0 Viruses – 0 Turbuidity <1 NTU Water testing **recommended** quarterly
Community/Public Water System (as defined by U.S. EPA)	Total Coliform <500 CFU/100 mL Fecal Coliform <100 CFU/100 mL Water testing **recommended** annually	Total Coliform - 0 Fecal Coliform – 0 Protazoan Cysts – 0 Viruses – 0 Turbuidity <0.3 NTU Water testing **required** quarterly In addition, the water must meet all other public water supply regulations and water testing requirements per local jurisdiction.

It is generally thought that upholding these parameters will provide safe drinking water (U.S. EPA, 2009). It is important to note, however, there are no mandatory monitoring guidelines for private rainwater systems, and the absence of coliform bacteria is not necessarily indicative of having no other pathogens or other harmful contaminants in the water.

3.6 MICROBIOLOGICAL CONTAMINANTS

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3.6.1 Microbial Regrowth

Key words: regrowth, assimilable organic carbon (AOC), micronutrients, water age

3.6.1.1 Introduction. The growth of microorganisms in drinking water systems can cause a host of issues, including waterborne disease, tastes and odors, increased corrosion, and violation of primary and secondary drinking water standards. The term microbial regrowth refers to growth of microorganisms that occurs downstream of a treatment step. It is often referred to as a "regrowth potential," and measured by observing biological growth in culture assays over several days. Regrowth potential indicates the maximum growth potential of a heterotrophic microbial community based on all available nutrients in a water sample. Premise plumbing, the portion of the plumbing system beyond the public utility main and service lines, has several characteristics that vary markedly from main water distribution systems, such as increased surface area to volume ratios, stagnation periods, diverse plumbing materials, and lower disinfectant residuals that make it more prone to encounter problems with regrowth. The problem of microbial regrowth is a complex interaction between many components of system design and operation, including chemical, physical, operational, and engineering parameters and no one factor can be attributed to regrowth issues alone.

3.6.1.2 Anticipated link to green buildings. The increased water residence time in green buildings can lead to loss in disinfectant residuals, corrosion of plumbing materials, reactions with pipe and plumbing materials to release nutrients, and changes in water chemistry that promote bacterial growth (see Sections 3.1, 3.3, and 3.4).

3.6.1.3 Factors affecting regrowth. *Water age*. Overnight stagnation can increase the concentration of microbes in the water and change microbial communities, especially within premise plumbing. Lautenschlager et al. (2010) observed a 2-3 fold increase in cell concentration by flow cytometry, 2-18 fold increase in ATP levels, and 4-580 fold increase in heterotrophic plate counts (HPCs) during overnight stagnation. In addition, the microbial community associated with these field samples changed significantly, as observed by denaturing gradient gel electrophoresis (DGGE). In another study, 68% of overnight stagnation samples in eight households had greater than 500 CFU/mL, the U.S. EPA recommendations for drinking water for heterotrophic plate counts (Pepper et al., 2004). The average concentration for these samples was 3,072 CFU/mL as compared with 22-56 CFU/mL at various stages of the source and distribution system waters. The densities at dead ends in plumbing systems, where water residence times are very high, increased to greater than 10^6 cells/mL (LeChevallier et al., 1987).

3.6.1.4 Hydrodynamics. The hydrodynamics in the pipes also plays an important, but not fully understood, role. The effects of continuous versus intermittent flow, regardless of overall water age, and the effects of high versus low flow rate are unclear. If there is continuous flow, the likelihood of delivering a disinfectant – whether it is a chemical disinfectant residual, high water temperatures, or some other microbial growth inhibitor – is increased. However, if disinfectants are absent from the water, continuous flow can increase the delivery of key nutrients to biofilms, actually increasing growth (e.g., Liu et al., 2006).

If flow rate is very high, shear stresses on biofilm attached to plumbing materials are increased, possibly leading to more biofilm sloughing off the pipe wall, thereby increasing

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exposure to the microorganisms in the biofilm. However, if high flow rate is continually maintained, as it is in many distribution system mains, then biofilm growth could be limited. These concepts have not been fully developed in the literature. Liu et al. (2006) has touched on this issue. Although several peer-reviewed publications determined that overall stagnation increased the growth of *Legionella* (Ciesielski et al., 1984; Harper, 1988;), this study found that turbulent (i.e. "high") flow actually promoted the growth of *Legionella* in the biofilm matrix over laminar (i.e. "low") and stagnant flow. However, this study was completed at room temperature (24 °C) with 95% of the water recirculating within the system. Although chlorine levels were not reported, it is likely that over the course of the experiment any residual initially present had dissipated. Adding another layer of complexity, intermittent high and low flow could further alter how microorganisms grow and are released from biofilms. Clearly, studies examining stagnation versus flow, and high versus low flow rate, have shown contradictory results thus far. There is a need for more research in this area to help explain these discrepancies.

3.6.1.5 Temperature. The temperature delivered to specific sections of a plumbing system is certainly dependent on water age and hydrodynamics; however, it is also clearly dependent on plumbing system design and set points of the hot water systems. Recent research of on-demand, conventional, and recirculating hot water systems suggested that at a hot water heater setting of 49 °C, the majority of the storage capacity in electric water heaters was at ideal growth temperature (<46 °C) for microorganisms for both conventional and recirculating systems (Brazeau and Edwards, 2013). As the water heater set point increased to 60 °C, the percentage of the tanks below 46 °C decreased; however, a large enough portion of the tanks remained below 46 °C to allow for growth even at 60 °C (22% for a recirculating system and 31% for a standard system). This study also examined how the presence of micronutrients such as dissolved oxygen (DO) and hydrogen evolution were affected. On-demand systems had nearly fully saturated values of DO (~10 ppm) while recirculating and conventional system had lower values of DO (~5 ppm and 8 ppm, respectively). The on-demand system produced virtually no hydrogen, while the recirculating line produced 4-6.5 times more hydrogen than the standard system. In addition to these individual system differences due to design, distribution system temperature increases are often accompanied with increased nutrient levels and turbidities (Geldreich, 1996).

3.6.1.6 Disinfectants. Although there is detailed information about in-building disinfection systems earlier in this chapter, the primary concern for utilities in disinfection stability is with maintaining a free chlorine or monochloramine residual throughout the distribution system. The stability of these disinfectants in distribution and premise plumbing systems is discussed at length in this first section of this chapter. Briefly, there seems be a trade off in overall efficacy of the residual type with residual stability and the tendency to form disinfectant byproducts (LeChevallier et al., 1990). Monochloramine is thought to have better stability in distribution systems because it is generally less reactive than free chlorine, allowing it to penetrate deeper into biofilm layers in some circumstances (Wolfe et al., 1984). Free chlorine, however, is thought to be more effective at oxidizing planktonic bacteria (bacteria in the bulk water, and not attached to materials in the biofilm) (Wolfe et al., 1984). As a result of the increased oxidative power, free chlorine disappears more quickly (LeChevallier et al., 1990). In addition, there is some evidence to suggest that the efficacy against certain microorganisms is different for both monochloramine and chlorine. For instance, Pryor et al. (2004) observed a shift in the pathogen community in one distribution system

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from a *Legionella*-dominated community to a *Mycobacterium avium* complex-dominated community upon a shift from using free chlorine to monochloramine.

3.6.1.7 Other factors: nutrient and pipe material. Drinking waters are oligotrophic environments where nutrients are often the limiting factor for growth. Specifically, a portion of biodegradable organic carbon (BDOC), called assimilable organ carbon (AOC), has been thought to limit the growth of microorganisms in drinking water systems (van der Kooij, 1992; LeChevallier et al., 1987). The amount of AOC effective at curbing growth has been estimated at 50 µg AOC/L (van der Kooij, 1992), which is difficult to consistently measure accurately. There are several sources of AOC that have the ability to undermine reduction of AOC at the treatment facility that are worth mentioning, including leaching from cross-linked polyethylene (PEX) pipes (Skjevrak et al., 2003; Durand and Dietrich, 2007; Heim et al., 2007), production of new biomass from inorganic carbon through nitrification (Zhang et al., 2009), humic acid sorption to metal oxides from pipe scale, water heater anode rod corrosion (Butterfield et al., 2002a, 2002b; Edwards et al., 1993; Camper et al., 2004), carbon fixation into new biomass using H_2 from hot water heater anode rods as an electron donor (Bowien and Schlegel 1981; Schlegel and Lafferty 1971; Igarashi 2001; Morton et al., 2005), and possible AOC reservoirs from household water filters.

While these factors are important to understanding microbial regrowth and are included here for completeness, there is nothing inherent in these factors that link them specifically to green buildings. However, there is circumstantial evidence that increased stagnation times can increase the leaching tendency of AOC from PEX pipes. For instance, an increased flushing protocol in one study decreased the prevalence of taste and odor causing compounds that were leaching from a PEX pipe experimental setup (Durand and Dietrich, 2007)

3.6.1.8 Remediation strategies. While all of these factors interact with one another, and the best strategies will incorporate as many of them as possible, a good place to start is hitting disinfectant residual and temperature targets. This means, maintaining a residual throughout the entire distribution system for cold water systems and hitting the water heater set point throughout the hot water system, both of which may require the reduction of water age through regular flushing protocols.

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3.6.2 Metered Faucets

Key words: metered faucet, electronic faucet, hands-free faucet, flow, water age

3.6.2.1 Introduction. The electronic faucet, also known as the non-touch, eye, metered, or hands-free faucet, is an example of an engineered water saving device that has been implemented in public and commercial buildings to reduce bacterial cross-contamination amongst consumers. Originally, electronic taps were assumed to promote hygienic hand-washing by preventing users from touching the faucets during operation and reducing potential exposure to germs. However, several studies have shown that there is an increased cause for concern regarding opportunistic pathogens in water coming from electronic faucets in both new construction and renovated plumbing.

3.6.2.2 Anticipated link to green buildings. Reducing potable water demand is one objective inherent to all green building designs. As an incentive to focus on this objective, the Leadership in Energy and Environmental Design (LEED) accreditation system awards 2-4 points toward certification for reducing the water demand from conventional levels by 30%-40%. This reduction has significant implications for the flow rate and water age in green buildings. Metered faucets, by design, have aerators installed that are up to five times more restrictive in flow than conventional faucets counter parts. While achieving water conservation is an important and noble goal, for reasons that are not yet clear - perhaps because of lower flow or specific components of these devices, these devices may pose a health concern to some individuals.

3.6.2.3 Hypothesized cause(s) for concern. Metered faucets are thought to reduce the spread of germs by avoiding cross contamination when operating the faucets. However, there is no scientific evidence to back this claim and, in fact, recent research has identified electronic faucets as a possible sink for human pathogens including *Legionella* spp. and *Psuedomonas aeruginosa* in hospital settings (Halabi et al., 2001, Chaberny and Gastmeier, 2004; Yapicioglu et al., 2011, Sydnor, 2012; Berthelot et al., 2006). There are several hypotheses for the increased risk of exposure to OPPPs (Table 3.9). The low flow through water-reducing faucets is linked to low pressure and an increased stagnant volume of water in the pipes leading to the tap. This could provide ideal growth temperatures (35°C) for both *Legionella* spp. and *Pseudomonas aeruginosa* (Halabi et al., 2001). The reduced flow and pressure could be incapable of providing enough water volume or turbulence to properly flush and "clean" the faucet (Chaberny and Gastmeier, 2004; Yapicioglu et al., 2011), which has implications for biofilm attachment and release rates that are not well understood. In addition, the physical properties of the materials used to make the electronic faucets could be a contributor to pathogen growth. The rubber and PVC pipes that lead from the magnetic valve to the outlet have been shown to be suitable for *Pseudomonas aeruginosa* biofilm growth (Halabi et al., 2001; Chaberny and Gastmeier, 2004; Yapicioglu et al., 2011). The magnetic valves also have the capability to be contaminated during manufacturing. Berthelot et al. (2006) showed that the magnetic values could have a residual amount of stagnant water contaminated with *Pseudomonas aeruginosa* from QA/QC tests at the manufacturing plant during which water is passed through the device to ensure it functions properly. Assadian et al. (2002) suggested the length of pipe from the magnetic valve to the water outlet is a primary design parameter increasing the likelihood of pathogen growth. Another known contributing factor to pathogen contamination could be plumbing pipe material and age. Van der Kooij et al. (2005)

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reported bulk water *L. pneumophila* concentrations in stainless steel and cross-linked high-density polyethylene pipes that were 10 times higher than the concentration found in copper pipes. In that water, however, this difference gradually disappeared after approximately 250 days of operation simulating domestic use, most likely due to the accumulation of corrosion products (copper hydroxides and carbonates) from the copper pipe. Further, some electronic faucets mix hot and cold water upstream of the tap, creating several feet of pipe that have the ideal temperatures for pathogen growth and that is seeded by microbes from both the hot and cold taps.

Unfortunately, the studies currently in the literature involving electronic faucets are all associated with field investigations responding to known cases of opportunistic pathogens or to routine sampling that identified elevated numbers of bacteria. They do not investigate subtle differences inherent in each design as a possible problem cause for problems in head-to-head comparisons. Additionally, no obvious theme behind the use of new or old pipes, different pipe materials, or flow rate could be identified in the literature. Contamination problems have been found in new construction, renovations, and simple faucet replacements. Future work needs to study and isolate causal factors so that there is a basis for rational decision-making on how to remediate problems that occur, or whether these faucets should be installed at all in some settings.

3.6.2.4 Remediation strategies. Once the faucets become contaminated with *Pseudomonas aeruginosa*, it is cumbersome to disinfect them. Hyperchlorination, although a drastic measure, has proven in many instances to be ineffective (van der Mee Marquet et al., 2005; Leprat et al., 2003; Merrer et al., 2005). Extended thermal flushing at 70°C for 30 minutes (van der Mee Marquet et al., 2005) and replacing the faucets with conventional or elbow operated taps have proven to be effective in some situations.

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Table 3.9
Summary of current literature on metered faucets

Publication	Pipe age status	Number of EFs	P. aeruginosa growth	EF deficiency	Comments
Assaidian et al., 2002	Not specified	18	0%	Distance from valve to outlet	
Berthelot et al., 2006	Tap replacement	NA	Yes	Magnetic valve	Letter to the editor. No contamination before magnetic mixing valve was observed. Several disinfection methods attempted.
Chaberny and Gastmeier, 2004	Renovation	27	8%	Low flow Low pressure Pipe material	73% of EFs exceeded 100 CFU/mL. None of the manual control faucets exceeded this reference value.
Halabi et al., 2001	Tap replacement	23 without temperature control 15 with temperature control	74% 7%	Low flow Temperature Pipe material	None of the taps showed contamination with indicator organisms. 10 EFs without temperature control were tested for Legionella spp. and all 10 were positive
Leprat et al., 2003	Renovation	3	100%	None explicitly stated	Disinfection using chlorination attempted 6 times, all unsuccessful. Reverting back to conventional taps yielded no contamination
Merrer et al., 2005	Not specified	92	39%	None explicitly stated	Took place in two separate hospitals. Overall, 1% of manually operated faucets were contaminated.
Van der Mee-Marquet et al., 2005	New construction	87	100%	None explicitly stated	Hyperchlorination was ineffective. Thermal disinfection (70°C flushing for 30 min.) was effective in eliminating *P. aeruginosa* contamination
Yapicioglu et al., 2011	Tap repl.	NA	100%	Low flow Low pressure Pipe material	Found 90.7% similarity in *P. aeruginosa* strains in water samples and patient blood.

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3.7 GREEN BUILDING ASSESSMENT AND PLUMBING CODES

Key words: International Green Construction Code, ASHRAE 189.1, green plumbing codes

3.7.1 Background

In the United States, a range of tools have been developed by the government, independent third party organizations, non-profit grass-roots organizations, and entrepreneurs to assess individual products and whole building systems marketed as environmentally friendly. Three general categories of green building assessment tools include individual product rating systems, whole building rating systems, and standards (Table 3.10).

Whole building and individual product rating systems were developed to help building owners achieve their goal of environmentally sustainable design, while at the same time ensuring that the practices applied to that building are considered to be beneficial to the environment and occupants. Standards provide a legal framework, if adopted by a local jurisdiction and turned into a code, and are developed to ensure the safety of the building and establish standard practices for building designers. Evaluating how *green* building standards, specifically, influence practices that affect water age and water quality is important.

Both the International Green Construction Code (IgCC) and the American Society for Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) Standard 189.1 are American National Standard Institute (ANSI) approved standards. Features of the ANSI approval process include broad-based public review and consensus of stakeholders. These standards were written in code language to facilitate individual jurisdiction adoption. Both standards are collaborative efforts across many building standards organizations.

3.7.2 International Green Construction Code

The International Green Construction Code (IgCC) is a commercial building construction code. It does not apply, unless otherwise noted by the local jurisdiction adopting the standard, to residential housing, temporary structures, or industrial and manufacturing facilities. These restrictions include one- and two-family dwellings, townhouses, apartment buildings, and dormitories. The legal ramifications of this standard are set by local jurisdiction and responsibility and compliance with this standard lies with the building owner/operator. The IgCC has clauses that allow for innovative designs beyond the scope of the standard that can be approved by the local jurisdiction. In addition, the jurisdiction can opt-out of specific sections of the standard. In general, the code is supportive of sustainable building features.

There are several practices outlined in the IgCC that do not inherently change the quality of municipal water being delivered, but do increase the water age within the building. One example of this is in Section 403: Storm water management. The IgCC promotes storm water mitigation practices such as infiltration, evapotranspiration, rainwater harvesting for non-potable uses, and storm water runoff reuse. It specifies certain benchmarks to achieve such as retention of a 95th percentile magnitude of storm while maintaining pre-development runoff hydrographs.

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Table 3.10
Summary of selected U.S. standards and rating systems for green buildings and green devices

STANDARDS	
IgCC (supported by ANSI, NAHB, IES)	Expands upon ICC plumbing code, specifically related to green building features; Basic protection from cross-connections and sustainable design approaches
ASHRAE 189.1 (supported by ANSI, USGBC, IES)	Covers basic protection from cross-connections and sustainable design approaches
BUILDING RATING SYSTEMS	
Green Point (Created by Build it Green)	Individual home assessment in California; Basic certification of sustainable design based on non-invasive, no monitoring
ICC 700 (Supported by ANSI, NAHB)	Residential rating system
Living Building Challenge (Created by International Living Building Institute)	Net-zero energy and water buildings; Goes beyond basic strategies; Focuses on ecology of the water systems
Green Globes (Supported by ANSI, Created by Green Building Initiative)	Whole building rating system; Point-based; More flexible than LEED certification (e.g. no pre-requisites for certification)
LEED (Created by USGBC)	Whole building rating system; Point-based
PRODUCT RATING SYSTEMS	
Energy Star (Created by U.S. EPA)	Certification for individual appliances to meet energy efficiency standards
Water Sense (Created by U.S. EPA)	Certification for individual appliances that meet water use standards

While section six of the IgCC primarily deals with energy conservation of appliances and building systems, there is a significant amount of overlap with water quality. The IgCC recommends that users should be allowed to adjust the temperature of their hot water heater to temperatures between 50-100 °F (10-38 °C; Section 607.2.2). At the higher end of this temperature range, the water is not hot enough to ensure control of pathogens or limit microbial growth (e.g. *Legionella* proliferate vigorously from 32-42°C; Yee and Wadowsky, 1982). This section (607.7) also recommends circulating hot water systems with controls that allow continuous, timer-activated, or water temperature-activated circulation. Continuously recirculating electric water heaters have been shown to be 32-36% less energy efficient than standard, non-recirculating electric water heaters (Brazeau and Edwards, 2013). Even on-demand water heaters, while extremely efficient when purchased, can often exhibit rapid scaling problems, electric versions can require costly infrastructure upgrades, and they are sometimes unable to achieve desirable bathing temperatures (Brazeau and Edwards, 2013). In addition, for some consumers, the recirculating line

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activation switches required to improve energy efficiency are unrealistic, burdensome, and rarely installed.

In section seven, there are several clauses that would increase building water age. Essentially all appliances installed are required to be WaterSense® or Energy Star labeled because there are specific limitations on the amount of water each type of device can use on a flow rate or per cycle basis. Both WaterSense® and Energy Star stress water efficiency of the devices. The IgCC also encourages the use of recycled municipal water systems for non-potable indoor and outdoor uses when a supply is accessible. The standard defines accessible as a reclaimed supply access that is no greater than 150% the distance to a regular potable water supply, or if there is a municipal reclaimed water hookup within 100 ft of a potable water supply (Section 702.7). A unique component of the IgCC includes the consideration of total water volume within the system. The standard limits the allowable length of pipe of certain diameters in hot water recirculating and non-recirculating systems. While this is most likely aimed at reducing the amount of heat loss in pipes (i.e. wasted energy), it is a good practice to observe and could serve as a logical basis for similar considerations in cold water systems to limit overall system volume. Lastly, there are concerns of the recommendation to use self-closing (electronic/metered) faucets and other low-flow devices. These devices not only inherently increase the water age within the building by using less water than their conventional counterparts; they also seem more prone to colonization by opportunistic pathogens (See Chapter 3, Microbial Regrowth section).

This standard does not appear to cover fire suppression systems. While recommendations for fire system design and sizing vary by jurisdiction, it seems apparent that when water use is reduced but the overall fire suppression system volume the same, there is increased opportunity for the water to be degraded based on minimum pipe diameter requirements. Since fire suppression systems have been documented to cause main distribution system contamination (U.S. EPA, 2001), it would be appropriate for this to be covered in this building code.

3.7.3 American Society for Heating, Refrigeration, and Air-Conditioning Engineers Standard 189.1-2011

The ASHRAE Standard 189.1-2011 had a similar approach as the IgCC in that it was a collaborative effort between many organizations, was written in readily adoptable code language, and had similar recommendations for green buildings to limit storm water runoff and promote potable water demand reduction. One positive attribute of this standard related to water efficiency is that it set specific goals for storm water mitigation and water reuse practices based on climatic region; however, it did not include specific recommendations or restrictions on water volumes, any information on hot water systems, or any specific water treatment devices.

3.7.4 Green Building Construction Code Summary

Primary focuses of green building performance evaluation criteria are energy consumption, indoor environment, and water conservation, but little if any focus is given to the quality of water that results from water conservation.

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CHAPTER 4: CASE HISTORIES

4.1 SELECTION OF CASE HISTORIES

The case histories were selected to illustrate a diverse range of problems typically encountered in premise plumbing. Although not every case study presented occurred in a green building, each had features related to green buildings. For each case presented, a brief introduction and background is provided, along with the details of the case and key lessons learned. Many of these cases have been published in the literature. Where appropriate these references are provided.

4.2 ORANGE WATER AND SEWER AUTHORITY/UNIVERSITY OF NORTH CAROLINA-CHAPEL HILL (OWASA/UNC-CH)

4.2.1 Case

Taste and odor complaints occurred in two new buildings at the University of North Carolina at Chapel Hill (UNC-CH) that employed several green-technologies that reduced potable water demand. Importantly, problems were originally identified by complaints of consumers using the water systems in these buildings. Through use of non-potable water (treated rainwater) to flush toilets and installation of low-flow devices, demand was reduced up to 10X in these buildings compared to conventional buildings on campus of the same type (Nguyen et al., 2012). A thorough investigation of the water quality in the premise plumbing system revealed elevated lead levels, frequent absence of disinfectant residual, elevated water temperatures, and very high levels of microbial growth. A full-scale case study was developed and reported on in two peer-reviewed articles (Elfland et al., 2010; Nguyen et al., 2012). Here, a brief summary of key findings is discussed.

4.2.2 Key Issues

Lead levels in drinking water above the U.S. EPA Lead and Copper Rule (LCR) (level above 15 ppb Pb and 1.3 ppm Cu) were detected after consumer complaints about the aesthetics of the potable water were investigated. The problem was traced back to leaded brass devices in the premise plumbing of buildings with low water demand due to reduced flow via rainwater toilet flushing. NSF Standard 61 addresses brass devices in sections 8 and 9 for in-line and end-point brass devices, respectively; with regards to section 8, there is some debate to the overall comprehensiveness of the testing conditions defined (Dudi et al., 2005). Although, it is possible for brass devices to leach lead in certain waters (Lytle and Schock, 1996; Kimbrough et al., 2001, 2007), the risk of levels exceeding the action limit should be reduced if a device passes NSF 61. In these UNC-CH buildings, all end-point brass devices were sold as NSF 61 section 9 or California Proposition 65 compliant; however, second-draw samples regularly had greater lead content than first draw samples, suggesting that in-line brass devices were contributing to the elevated lead.

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The UNC potable water is a low-alkalinity, low-hardness surface water using a 70/30 blend of orthophosphate/polyphosphate for corrosion control and was considered "non-corrosive" in 2005 and 2008 using North Carolina LCR guidelines (Division of Environmental Health, 2008). Attempts were made to passivate the brass devices in the buildings exhibiting problems through commissioning of the lines. In this process, two commissioning programs were employed: one with a high water demand where water was flushed for approximately 72 hours and one with a lower water demand flushing for only 24 hours to save money and water during a local drought. The reduced flow program revealed a decrease in the effectiveness of the commissioning. The results of this study suggest that lead-leaching from brass is more likely when the potable water is moderately corrosive to brass, the leaded brass has a high lead content on its surfaces, and the premise plumbing lines have relatively low water demand.

The potable water for UNC-CH has a chloramine disinfectant residual. In the premise plumbing system of the two buildings in question with green conservation practices, the residual was completely absent from the water. In some circumstances it took up to 40 minutes of flushing to bring levels back above 2 mg/L as NH_2Cl-Cl_2 at a given tap. In this case, it is likely that abiotic reactions with the copper tubing and the long potable water residence time of the building (estimated to be several days to weeks when fully occupied) were the main contributing factors to disinfectant residual decay. There was a 90% decrease in the use of potable water in one building, which translated to a 10X increase in the water age with temperatures that regularly exceeded 30 °C.

Very high levels of heterotrophic plate counts (HPCs >308,000 CFU/mL) were detected in comparison to the 500 CFU/mL used by the U.S. EPA to trigger a violation of the Total Coliform Rule (U.S. EPA, 1989). These results were negatively correlated with chloramine concentrations (Nguyen et al., 2012). Hence, a lack of disinfectant residuals was likely contributing to increased detection of HPC microbes. There was a 3-log reduction in HPCs following one minute of flushing resulting in a 0.7 mg/L NH_2Cl-Cl_2 increase in disinfectant in the water at each tap. In addition to HPCs, heterotrophic aerobic, denitrifying, and acid producing bacteria were sometimes elevated.

4.2.3 Remediation

An automated flushing system was installed near the end of the premise plumbing system in one building to introduce new distribution water through the plumbing system. The wasted water represented less than 1% of the buildings total daily potable water demand. By bringing a modest amount of new water into the building on a regular and scheduled basis, a chlorine disinfectant residual was more frequently present, microbial growth subsided over time, and the original taste and odor problem reported was resolved. Although the specific abiotic reactions leading to loss of disinfectant are still unknown, decreasing the water age in the building effectively remedied the issue at hand.

4.2.4 Lessons Learned

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This is an important case study because it highlights many levels of the multiple stakeholder approach outlined in a recently completed Water Research Foundation Project 4379, Research Needs for Opportunistic Pathogens in Premise Plumbing: Experimental Methodology, Microbial Ecology and Epidemiology (Pruden et al., 2012). The code developers, manufactures, and standards organizations, while attempting to implement water conservation strategies, have not yet anticipated the range of conditions and adverse consequences, likely to be encountered in practice as demonstrated herein with NSF Standard 61. Recent steps taken to tighten the standards should be helpful (Triantafyllidou and Edwards, 2007).

Utilities have at least some role in maintaining water quality all the way to the consumers tap. It seems likely that use of orthophosphate and other treatments can produce more persistent residuals, at least in some circumstances. The knowledge represented by consumers who drink the water on a daily basis cannot be understated, and investigating/documenting their insights can uncover serious problems.

To summarize:

- Consumers can serve as important sentinels to aesthetic concerns, which might be linked to more serious problems in premise plumbing systems that can pose a direct health risk,
- While codes provide a good basis for avoiding potential problems in water systems, they do not guarantee protection from the issues they cover, and
- Premise plumbing design should consider impacts of enhanced conservation features on water quality from an aesthetic and water quality perspective. In some cases regular wasting of a modest amount of water, or design of pipes with a smaller diameter and water residence time, might be warranted.

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4.3 MIAMI HOTEL

4.3.1 Case

On November 2, 2009, the Miami-Dade County Health Department (MDCHD) received a report of a death from Legionnaires' Disease (LD). The victim was a 57 year-old male tourist from England who had recently stayed at a local Miami hotel prior to a cruise. Once on the cruise ship, the man began to show symptoms of an upper respiratory infection and had a positive urine antigen test for LD. Two weeks later, the MDCHD Office of Epidemiology, Disease Control, and Immunization Services (EDC-IS) received information related to another traveler, from Germany, who tested positive for LD and had stayed at the same hotel. In the same week, the Centers for Disease Control (CDC) reported a third laboratory-confirmed case of LD in a traveler from Spain who also stayed at the same hotel. This sparked a six-month epidemiologic and environmental investigation to evaluate the hotel as an exposure point causing disease and to implement and verify remedial actions.

4.3.2 Key Issues

The hotel, which opened 11 months before the outbreak, is a 54-story, 677 unit building housing 411 hotel rooms and 266 residential condos. On December 9 and 13, 2009, MDCHD measured chlorine residuals, total coliform counts, and attempted to culture *Legionella pneumophila*. The immediate finding was that the chlorine residual was completely absent (all taps sampled had < 0.5 ppm Cl_2). The Department of Business and Professional Regulation (DBPR) issued a bottled water use only notice, and MDCHD issued a health advisory to cease use of potable water in the building. The hotel voluntarily closed and relocated guests and permanent residences until remedial actions could be taken.

The MDCHD began an epidemiological study of recent guests, residences, and workers at the hotel by attempting to individually survey each person who could have been exposed to *L. pneumohila*, the microorganism which causes LD. People who stayed at the hotel from November 26 to December 11, 2009 were targeted for the survey because this was the approximate incubation period for LD following the first report of occurrence. Of the 1,700 people that were potentially exposed to the *L. pneumophila* during this time period, only 700 had email addresses listed as contact information and the rest were attempted to be contacted by phone. An epidemiologic questionnaire was created to interview potentially exposed persons and case definitions were established to define a probable and confirmed case of LD. Of the 1,700 people in the building during the incubation period of the initial case reported, only 109 interviews were conducted, representing only 6% of potential cases. Seven confirmed cases and three probable cases resulted from the survey. Of the seven confirmed cases, one man died and three people hadn't recovered at the time the reports were written nearly seven months later.

Several site visits were conducted to evaluate the environmental factors that could have contributed to exposure. Samples were taken for total coliforms following the initial samples that revealed the absence of a disinfectant residual, all of which were negative except for one sample taken from a cooling tower. Of 20 random water samples initially taken, one sample was positive

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for *L. pneumophila*, which was determined to be serotype 5. Later, it was realized that the absence of a disinfectant residual was due the installation of a point-of-entry activated carbon filter system in June of 2009 that was approved by the DBPR. The system had a flow rate of 1,000 gal/min and was regularly and properly maintained by the manufacturer according to manufacturer instructions.

4.3.3 Remediation

MDCHD recommended that the carbon filters be disconnected to allow the utility water to pass through the system, which had a disinfectant residual and met all U.S. EPA regulations. In addition to this, the hotel decided to follow ASHRAE Guidelines 12-2000: Minimizing the Risk of Legionellosis Associated with Building Water Systems and super-chlorinate the entire plumbing system and disinfect plumbing fixtures and cooling towers. In addition to physical remediation, the hotel was encouraged to develop a remedial action plan to prevent opportunistic waterborne pathogens and biofilms from establishing in the building plumbing again. This was to include removal of dead-end segments of pipe the in plumbing system and regular monitoring of the chlorine disinfectant level in the building; however, if any residences or hotel rooms were unoccupied for any length of time, these would represent unintentional dead-ends. In addition to the removing the activated carbon filters, the consultants hired by the hotel also suggested the installation of copper-silver ionization units to aid in disinfecting the system. An intensive routine of flushing for 15 minutes every day on a different floor was also adopted to ensure high levels of disinfectant residual remained in the building.

4.3.4 Lessons Learned

This case study highlights the importance of preparedness in preventing and dealing with opportunistic premise plumbing pathogen waterborne disease outbreaks. Many buildings do not have response plans for prevention or remediation of a waterborne disease outbreak in place. Without a plan for maintenance, prevention, and response, the potential for expensive and extensive remediation is increased. According to new ASHRAE Standard 188 (under its third public review at the time of writing), not having a response plan in place exposes the building owners and managers to potential lawsuits due to negligence. According to this standard all buildings should plan for maintenance, monitoring, prevention and reaction to pathogen outbreaks.

Whole system granular activated carbon filters have the ability to increase the aesthetic quality of the water, and they can effectively remove the disinfectant residual and leave no protection from microbial regrowth. The complexities of the large building plumbing systems provide the opportunity for dead ends to occur, increasing the propensity for pathogen growth in some circumstances. The balance between aesthetically pleasing water and public safety should be better informed and the installation of devices that alter municipal water qualities such as carbon filters should be thoroughly evaluated on a case-by-case basis.

To summarize:

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- Building-level treatments can sometimes work to undermine the quality of water the utility provides by changing the disinfection regime or removing disinfectant residual
- Building pathogen outbreak preparedness, despite numerous guidelines, standards, and on-going research efforts, still needs to be clarified and disseminated.
- Retroactively developing an opportunistic pathogen management plan can be more time and resource intensive than being prepared before an outbreak occurs.

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4.4 MAUI, HAWAII

4.4.1 Case

In 2001 the Maui Department of Water Supply (DWS) exceeded the U.S. EPA Lead and Copper Rule (LCR). The utility decided to dose zinc orthophosphate to the water as a lead corrosion control strategy. DWS had been using chloramines since 1985 and lead problems were quickly reduced with addition of zinc orthophosphate; however, public concern emerged regarding possible health effects originating directly or indirectly from dosing the corrosion inhibitor, including itchy skin, rashes, eczema, blurring and burning eyes, respiratory problems, and throat irritation. These problems were at least temporally linked to the dosing of the corrosion inhibitor and have also been linked to microbial growth issues. This claim was supported by a randomized blind survey (Rohner et al., 2004). In 2003, DWS switched to orthophosphate alone instead of zinc orthophosphate. The public complaints were consistent with emerging understanding of these microbial-driven problems such as hot tub folliculitis (aka "hot tub rash") or hypersensitivity pneumonitis (aka "hot tub lung") and it was deemed possible that the combination of chloramine use, the phosphate-based corrosion inhibitor, and relative differences in premise plumbing with respect to the main distribution system could have contributed to these public health concerns. Together, *Legionella*, *P. aeruginosa*, and *M. avium* are the bacteria that typically cause hot tub rash and hot tub lung. To the extent the regrowth of these microorganisms are prevented, these aesthetically aggravating and health threat diseases can be largely avoided. They are termed "hot tub" rash and lung because a poorly maintained hot tub provides ideal conditions for these organisms to grow. However, these conditions (i.e., low disinfectant residual, warm water temperatures, long periods of stagnation) are also present in many green building water systems. Prevention of bacterial regrowth is the key step to limit the exposure to these bacteria.

4.4.2 Key Issues

4.4.2.1 Background. Problems with microbial regrowth can arise for systems using chloramines as the disinfectant residual when it decays. Chloramines decay to form free ammonia, which can be used by autotrophic nitrifying bacteria for growth, producing organic carbon in the form of biomass. One Dutch study suggested that less than 10 µg/L of organic carbon (as assimilable organic carbon – AOC) was sufficient to limit re-growth. In a study completed in the U.S., AOC levels below 50 µg/L were considered desirable to control coliforms in disinfected distribution systems, whereas problems can be expected for AOC concentrations above 100 ug/L (LeChevallier et al, 1991). Further, each µg C could lead to growth of 5×10^5 to 1×10^6 CFU bacteria in carbon-limited systems (van der Kooij et al., 1992). For a system using 4 mg/L (as Cl_2) chloramine, 1 mg/L free NH_3-N can be released to the water as it decays. Using conservative estimates, 25 µg/L organic carbon can theoretically be created if 1 mg NH_3-N is consumed during nitrification (Zhang et al., 2009). Thus, limiting the amount of AOC entering the distribution system, an effort which is the responsibility of the utility, may be undermined by the production of AOC in the distribution system as chloramines decay. To illustrate this, no correlation between microbial growth (heterotrophic plate counts) and AOC measured in the distribution system was reported in one system using chloramine (Gibbs et al., 1993), suggesting that AOC is not an effective growth limitation strategy on its own. These studies investigating AOC as a limiting

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nutrient focused on coliform bacteria whereas concerns of waterborne illness outbreaks due to fecal-derived pathogens have become less of a concern than certain opportunistic pathogens such as *Legionella*, *Mycobacterium avium* and *Pseudomonas aeruginosa* (EPA, 2002). It is likely that AOC limitation at the treatment facility will be less effective for controlling growth of opportunistic pathogens.

Autotrophic nitrifying bacteria convert the free ammonia to nitrite and nitrate. Nitrites formed as an intermediary can further aid in the consumption of chloramine (Powell et al., 2004). In main water distribution systems, utilities often start to have nitrification problems below 2 mg/L (as Cl_2) chloramine residual (Yang et al., 2004). Therefore, if the total chlorine concentration drops below about 2 mg/L as Cl_2, flushing of the distribution system and associated storage provisions is often required to prevent nitrification and maintain adequate levels of chloramine (Powell, 2004).

Problems of regrowth are typically associated with premise plumbing systems as opposed to the main distribution system. Since premise plumbing systems are essentially dead ends, with long detention times, higher temperatures, and lower chlorine residuals than in the distribution system itself, utilities may not be detecting the true extent of problems associated with nitrification. Indeed, while routine bacterial monitoring by utilities often uses taps located within buildings, most standard protocols require flushing for 3-5 minutes before collecting samples. The water that is sampled is therefore representative of bacterial concentrations in the water mains and not within homes.

Even if re-growth in homes was not a significant public health problem at a given time, changes in consumer behavior might make such risks more significant. Specifically, there has been a noteworthy trend in the U.S. to decrease water heater temperature to minimize scalding and save energy. Lower temperatures may increase problems with re-growth relative to higher temperatures that were once present, especially for *Legionella* and *Mycobacterium avium* (Borella et al., 2004; EPA, 2002). Other consumer options such as increased use of low flow showerheads might also alter consumer exposure to pathogens and other harmful or irritating bacteria. Many households now use packed bed granular activated carbon (GAC) for chloramine removal. Some work has indicated that once nitrifying bacteria are established on these media (Fairey et al., 2004), their growth cannot be controlled even with chloramine residuals as high as 4 mg/L. These devices could serve to generate organic carbon that would support high levels of bacteria re-growth.

4.4.2.2 Maui Case. The original water, before addition of zinc orthophosphate, had undetectable levels of phosphate. Health problems began occurring concurrently with the zinc orthophosphate dosing and other water treatment changes and it should be noted that the Maui climate is tropical, so observations may not translate to other, more moderate, climates. Bacterial regrowth problems were worse in premise plumbing systems, especially after stagnation. During first flush samples, one sampling location had 3 $\times 10^6$ CFU/mL versus 1,100 CFU/mL after 3 minutes of flushing. When both chloramine and phosphates were being used, the majority of consumers reporting problems had non-detect levels of chloramine. These results suggest that as chloramines decay, especially with the presence of the phosphorous corrosion inhibitor, locations where water residence times were high had the worst problems.

Laboratory experiments confirmed that growth was indeed increased when phosphate was added to chloramines. The chloramine and phosphate condition had more growth than any other condition tested. The phosphate and chloramine condition had 20,000 CFU/mL versus <1,000

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CFU/mL for all other conditions tested except for chloramine alone. In that case, once the chloramine had fully decayed, increased growth was still observed above 1,000 CFU/mL relative to the 500 CFU/mL U.S. EPA action limit. In addition, residual measurements after 48 hours stagnation showed counterintuitive results. Typically, because chloramine is thought to be less reactive than free chlorine, it is believed that chloramine is more stable throughout drinking water systems. However, results after this stagnation revealed that the chloramine actually decayed more quickly than free chlorine. It is apparent that chemical and/or biological reactions during stagnation were causing chloramines to decay more rapidly than free chlorine.

4.4.3 Remediation

There were several rounds of remedial action taken before a solution to both the lead and microbial growth problems were found. First the switch to zinc orthophosphate, while decreasing the lead concentrations, was followed by increased microbial regrowth issues in premise plumbing. The subsequent switch to only orthophosphate did not seem to improve the microbial regrowth issues and again began to fail the LCR compliance criteria with 90 percentile lead concentrations of 41 ppb. Soda ash was then applied with target pH of 8.6 to control lead corrosion and a switch was mode to free chlorine. Although no or very little free chlorine detected after 5 minutes of flushing, lower levels of bacteria were observed in comparison to when chloramine alone or chloramine and an orthophosphate corrosion inhibitor were being applied.

4.4.4 Lessons Learned

This case highlights the complexity of diagnosing and addressing microbial regrowth issues. At the time the original article (Edwards et al., 2005) was published, it also represented a new way of thinking about regrowth, in general, identifying alternate sources of organic carbon for regrowth as well as suggesting that the stagnation (and subsequent loss of disinfection residuals) led to increased microbial growth that had negative public health outcomes. In addition, this case study identifies scenarios where the assumed benefit of chloramines being more stable in the distribution system, and specifically premise plumbing system, were not realized in practice.

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4.5 HOT WATER SYSTEM RESEARCH AT VIRGINIA TECH

4.5.1 Case

Creating energy efficient hot water systems is a primary concern of green building water system design. Domestic hot water systems account for the second largest energy demand in residences, and use more energy than all of the water and wastewater treatment industry combined. Recent research at Virginia Tech explored several sustainability claims of a standard water heater, a system with a recirculating line, and instantaneous water heater including the interplay between water temperature, energy efficiency, microbial regrowth potential, and scaling potential. This work was the first practical assessment of residential water heating infrastructure performance in terms of public health, environmental impacts, and consumer drivers. Key conclusions from this work are summarized below.

4.5.2 Key Issues

Selection of a hot water system is a multi-faceted task that incorporates capital costs, comfort, reliability, maintenance, and occasionally genetic/immuno-susceptibility to waterborne disease. Selection based on performance and environmental friendliness is guided by limited data that have been extrapolated to normal hot water system uses. In some cases, selection of a system can be influenced by available tax credits for sustainability practices. Moreover, existing recommendations for system selection can be misleading and unfounded under conditions that are observed in the field due to scaling, corrosion, and climate impacts.

Most hot water systems can be categorized into four broad categories, including: 1) tank storage with no recirculation ("standard"), 2) tank storage with recirculation ("recirc"), 3) centralized instantaneous heaters with no storage and no recirculation, and 4) point of use instantaneous heaters with no storage and no recirculation ("on-demand"). Energy losses in tanks with storage are dependent on environmental conditions including climate region. For tanks with storage, there are two distinctions in water heaters. Gas heaters heat water from the bottom of the tank, usually resulting in a tank of uniform temperature. Electric heaters use heating elements in middle of tank and can become stratified as the cooler influent water is introduced and remains at the bottom of the tank while the hotter water rises to the top due to the variable density of water as a function of temperature. In scaling waters either gas or electric heaters could be problematic as scale builds up and decreases heat transfer efficiency from the heating element or gas flame to the, resulting in increased energy losses.

For tanks with storage, there systems that recirculate the water and systems that do not. Tanks without recirculation more common in households; however, due to tax deductions and perceived energy efficiency, recent trends suggest that recirculating systems are becoming more common. The claim that these tanks decrease water wasted while waiting for hot water at the tap, and the associated energy savings are highly dependent on consumer behavior. Any water not used is partially cooled (heat is lost to the environment from the recirculating pipe) and then reheated and recirculated using a pump. These systems are 32-36% less energy efficient than standard hot water systems unless the pumps on the recirculating system are optimized. Pumps can be set to timers or to activated by consumers using a push-button. This minimizes energy wasted in running the pump at all times.

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Instantaneous water heaters can be centrally located in buildings or at the point of use. Savings are dependent on flow rate, overall water use, and installation of low-flow devices. There is typically a high initial capital cost of installation and increased possibility of scalding, though head to head comparisons and optimization of on-demand systems are missing from the literature.

Head to head comparisons were made between a standard, recirculating, and on-demand hot water system at Virginia Tech. Two different water use patterns (high use and low use), two different hot water settings (49°C and 60°C based on U.S. EPA and WHO recommendations, respectively), as well as several attempts to optimize the recirculating system were tested. In the initial study comparing the baseline systems, the standard system out-performed recirculating for both water use patterns and both temperature settings. The standard system had only a modest increase in energy efficiency when operating at lower temperature of 49°C vs 60°C (Table 4.1). This result suggests that further energy savings could be realized using a smaller tank set at a hotter temperature while tempering the water at higher cold:hot water ratios, although the potential for scalding would increase.

Table 4.1
Total energy input, output and overall efficiency for standard and recirculating water heaters (Source: Brazeau and Edwards, 2013a)

	Total Energy Consumption (kWh/Day)		**Energy Output (kWh/Day)**		**Energy Efficiency (%)**	
Condition	STAND	RECIRC	STAND	RECIRC	STAND	RECIRC
60°C, High Use	8.1	10.5	7.04	5.82	86.9	55.4
49°C, High Use	4.8	7.5	4.27	4.12	88.3	55.0
60°C, Low Use	3.2	7.9	1.68	1.5	55.2	19.0
49°C, Low Use	2.7	5.5	1.47	1.25	55.1	22.7

The on-demand system was the most energy efficient, but output temperatures are dependent on input temperature. For example, in winter months when water temperature is <10 °C, at the hottest temperature setting, the flow rate would have to be 1.25 gpm to achieve a 32 °C maximum water temperature, which is the minimum adequate showering temperature. For lower temperature settings on the on-demand heater, there is no flow rate that would provide adequate temperature for showering. In addition, for the system tested, thermal disinfection (60 °C) was never achieved regardless of influent water temperature or flow rate.

This research also indicated that temperature profiles within the hot water tanks varied by temperature setting and use pattern. For example, the volume of water within the tank at temperatures that are ideal for pathogen growth was examined (Table 4.2). At a hot water setting of 49°C, the standard system had more volume at risk for microbial regrowth during high use; however, at low use, the standard system was more favorable. Similar results were observed at 60°C.

Table 4.2

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Average percent of tank volume below key temperature ranges for a 24-hour period under the various test conditions (Adapted from Brazeau and Edwards 2013b)

Water Heater Type	Percentage of Tank Below 46°C During High Use		Percentage of Tank Below 46°C During Low Use	
Tank Setting	60°C	49°C	60°C	49°C
STAND	31%	78%	14%	38%
RECIRC	22%	100%	0%	88%

Other water quality parameters were also measured, including dissolved oxygen (DO), aluminum ions (from the anode rod to assess corrosion), copper ions, and H_2. Autotrophic bacteria can use H_2 for growth when other nutrients are absent. Because H_2 is a potential corrosion byproduct of regular anode rod decay, it is currently thought that H_2 could trigger autotrophic microbial growth. Autotrophs can in turn provide a food source to heterotrophic bacteria and amoeba growing in the biofilm. The production of H_2 may be undesirable because opportunistic pathogens can grow within amoeba hosts, using them as a food source and for protection against thermal and chemical disinfection. The recirculating system in this experimental setup had higher weight loss of the anode rod, which resulted in higher alumninum and H_2 concentrations in the tank and recirculating loop (Table 4.3). the DO in the standard system was stratified due to the temperature stratification of the tank while the recirc line remained uniform. Dissolved oxygen is necessary bacterial respiration to occur and can provide an alternative corrosion pathway for the anode rod.

Several attempts were made to optimize the operation of the recirculating line, including installation of a check valve to prevent short-circuiting, minimizing the use of the recirculating pump to just before a hot water demand occurred, and a combination of both the check valve and pump minimization. The combination condition was the only recirculating system condition that approached the energy efficiency of the standard system at any of the use patterns or temperature settings. There was only an 8% difference in energy consumption when both the pump was optimized and the check valve was installed. As for the temperatures, the standard system had 40-430% more volume at ideal temperatures for pathogen growth while the recirculating line had 2.5 times less water volume at that temperature. However, the standard system always had better chlorine residual stability, likely due to reactions with the copper pipe during recirculation.

4.5.3 Lesson Learned

The hot water system research conducted at Virginia Tech was a 19 month endeavor. The above summary of key findings only covers a fraction of information obtained during that time. Several peer-reviewed publications are available for reference (Brazeau and Edwards 2011; 2012; 2013a; 2013b).

To summarize:

During the baseline study:

- Without a check valve, cold water can “short circuit” in the recirculating system – resulting in rapid cooling of water delivered to the tap during flushing

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- The on-demand system may not provide enough hot water depending on incoming temperature and electrical capacity
- The recirculating system was 32 – 36% less energy efficient than the standard systems
- The recirculating system would have cost consumers up to 300% more than standard system annually in utility bills
- The recirculating system had 4–6.5 times more H_2 than the standard system
- The recirculating system had the lowest (and most stable) DO concentrations and higher metal concentrations
- The standard system had 40–850% higher concentrations of total chlorine than the recirculating system, while the on-demand system had little chlorine demand and negligible H_2 evolution

During the optimization study:

- Recirculating lines have comparable energy efficiency only if they are installed with a check valve, have a switch to activate the recirculating pump just before hot water demand, and the system is used EXACTLY as designed (i.e., no wasted water) with good pipe insulation
- Optimization of the recirculating system could increase energy efficiency 5.5 – 60% compared to the baseline recirculating system, which equates to 5 – 140% cost savings
- All recirculating setups tested had lower chlorine residual than the standard system, but optimization improved residual by up to 560% compared to the recirculating baseline

These results suggest that the systems marketed to the public and sometimes awarded tax credits for being more energy efficient are simply inaccurate. More scrutiny should be given to purportedly green systems before they are widely accepted.

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Table 4.3
Quantitative results for water quality parameters (Adapted from Brazeau and Edward, 2013b)

Water Heater Type	DO (mg/L)		Total Al (ppb)		Soluble Al (ppb)		Total Cu (ppb)		Soluble Cu (ppb)		H2 (ppm)		Anode Rod
Temperature, Use, or Location	**Top of Tank**	**Bottom of Tank**	**60°C**	**49°C**	**60°C**	**49°C**	**60°C**	**49°C**	**60°C**	**49°C**	**High Use**	**Low Use**	**Weight Loss (%)**
STAND	5.5	8.1	1034	126	366	80	130	24	14	12	210	580	13
RECIRC	4.9	4.9	3467	2676	174	294	751	310	32	56	1240	2360	24
DEMAND	N/A	10	20	38	18	38	170	20	62	12	80	0.7	N/A

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4.6 PINELLAS COUNTY, FLORIDA

4.6.1 Case

Pinellas County Utility (PCU) offers a unique perspective of and insight into the effects of changing the disinfection regime applied by a large utility from free chlorine to monchloramine. Like many utilities using chlorine as the primary disinfectant and high natural organic matter (NOM) content water, PCU made the switch to monochloramine (MC) from chlorine to comply with the US EPA Disinfectants and Disinfection Byproducts Rule to reduce the formation of trihalomethanes in the distribution system. The switch to MC residual occurred in May of 2002. There were several peer-reviewed publications that examined differences in water quality before and after the switch to chloramines. The PCU source water comes from five well fields and the distribution system, from an operations standpoint, is two separate systems. One set of well fields is treated by forced aeration, disinfected, pH adjusted, and an orthophostphate corrosion inhibitor applied. The other set of well fields is minimally treated with sodium hydroxide for pH adjustment, disinfected, and distributed.

Before and after the switch to MC, extensive field studies (Moore et al., 2006; Pryor et al., 2004; Wang, 2012) were conducted to monitor and document differences that occurred between the two treatment regimens with focus on microbiological communities, temperature profiles, disinfectant residual profiles, and water use. Moore et al. focused on building sampling that included hotels (n=355), government office buildings (n=149), and residences (n=74) in Pinellas County. Three different types of samples were collected in each building: a central bulk sample from a hot water heater, a biofilm swab from a distal site such as a shower head or faucet, and a bulk water sample from the same distal site as the biofilm swab. Monochloramine and total free chlorine, temperature, pH, magnesium, and calcium were measured and all samples were cultured for *Legionella* and amoeba. Data analysis was performed in two ways: first, each building was treated as an independent observation, meaning that if any one sample tested positive for *Legionella* or amoeba, the building was considered colonized. Second, each individual sampling location within each building was treated as an independent observation. In each case, predictors for colonization were analyzed using odds ratios, 95 percent confidence intervals, McNemar's test, Fisher's exact test, and paired t-tests.

Pryor et al. focused their study on sampling bulk water and biofilms at 12 production wells and 32 sites within the distribution system. Samples were taken before, during, and after the switch to monochloramine. Similar to the Moore et al. study, basic water quality parameters, including pH, temperature, and disinfectant residual were measured. However, this study used both culture methods and PCR to identify the presence of *Legionella* and *Mycobacterium*. Phospholipid fatty acid analysis (PLFA) and denaturing gradient gel electrophoresis (DGGE) were used to characterize microbial communities in the biofilm of the distribution system samples and protozoa characterization was done for the production well samples.

The study conducted by Wang et al. compares PCU water to that of the Blacksburg-Christiansburg-VPI Water Authority (BCV), another chloraminated distribution system in a distinctly different climate region. The study focused on identify and making connections between the microbial communities, including known pathogens of *Legionella* spp., *L. pneumonphila*, *Mycobacterium* spp., *M. avium*, *P. aeruginosa*, , and *Acanthamoeba* spp., as well as two *Legionella* amoeba hosts, *Acanthamoeba* and *H. vermiformis*. The BCV is located in southwest Virginia and

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treats surface water by flocculation, sedimentation, dual media filtration, and chlorination. Chloramines have been the disinfectant residual since June 2005. For the BCVWA portion of the this study, three to seven houses were sampled for each of five water age categories (3 to 6 d, 6 to 8 d, 8 to 10d, 10 to 12d, and ≥ 17d) as supplied by the utility. At one distal site in each home one liter samples were collected before flushing the sampled tap, after flushing for 3 min, and from the safety valve and bottom drain valve of corresponding water heaters when available. The sample procedure conducted for the PCU water was identical to that of the BCVWA with addition of a bulk water sample from shower heads when available. Quantitative-PCR was the primary method for detecting and quantifying the microbial communities and terminal restriction fragment length polymorphism (t-RFLP) was used to identify the diversity in the microbial community. As in the previous two studies, temperature, pH, total ammonia, and total chlorine were measured as well.

4.6.2 Key Findings from each Publication

Moore et al. determined that building type, presence of a water softener, calcium concentration, magnesium concentration, and water heater type were not significant predictors in *Legionella* colonization while chlorine was being used as the disinfectant residual; however, the presence of recirculating lines (OR 5.1), water source (site-dependent), and presence of amoeba (OR 24.6) significantly increased the likelihood of *Legionella* colonization. Overall, houses were more likely to be colonized than government buildings or hotels and sites with measureable chlorine concentrations were more likely to not be positive for *Legionella* (not significant; P-value = 0.08 Fisher's exact test). While monochloramine was being applied as the disinfectant, there were no statistically significant design factors identified for *Legionella* colonization; however, the building type (hotels), water source (well field-specific), and presence of a softener generally distinguished the buildings that were colonized. Unfortunately, no multivariate statistical model could be constructed to evaluate these factors. The presence of amoeba hosts was associated with *Legionella* colonization (OR 46). Although monochloramine was detected throughout the system and in hot water heaters, only low concentrations were observed. Importantly, the portion of buildings colonized by *Mycobacteria* increased after the switch to monochloramine (19.1% before to 42% after).

Pryor et al. detected *Legionella* by culture and PCR in the source water in the bulk water (4/6 and 2/6 wells for culture and PCR, respectively) and the biofilm (3/6 wells for both culture and PCR). In the distributions system, dead ends and neighborhoods that received water from more than one direction had higher incidence of colonization, suggesting that flow plays an important role with attachment, growth, and release of *Legionella*. In general, engineering interventions that improved water flow decreased the prevalence of colonization. During this study, mycobacteria were largely absent from the production wells sampled (based on limited number of samples), but were commonly found in the distribution system after monochloramine dosing was begun. In addition, the microbial community was significantly altered by the switch to monochloramine. Certain bacteria strains become more dominant in the community, one of which was *Pseudomonas*, and the presence of coliform bacteria increased from 2 samples in 2002 to 21 after the switch.

Wang et al. observed that *Legeionella* spp. and *Mycobacteria* spp. were consistently detected (in 30% and 94% of samples, respectively) in BCV water. Of the water sampled, average proportions of *Legionella pneumophila* and *Mycobacterium avium* accounted for 15% and <0.1% of the total *Legionella* spp. and *Mycobaceria* spp., respectively. *Hartmonella vermiformis* was

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twice as prevalent as *Acanthamoeba* spp. For PCU water, *Legionella* spp. and *Mycobacteria* spp. were detected in 100% of the samples taken. The average proportions of *Legionella pneumophila* and *Mycobacterium avium* accounted for 20% and 33% of the total *Legionella* spp. and *Mycobaceria* spp., repectively. *Hartmonella vermiformis* was again more prevalent than *Acanthamoeba* spp.

The average concentration of targeted genes were reduced by 6- to 45-fold after just a three minute flushing and no *L. pneumophila* or *M. avium* were detected in flushed water samples. Some correlations existed between specific genes quantified. For example, correlations between *Mycobacterium* spp. and overall bacteria (16S rRNA genes) were observed in BCV bulk water samples (P-value <0.001) and PCF biofilm samples (P-value < 0.001). Low to moderate correlations were observed between *H. vermiformis* and overall bacteria (P-value < 0.05) in bulk water samples in both systems and between *H. vermiformis* and *Legionella* spp. (P-value < 0.05) in BCV water. Correlations were also detected between specific genes and abiotic facts. For example, moderate negative correlations were detected between chloramine residuals and *Mycobacteria* spp. (P = 0.004) and between chloramine residuals and 16S rRNA genes (P=0.007) for BCV first draw samples, but not with PCF water. Moderate correlations were detected for *Mycobacteria* spp., *H. vermiformis*, and total 16S rRNA with TOC concentrations (P < 0.05) in BCV first draw samples. *Legionella* spp. correlated with TOC in water heater samples in PCU water (P = 0.01). Surprisingly, no correlations with temperature were found. With the broader microbial community, there was high variability within distribution system samples (as determined by multidimensional scaling analysis). For over half (55%) the water samples collected, there were significant community changes observed between first draw and flushed samples (multidimensional scaling analysis).

4.6.3 Lessons Learned

- Monochloramine lowered likelihood of system colonization of *Legionella* by 69% within a 1-month period, most likely by being able to penetrate biofilms more effectively. This had little effect on presence of amoeba. While other factors known to affect *Legionella* growth had little change, monochloramine was detected in 88% of water heaters and 93% distal sites sampled, supporting the claim that the switch to monochloramine in fact did cause the decrease in *Legionella* colonization.
- More consistent water use may be an important factor in the effectiveness of the disinfectant, as government buildings (which have lower and more varied use than hotels or single-family residences) were most likely to be colonized by *Legionella* after the switch to monochloramine.
- Amoeba appear to be the primary means by which *Legionella* can be shielded from disinfection as suggested by others
- The water source-specific nature of the *Legionella* colonization cannot be fully explained. The specific source that exhibited problems was treated with a corrosion inhibitor and passed through a hydrogen sulfide removal process.
- Increased incidence of mycobacteria could have resulted from the change to monochloramine.
- Water heater temperatures were lower than recommendations to control growth of opportunistic pathogens, regardless of their set point. Temperature setting is

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something that seems straightforward and is taken for granted by many system designers and operators. Steps should be taken to periodically ensure the temperature profiles desired are achieved in practice.

- The physiologic and genetic basis for the survival of *Legionella* species despite thermal and chemical disinfection in drinking water cannot currently be explained.
- While growth of amoeba hosts for pathogens seems necessary for pathogen growth, the broader microbial community plays an important role in growth of amoeba, therefore it is also an important factor for pathogen growth.
- TOC can be an important indicator for *Legionella* spp growth; however, conclusions about TOC may be misleading. Measurement of TOC may include the bacteria associated with the biofilm in a given sample while all of this TOC is not truly available for growth.
- Routine monitoring practices may overlook important aspects of the premise plumbing microbiome.

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4.7 COPPER PITTING

4.7.1 Cases

Sulfate reducing bacteria (SRB) have been largely overlooked with regard to their influence on corrosion. SRB in iron pipes have been found in many potable water systems. The sulfides that result from their activity are highly reactive with metallic pipes. Their activity can influence pitting corrosion of copper tubing in premise plumbing and recent work has identified SRB within tubercles formed during pitting. SRB are ubiquitous in natural systems and commonly found in groundwaters and anaerobic portions surface waters (e.g. in sediments); therefore it is likely that they would sometimes be detected in drinking water distribution and premise plumbing systems. Water utilities that use source waters with trace levels of sulfides often have to aerate and oxidize their water to remove them.

A series of communities across the U.S. were investigated as part of a separate Water Research Foundation project (Scardina and Edwards, 2008). Brief synopses of these case studies and key findings are presented below.

4.7.1.1 Case A. A relatively large amount of pinholes leaks were occurring in a new development of residential housing. This community was located toward the end of the water distribution system furthest away from the treatment plant and many of the newly built homes were unoccupied. The pinhole leaks were mainly in horizontal cold water pipes. Pipes with leaks were extracted from the homes and examined. To contrast these pipes, another house was assessed and a pipe harvested in a location where no pitting was occurring.

Five independent forensic methods identified SRB and sulfide production in the homes with pitting, but none in the home without it. Because the homes with problems were on the outskirts of the distribution system and all localized in one region, it is possible that low levels or no disinfectant residual may have contributed to the establishment of SRB in the copper pipes. First draw and some flushed water samples contained little chlorine (0.05 and 0.12 ppm total Cl_2 for first draw and flushed samples respectively). SRB were also detected in the source water and in the distribution system mains in portions that acted as dead ends (e.g., lines to homes that were not occupied).

4.7.1.2 Case B. Similar findings were observed in another community. The source water for this community was again groundwater. The utility had previously identified nitrification occurring in the distribution system, prompting a switch from chloramine to free chlorine residual. One homeowner in this community reported rotten egg smells after the utility periodically flushed the main line servicing his home, indicating there is some SRB activity in this line. Periodically, the utility would dose high levels of disinfectant to attempt to rid the system of SRB and nitrifying bacteria (up to 10 ppm NH_2Cl and 9 ppm Cl_2). This did not appreciably inactivate SRB, presumably protected by the tubercule and/or corrosion scale; therefore, conventional disinfection may not be adequate to inactivate SRB once they are established. More research on this topic is needed.

4.7.1.3 Case C. Drinking water in this community was supplied by two groundwater plants and an adjacent surface water plant, all using chloramine as a disinfectant. At different points in

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time, this community has dosed multiple phosphate corrosion inhibitors, yet nothing reduced the rate of pitting leaks. In fact, it is possible the phosphate in the corrosion inhibitor supplied SRB with nutrient for growth.

4.7.1.4 Case D. This community has had long-standing issues with pitting corrosion since the 1970s. The water in this community is supplied by two different groundwater utilities whose source water is from the same aquifer; however the second supplier also has a surface water plant. Although the surrounding communities, using the same water, also have problems with pitting, a survey of local stakeholders identified this particular community as having the most severe problems. Similar to the first case study, this community is located farthest away from the treatment facilities and could have been impacted by low or absent chlorine residuals and high water age. As a result of state regulations, this community began dosing a disinfectant which coincided with chlorine being delivered to the mains as well as an increase in pH. The incidence of pitting corrosion may have decreased with increasing pH and chlorine, which is consistent with peer-reviewed literature (e.g. Jacobs et al., 1998).

4.7.1.5 Case E. Pitting corrosion was studied on a military base in hot water lines. A central hot water system supplied hot water to several buildings on base. The majority of leaks appeared in building farthest away from the central heaters. The temperature of the water heater was maintained below 60°C; most of the system was 42 °C -50 °C , with lowest temperature (and most pitting) occurring at the most remote buildings. While some SRB can survive and thrive at very high temperatures, the metabolic growth rate of SRB typically drop off around 45 °C (Postgate, 1979); therefore, it is possible the slight decrease in temperature farther away from the central heating unit allowed SRB to establish and pitting to occur.

4.7.2 Remediation

Although pitting corrosion issues are usually easy to identify, they can be costly to correct. In many cases, the pipes with leaks are replaced. This is an intrusive process to the customer and replacement of the problematic pipes does not always remediate the larger water quality problem causing the leaks.

Water utilities with pitting corrosion problems have a variety of strategies to try to mitigate problems with SRB, but none seem to be effective for tall systems. Once SRBs are established in the distribution system, the tubercle likely protects them from oxygen in fresh water and thermal and chlorine disinfection strategies. The effectiveness of other typical corrosion controls is also uncertain. Phosphate added to some systems does not appreciably reduce pitting occurrence. Other controls are relatively impractical for controlling SRB in drinking water systems such as dosing levels of ions that are toxic to SRB (and sometimes humans). Although copper and sulfide (produced by SRB) are relatively toxic to SRB, the sulfide reacts rapidly with copper eliminating both of their biocidal properties (and consequentially is the cause for the development of pits). For cases in hot water systems, mitigation practices such as temporarily increasing temperatures above 60 °C, flushing, chlorinating, or switching anode rods seem to produce temporary solutions.

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The best approach to prevent copper pitting may to be limit the ability for SRB to establish in a distribution system. Presently there are no reliable mitigation strategies for potable water systems. Clearly, more research is needed in this area.

4.7.3 Lessons Learned

Sulfate reducing bacteria (SRB) seem to be clearly linked to copper pitting in residences. The case examples suggested that long water residence times and low chlorine residuals were common observations amongst the cases examined. Although pitting is generally a premise plumbing issue, these observations were made at the distribution system scale, meaning that problems tend to develop in one area of the distribution system. If issues tend to develop in areas with high water age and low disinfectant residual, problems in green buildings can be expected where SRBs have established in the main distribution system. Further, green buildings typically exhibit warmer cold water and cooler hot water due to stagnation.

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CHAPTER 5: CASE STUDIES

5.1 INTRODUCTION

In order to identify effects of green building plumbing design on water quality the following three field locations were visited during the course of this research (Table 5.1):

1) Field site #1 is a LEED-Gold out-patient healthcare facility. The LEED credit achieved by this building associated with water efficiency was to reduce their potable water demand by 20% compared to a conventional baseline by installing low flow commercial toilets and placing flow restrictors in lavatory sink taps
2) Field site #2 is a net-zero energy residential house that uses a solar collector to pre-heat water, before it enters an electric heat pump water heater.
3) Field Site #3 is a small net-zero energy and net-zero water office building. It collects rainwater for potable and non-potable uses, has no outdoor water demand such as landscaping and treats the rain water on-site. This facility is among only 91 Living Building Challenge registered projects across the world.

Table 5.1
Overview of Field Sites

Field Site	Type of Building	Green Water Features	Cause of High Water Age
#1	Out-patient health care; 20 exam rooms	LEED certified; low-flow metered faucets in bathrooms	High number of fixtures (for each exam room)
#2	Residence; net-zero energy house; control house with no green features	Solar water heater	Additional storage for solar water heater
#3	Small office; net-zero energy and net-zero water	On-site rainwater collection, storage, and treatment	Rainwater cistern storage

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The goal of the site visits was to document practices that might influence water quality, and to proactively consider and document any issues of concern. The general approach applied to each site included review of plans and unique design elements, survey of water use practices, review of available water quality data, and collection of new data.

5.2 METHODS

5.2.1 Water Quality Analysis

Where applicable, temperature, pH, ammonia, nitrite, and total chlorine were measured in the field at the time of collection. Temperature and pH were measured using a pH 110-Series meter (Oakton Research, Vernon Hills, Il). Ammonia, nitrite, and total chlorine were measured using a DR2700 spectrophotometer (Hach, Loveland, CO) according to standard methods 4500-NH3, 4500-NO2, and 4500-Cl. Aliquots of 10 mL for nitrate and anions quantification were transported back to the lab on ice and analyzed on a Dionex DX120 instrument with ion suppression conductivity detection. The analytical column used was a Dionex AS9-HC, with effluent solution of 9.0 mM Na_2CO_3 (Dionex Corporation, Sunnyvale, CA). Metals and cations were measured by inductively coupled plasma mass spectrometry (ICP/MS) after acidification with 2% nitric acid and a minimum of 24 hours holding time per Standard Method 3125-B (APHA, AWWA, and WEF, 1998). Samples of unacidified water were immediately passed through a 0.45 um pore size to differentiate "soluble" metals form particulate. Alkalinity was titrated according to Standard Method 2320 (APHA, AWWA, and WEF, 1998). Total organic carbon (TOC) was analyzed after acidification with 2% phosphoric acid and immersion purging with nitrogen gas for tree minutes on a Sievers 5310C Laboratory TOC analyzer.

5.2.2 Biological Sampling

Where applicable, presence/absence tests for certain classes of microorganisms were conducted on stagnant and three minute flush samples. Biological activity reaction tests (BARTs) for sulfate reducing bacteria (SRB), heterotrophic aerobic bacteria (HAB), denitrifying (DN), and nitrifying bacteria (NB) were conducted. These tests attempt to culture, or grow, microorganisms taken from the water system, and a color change or bubbling indicates a positive test for that type of microorganism. A positive result can only occur when live bacteria are captured and grown in the test media. A negative result is not necessarily conclusive in indicating the bacteria are absent, since 1) there could have been no live bacteria in the collected sample to grow on the media, or 2) the bacteria may not be able to grow in the test media (viable, but non-culturable state or inappropriate media). The BARTs were stored in a completely dark location and monitored daily for activity per the manufacturer instructions.

Adenosine triphosphate (ATP) is an indicator of overall microbial growth. ATP was monitored using a commercially available kit (LuminUltra, Ontario, Canada). Procols defined by the manufacturer were used. Briefly, after 60 mL of water was filtered through a 0.7 µm syringe filter to waste in order to collect bacteria on the filter in the field, 1 mL of an "UltraLyse" cell lysing solution was passed through the same filter to extract the ATP. At the lab, the filtrate from the previous step was diluted with 9 mL of "UltraLute" solution. Samples were combined with

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equal volumes (100 µL) of Luciferase and measured as relative light units on a Kikkoman Limitester C-100 spectrometer.

Acid-bath washed and autoclaved 1 L sample bottles were used to collect biological samples. The sampling containers were pre-dosed with 0.21 mL of 3% (w/v) sodium thiosulfate (Standard Method 9060 - APHA, AWWA, and WEF, 1998) to neutralize the disinfectant residual immediately after collection. Periodic samples were checked to confirm the residual was neutralized. Any aerators, strainers, or hoses were not removed to simulate regular exposure routes during use. Two-hundred and fifty milliliters of water was collected for first draw samples. While collecting the sample, the tap was fully opened and flow was not altered during sampling. Samples were transported to the lab in individual plastic bags at Virginia Tech on ice.

Upon reaching the lab, the samples were filter-concentrated immediately (<6 hours after arrival) using 0.22 µm mixed-cellulose ester filters (Millipore, Billerica, MA). Filters were aseptically fragmented prior to DNA extraction. DNA extraction was carried out using FastDNA® SPIN Kits (MP Biomedicals, Solon, OH) according the manufacturers protocol. *Legionella* spp., *Legionella pneumophila*, *Mycobacterium avium*, *Vermamoeba vermiformis* (formally known as *Hartmanella verimformis*), and 16S rRNA genes were amplified and enumerated using previously developed qPCR methods (Kuiper et al., 2006; Suzuki et al., 2000; Wilton and Cousins, 1992; Nazarian et al., 2008; Radomski et al., 2010). A Bio-Rad CFX96 real-time thermocycler, with a 10 µL reaction mixture, was used for TaqmanTM and EvaGreen® assays (Bio-Rad, Hercules, CA). Negative DNA controls were included on each qPCR plate run. In addition, trip and filed negative controls were used to quantify any contamination during transport and collection. Ten-fold serial dilutions of positive controls for DNA were included on each plate to quantify the bacteria present in each sample. All samples and controls were run in triplicate on each plate. Any sample that did not replicate consistently in 2/3 wells was considered below the quantitation limit. Samples were diluted at 1:10 to minimize qPCR inhibition and melting curve analysis was performed for EvaGreen qPCR assays to ensure specificity.

Table 5.2
Summary of water quality parameters

Metals unfiltered	Plastic, no preservative
Metals filtered	Plastic, no preservative
NO_3^-, Cl_2, SO_4^-, PO_4^-, Alkalinity	Plastic, no preservative, stored cold
Total chlorine, ammonia, pH, temperature, NO_2^-	Analyze in field
HAB, DNB, SRB, NB BART Test	Began in field, monitored, stored in darkness
ATP	Filtered in field, analyzed in lab
OPPP	Plastic, 3% sodium thiosulfate, stored cold

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5.3 FIELD SITE #1

5.3.1 Background

Field Site #1 (FS#1) is an approximately 6,500 ft^2 outpatient healthcare facility with 20 exam rooms, each with a manually operated faucet for hands-washing (1.5 gpm flow rate), five bathrooms and one kitchen/break room. It occupies approximately one-half of the first floor of a LEED-Gold office building which houses several other medical offices. Influent water is separated at the pump room such that this office in the building essentially had a separate plumbing system. This particular facility has high water age due to minimum pipe diameter restrictions in plumbing codes to ensure there is enough capacity in the system for all fixtures. To account for this, 1" copper pipe ran the length of the building, with ½" diameter copper pipes used for distal taps of the main line.

In early March of 2011, FS#1 experienced elevated copper levels in their potable water system. FS#1 initially contacted a large northeast surface water system (Utility #1) to identify and remediate the cause of a blue-green gel-like substance in their hot and cold potable water taps in multiple rooms. Utility #1identified the source of the problem as the water heater aluminum sacrificial anode rod, the corrosion of which was exacerbated by shock chlorination using *Liquichlor™* at initial pH 11 conducted earlier that year. The shock chlorination raised the chlorine residual concentration to 200 ppm for approximately 2.5 hours following standard methods (AWWA/ANSI C651); however, the cold water lines were not isolated from the hot water lines due to the presence of thermostatic mixing valves at the taps. This may have exposed the hot water lines and water heaters to the high pH and high chlorine water. This was identified by the manufacturer as the potential cause of the blue-green gel-like substance:

> *"In a few isolated parts of the United States where the water supply has a relatively high pH (8+), water conditions will react with the aluminum anode to form excessive amounts of aluminum hydroxide on the anode and in the bottom of the tank. Aluminum hydroxide looks like 'jelly beads' or a green, blue or gray gel like substance in the heater drain or at faucet aerators."*

After a rigorous flushing program, complaints about the blue-green gel-like substance stopped, but future sampling revealed that stagnant sample chloramine residuals were absent, pH was depressed, and temperature was slightly elevated.

5.3.2 Methods

Water entering FS#1's facilities is supplied by UTILITY #1, which uses a chloramine disinfectant residual and orthophosphate corrosion inhibitor. During the investigation, three sets of samples were collected from target taps during the visit. First, profiles of stagnant and flushed metal, anions, and selected bacterial and opportunistic pathogens in premise plumbing (OPPP) concentrations were collected from samples sitting stagnant for more than 8 hours. The second set of samples quantified the rate of disinfectant loss as fresh water was held in the pipe during a forced stagnation period. A third set of samples profiled one room with anomalously high rate of disinfectant loss. Water quality parameters measured in the field were pH, temperature, chlorine disinfectant (total chlorine as Cl_2), and ammonia and nitrite concentrations. Sub-samples were

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transported to the lab at Virginia Tech to measure dissolved metals, dissolved anions, alkalinity, and selected OPPPs concentrations.

5.3.2.1 Initial profile. For the first set of data collected, at each of five room locations (Consultation Rm, Exam Rm 14, Exam Rm 12, Exam Rm 9, and a restroom with electronic faucets), one 250 mL and two 1 L water samples were collected after 0, 0.5, and 3 minutes after flushing, respectively. The conventional taps had a flow rate of 1.4 gpm when fully opened while the electronic faucets had a flow rate of 0.61 gpm. The order of sampling was done such that rooms closest to the pump room were sampled first, minimizing the likelihood of disturbing water in the other taps. The hot water lines and the hot water heater were also sampled. Although hot water is not intended for human consumption, opportunistic premise plumbing pathogens (OPPPs) were a concern along with elevated concentrations of aluminum, copper, and zinc due to corrosion problems.

5.3.2.2 Changes in water quality during stagnation. To quantify the rate of chloramine decay and other changes in water during stagnation, all taps in the building were run fully open for 1 hour, and stagnation was then imposed. Small aliquots (< 250 mL) were taken at 0, 0.5, 1, 2, 4, 6, and 42 hours after the start of stagnation by briefly opening up the tap to the point the water flow was about the diameter of a pencil. A sample of flushed tap water was also placed in a glass container closed to the atmosphere, and aliquots from this water were also collected as a point of comparison to the corresponding samples held in premise plumbing.

5.3.2.3 Flushing at anomalous tap. Sampling during extensive flushing in Exam Room 14 was conducted because it proved to be the worst case of the taps monitored for stagnation effects. To study the tap more intensively, the tap was fully opened and run continuously for 90 minutes to collect profiles of the water. Grab samples (250 mL) were collected at regular intervals over the 90 minute sample period.

5.3.3 Results and Discussion

In the following sections, after reviewing profiles from representative taps during flushing, the effects of stagnation within premise plumbing are quantified (Sections 1.3.1 and 1.3.1). Section 1.3.3 reviews intensive sampling of a room which had anomalously low chloramine residuals and high decay rates.

5.3.3.1 Stagnant and three minute flushed sample. A typical water chemistry from water representative of the distribution system (3 minute sample from pump room; Table 5.3) had a temperature of 18°C, pH 7.1, and a total chlorine residual of 1.2 mg/L as Cl_2. Data from UTILITY #1 indicate that these values are comparable to those in the distribution system of 18°C, pH 7.26, and 1.47mg/L as Cl_2 as recorded at a nearby pump station.

There were significant changes in chemistry between the building entry point (pump room flushed samples) and first draw samples throughout the building (Table 5.3). For example, total chlorine was nearly absent in all samples (even 3 minute flush samples). In addition, there was some evidence that nitrification was occurring in at least some taps. Specifically, in all monitored exam rooms pH decreased 0.11 – 0.63 pH units from the pump room, and ammonia significantly

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decreased in at least three stagnant samples (Consult room, Exam Rm 14 and Exam Rm 9) while nitrite and nitrate increased slightly. BARTs confirmed the presence of some nitrifying bacteria in Exam Room 14. Furthermore, temperature was elevated by 4–6 °C, copper concentrations were consistently 0.30 – 1.01 mg/L higher in stagnant samples compared to the background levels in the pump room, and alkalinity increased 6-9 mg/L as $CaCO_3$. Further, phosphorous concentrations decreased up to 0.15 mg/L as P in some stagnant samples. Although these concentrations of phosphorous would not be considered a limiting nutrient in drinking water, the loss of phosphorous may be important in undermining the effectiveness of the corrosion control strategies by Utility #1.

After the three minute flush, only pH, alkalinity, phosphorous, and copper levels seemed to change significantly. pH was consistently lower in the stagnant samples in comparison to the three minute flushed samples. Alkalinity was consistently 9 mg/L (15%) higher in stagnant samples, but fell back to background levels after the three minute flush. Between stagnant and flushed samples, copper consistently decreased by at least 50%; however, copper levels observed were not unusually high for new copper tubing, and the lower levels of chloramine may have been attributable to natural decomposition reactions with premise plumbing pipes or corrosion products (Equation 1) and/or nitrifying bacteria in the water via the following set of reactions (Equation 2).

$$\tfrac{1}{2}\, NH_2Cl + H^+ + Cu^+ \rightarrow Cu^{2+} + \tfrac{1}{2}\, NH_4 + Cl^- \qquad \text{(Equation 1)}$$

$$NH_2Cl + NO_2^- + H2O \rightarrow NH_3 + NO_3^- + HCl \qquad \text{(Equation 2; Zhang et al., 2009)}$$

Clearly, either the pipe or biofilm at the point of use was strongly influencing water quality in stagnant samples.

The rate at which chloramine decays could double with a 0.7 decrease in pH (Thomas, 1987), 16 °C temperature increase (Sathasivan et al., 2009), or react with the free or copper solids in the plumbing system (Nguyen et al., 2010). All of these factors partly explain the absence of chloramine and presence of nitrifying bacteria (Table 5.3).

No *A. polyphaga*, *L. pneumophila*, and *P. aeruginosa* were detected in these samples. However, *H. vermifomis* and *Legionella* spp. were present in high levels (10^3-10^5 gene copies/mL) and *M. avium* was also identified at moderate levels (Figure 5.1). It is noteworthy that the concentrations of *Legionella* spp. were very high. OSHA standards indicate that *Legionella* levels about 10,000 CFU/L, as measured by culturing, should trigger immediate treatment of the system and levels over 100,000 CFU/L should trigger immediate treatment of the system and steps to be taken to minimize employee exposure risks (OSHA, 1999). Although there is some discrepancy between the concentrations given as a result of culturing and qPCR, due to culturing methods underestimating and qPCR overestimating the concentrations of viable cells, the concentrations detected in these samples were 100-1,000 times higher than the 10,000 CFU/L limit (Figure 5.2). The risk associated with high *Legionella* spp. is unknown. Although no *L. pneumophila* was detected, the physiological requirements for growth for both bacteria are not known to be markedly different. Therefore, it is generally thought that water that supports rampant growth of *Legionella* spp. could also support *L. pneumophila*. In a recent study conducted by the U.S. EPA, 47% of 272 samples from 63 public and private potable water systems were positive for *L. pneumophila* serogroup 1 in at least one sample (U.S. EPA, 2014). As this body of research develops, it seems likely that *Legionella* are ubiquitous in the environment, and some of the standards associated with culturing the organisms will have to be revised to obtain similitude with q-PCR results.

The presence of *M. avium* at ~10^3 gene copies/mL (Figure 5.1) is not unexpected or particularly alarming for a chloraminated distribution system as they are thought to be more

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resistant to chloramines than other OPPPs (Moore et al., 2011), Nontuberculosis mycobacteria (NTM) are ubiquitous in the environment, and are commonly found in drinking water. No action level has been set by OSHA or other decision makers.

The 16S rRNA data suggest that the majority (4 of 5) of stagnant samples in cold taps had a significantly higher (> 2 log increase) level of overall bacteria than the water in the distribution system (compared to the pump room). 16S rRNA levels of 10^4-10^5 gene copies/mL are not atypical for premise plumbing drinking water systems (e.g., Wang et al., 2012).

There was a strong correlation (R = 0.92; paired Spearman rank correlation coefficient) identified between 16 rRNA genes and *H. vermiformis* genes (Figure 5.2). *H. vermiformis* is an amoeba that is known to serve as a host for *L. pneumophila* (Kuiper et al., 2004) and other pathogens. At first glance the data presented herein would indicate conditions suitable for *L. pneumophila* growth (low disinfectant residual, high water age, presence of host), yet none were detected despite high levels of *Legionella* spp.

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Table 5.3
Typical water quality parameters entering FS#1 and in several locations examined

Parameter	Pump Rm	Consult - Stagnant	Consult - Flushed	Exam Rm 12 - Stagnant	Exam Rm 12 - Flushed	Exam Rm 14 - Stagnant	Exam Rm 14 - Flushed	Exam Rm 9 - Stagnant	Exam Rm 9 - Flushed
pH	7.09	6.84	6.98	6.5	6.61	6.46	6.69	6.51	6.7
Temp. (°C)	18	22	24	23	24	23	22	24	24
Total Chlorine (mg/L as Cl_2)	1.2	0.04	0.08	0.01	0.19	0.02	0.22	0.01	0.15
NH_3^- (mg/L as N)	0.36	0.1	0.35	0.34	0.37	0.26	0.38	0.2	0.39
NO_2^- (mg/L as N)	0.009	0.002	0.008	0.015	0.006	0.025	0.005	0.024	0.009
NO_3^- (mg/L as N)	1.21	1.47	1.35	1.21	0.97	1.40	1.06	1.67	1.03
Alkalinity (mg/L as $CaCO^3$)	50	56	49	57	49	59	48	57	48
Cu^{2+} - filtered(mg/L)	0.008	0.75	0.37	0.89	0.34	0.89	0.31	0.80	0.36
Cu^{2+} - unfiltered(mg/L)	0.012	0.86	0.40	1.02	0.37	1.02	0.35	0.82	0.39
Phosphorus - filtered (mg/L as P)	0.45	0.38	0.44	0.30	0.46	0.31	0.46	0.42	0.46
Phosphorus - unfiltered (mg/L as P)	0.48	0.41	0.47	0.34	0.48	0.33	0.49	0.43	0.48
PO_4^- (mg/L)	0.34	0.15	0.24	0.00	0.37	0.00	0.31	0.11	0.31
SO_4^- (mg/L)	23.53	27.49	21.79	27.47	21.23	28.22	21.77	25.51	21.39

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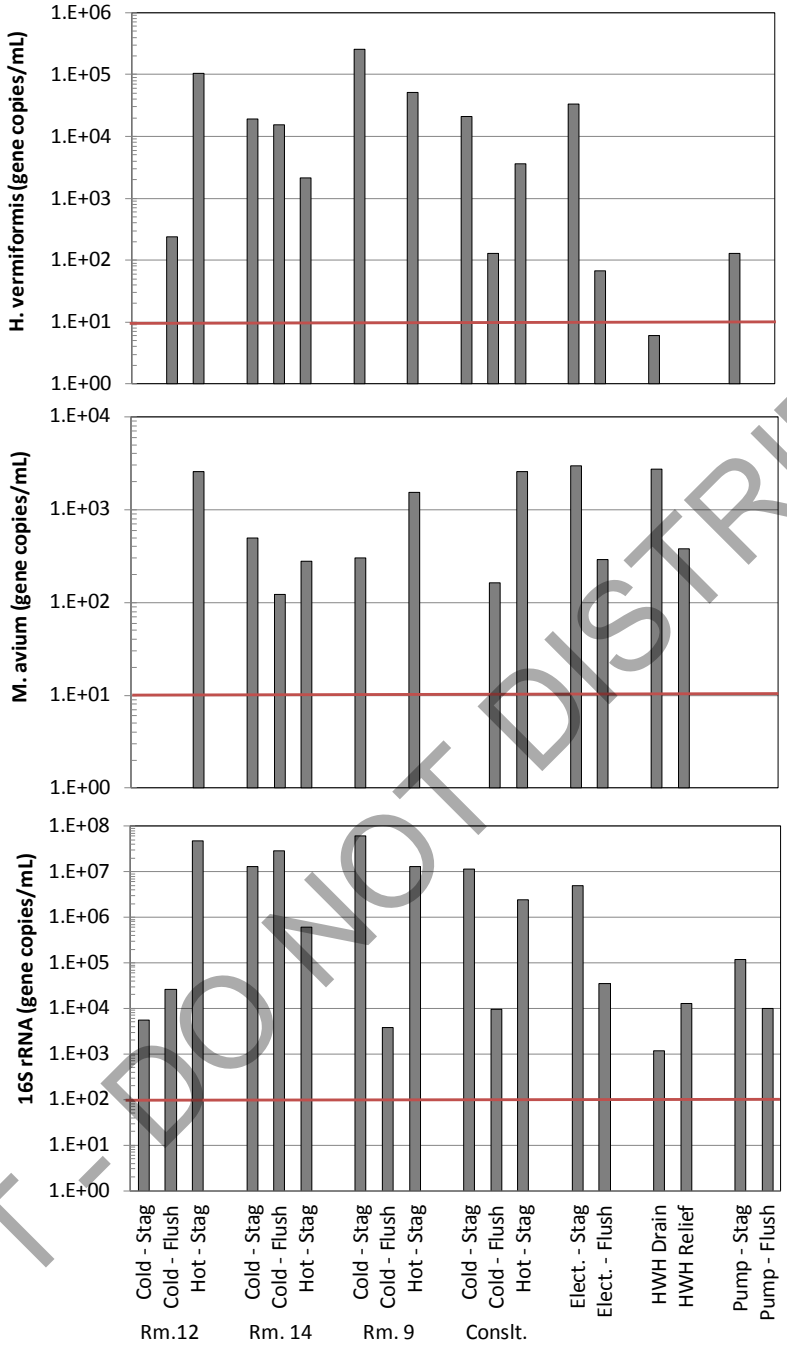

Figure 5.1. ***H. vermiformis*, *M. avium*, and 16S rRNA qPCR results. Detection limits for each assay are represented by the horizontal red line.**

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Figure 5.2. Log-log transform of (top) 16S rRNA and *H. vermiformis* genes; paired Spearman-rank correlation coefficient = 0.92 and (bottom) 16S rRBA and *Legionella* spp.; poor coorelation.

5.3.3.2 Water quality as a function of stagnation. Of the parameters monitored during a 42 hour stagnation period, pH, temperature, disinfectant, and copper changed markedly. Each is discussed separately in the paragraphs that follow.

pH. Metallic corrosion rates and microbial metabolic rates influence the pH of the water during stagnation. In this system, the pH increased nearly 1 pH unit during stagnation in many sampling locations within an hour (Figure 5.3) and proceeded to gradually decrease again 0.5 – 1 pH units over the next 42 hours (data not shown). It would normally be expected that the initial pH should be that of the distribution system (pH 7.09 – Table 5.3), but the initial pH at each tap

after 1 hour of flushing was 0.3 – 0.5 pH units below that of the distribution system, indicating that reactions with the several hundred feet of premise plumbing during flushing contributed to lower pH even in flowing water. It is unclear what biological and/or corrosion reactions are responsible for the pH changes that were observed.

Figure 5.3. pH as a function of stagnation time at all sampling locations. Note, only the first 6 hours of data are presnted here.

*Temperature***.** The temperature in premise plumbing potable water lines is often elevated in comparison to the distribution system because it often sits stagnant in thermally conductive pipes at room temperature. The temperature of the water in FS#1 began to increase immediately after stagnation begun (Figure 5.4). In exam room 14 the temperature rose 10 °C in one hour. Some of this increase may be attributed to the proximity of the hot water taps, as the temperature tends to level off above room temperature (22°C) at 23°C – 25°C. For cold water taps, it is advised to keep temperature below 20 °C to minimize bacterial growth, including that of pathogens (ASHRAE, 2000).

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Figure 5.4. Temperature as a function of stagnation time at all sampling locations. Note, only 6 hours of data are presented here and overlap of temperature is due to the accuracy of the probed used (1°C). Overlab between Exam Rooms 9, 12, and the consult room make it difficult to distinguish between rooms.

Disinfectant Residual. The chloramine residual at FS#1 was completely absent in stagnant samples. It is not necessarily unusual for premise plumbing systems to have low disinfectant residuals in stagnant samples, but the residual also disappeared very quickly (Figure 5.5) which could maximize the opportunity for microbial growth. The rate of chloramine decay at taps was compared to the rate of chloramine decay for the corresponding water held in a glass jar closed to the atmosphere. All decay fit a first-order decay rate function. For Exam Rooms 12 and 9 and the Consulting room, the average decay rate coefficient was of 0.79 hr^{-1} while Exam Room 14, the worst case for many parameters, was 5.56 hr^{-1}. The decay rate in the glass control was only 0.04 hr^{-1} (Table 5.4). This result indicates that reactions with the pipe material and associated biofilms, and to some extent elevated temperatures and possibly copper concentrations, were the cause of the rapid disinfectant residual loss. The fixture at Exam Room 14 had recently been replaced due to continued release of high copper concentrations after the initial aluminum hydroxide had been mitigated, and may have contributed further to the accelerated decay at this tap in comparison with the others. Newer pipes materials tend to have higher chlorine demands than materials that have been naturally or artificially passivated. The decay rates found here are consistent with decay rates found in one study with reactions occurring between the residual and cupric hydroxides (Nguyen et al., 2010). The decay rate observed in that study was 1.2 hr^{-1}. However, those reactions were occurring with pre-formed $Cu(OH)_2$ (s) in laboratory reactors, so results do not necessarily translate to practical considerations here. In a field study by the same authors, the decay rates were

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dramatically reduced, and the disinfectant residual was maintained, by automatically flushing (i.e. wasting water) a small volume (4 gallons per day) of water on a regular basis (Elfland et al., 2010). This represented less than 1% of the total daily water demand of the building, and such flushing might be beneficial in this case as well.

Table 5.4
First-order decay coefficients for total chlorine decay for all sample locations and a control.

Room	Rate (hr^{-1})
Consult	0.78
Ex Rm 12	0.65
Ex Rm 14	5.56
Ex Rm 9	0.93
Control	0.04

Figure 5.5. Total chlorine residual at all sampling locations. Note, only the first six hours of data are presented here.

Copper. Only one copper concentration was observed above the U.S. EPA action limit of 1.3 mg/L (Table 5.5). This sample occurred in Exam Room 12 six hours after the start of stagnation and had 1.26 mg/L particulate and 0.19 mg/L soluble copper for a total of 1.45 mg/L. Of all samples taken during stagnation, most copper was soluble (~77%). Further flushing of the

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pipes may aide in passivation of the pipes due to the fact that UTILITY #1 doses water with orthophosphate corrosion inhibitor.

Table 5.5
Filtered (soluble) and unfiltered (total) copper levels for all sampling locations during stagnation.

Stagnation Time (hr)	Consult Room		Exam Room 12		Exam Room 14		Exam Room 9	
	Cu^{2+} - Filtered (mg/L)	Cu^{2+} - Unfiltered (mg/L)	Cu^{2+} - Filtered (mg/L)	Cu^{2+} - Unfiltered (mg/L)	Cu^{2+} - Filtered (mg/L)	Cu^{2+} - Unfiltered (mg/L)	Cu^{2+} - Filtered (mg/L)	Cu^{2+} - Unfiltered (mg/L)
0	0.05	0.05	0.04	0.05	0.04	0.05	0.04	0.06
0.5	0.10	0.12	0.07	0.13	0.30	0.33	0.09	0.12
1	0.16	0.18	0.11	0.10	0.35	0.42	0.15	0.18
2	0.19	0.20	0.12	0.13	0.38	0.45	0.20	0.21
4	0.23	0.25	0.15	0.18	0.27	0.37	0.25	0.29
6	0.27	0.40	0.19	1.45	0.31	0.52	0.30	0.58
41.67	0.32	0.42	0.18	0.32	0.32	0.46	0.37	0.63

***5.3.3.3 Water quality as a function of flushing – Exam room* 14**. Intensive monitoring of water quality parameters as a function of flushing in Exam room 14 highlighted trends described in previous sections of this report. The samples described in the following paragraphs were collected during flushing after the 42 hour stagnation described above.

pH. The change in pH as a function of flushing time (at 1.4 gpm) revealed an increase in pH directly after flushing began. Within the first minute of flushing, the pH returned to levels observed in the three minute pump room flush (Figure 5.6; Table 5.3). There was another sudden increase in pH observed after approximately 80 minutes of flushing. This mostly likely represents distribution water finally reaching the tap, relatively uninfluenced by the premise plumbing. Overall, the results confirm significant chemical and/or biological reactions along the entire length of the plumbing system.

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Figure 5.6. pH as a function of flushing time in Exam room 14.

Temperature. The temperature monitored in Exam Room 14 showed a similar trend. Initially, the temperature was only slightly above room temperature, but as flushing began it spiked up to 28 °C, representing water temperature in stagnant pipes in the ceiling (Figure 5.7). After approximately 80 minutes of flushing the temperature decreased down to distribution system temperatures of 17°C – 19°C. These findings are consistent with the fact the potable cold water lines near the faucets are being heated beyond ambient room temperature. Contact with heat sources should be avoided in the premise plumbing to keep the potable water lines as cool as possible. Regular flushing may aid in the resolution of this problem.

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Figure 5.7. Temperature as a function of flushing time in Exam room 14.

Disinfectant Residual. The chlorine residual was generally completely absent at the end of the stagnation period, and took nearly 80 minutes of flushing at a high rate to achieve even 1 mg/L Cl_2 (Figure 5.8). After 20 minutes of flushing, the chlorine residual was still completely absent. Hence, during routine use of the taps in the hospital exam rooms, there may never be a significant residual at this tap.

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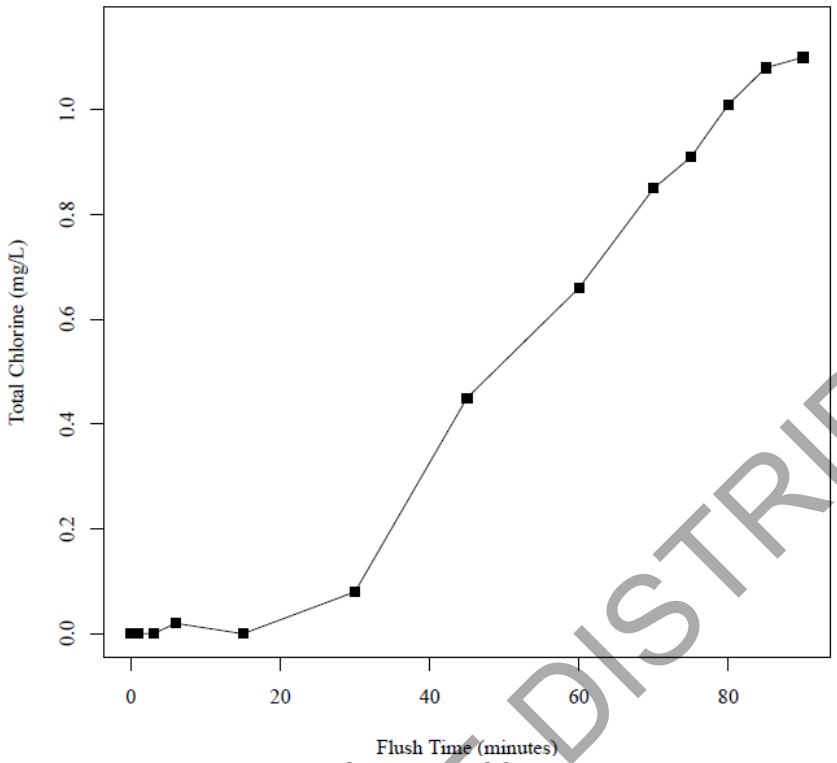

Figure 5.8. Total chlorine residual as a function of flushing time in Exam room 14.

5.3.4 Conclusions

The investigation into the water quality at the FS#1 has provided several insights:

- There are no immediate health threats associated with *L. pneumophilla* in this facility.
- Copper levels were not abnormally high.
- Disinfectant residual in the system is regularly absent at all sampling sites, and disappears at very high rates during stagnation. At some taps, it is likely there is rarely (if ever) a disinfectant residual.
- Although there are no pathogens present in the plumbing system, high numbers of *Legionella* spp. and host amoeba to *Legionella* are present and were strongly correlated with the amount of 16S rRNA gene (i.e. total bacteria numbers) in the water. Better guidance is needed to interpret and respond to these elevated concentrations.
- Fluctuations in pH and total nitrogen levels suggests there is at least mild nitrification occurring at the taps, and possibly in other parts of the premise plumbing system, with high water age and low concentrations of disinfectant residual.

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5.4. FIELD SITE #2

5.4.1 Background

The second field site (FS#2) is an experimental single-family dwelling that simulates hot water demand of a family of four (65-85 gpd). Water is supplied to FS#2 by a large eastern surface water drinking water utility (Utility #2), which uses a free chlorine disinfectant residual and orthophosphate corrosion inhibitor. The purpose of the experimental building is to evaluate the feasibility of achieving net-zero energy in a typical residential setting using various energy-conserving technologies. For the hot water system, an 80 gallon "pre-heat" tank is installed upstream of an 80 gallon electric heat pump water heater to decrease the electrical demand for the entire hot water system (Figure 5.9). The pre-heat tank uses a glycol heat exchanger from the solar panels. Copper pipes are used upstream of the water heaters and hot and cold water distribution manifold. All plumbing downstream of the manifold is $^{3}/_{8}$" diameter flexible cross-linked polyethylene (PEX) tubing.

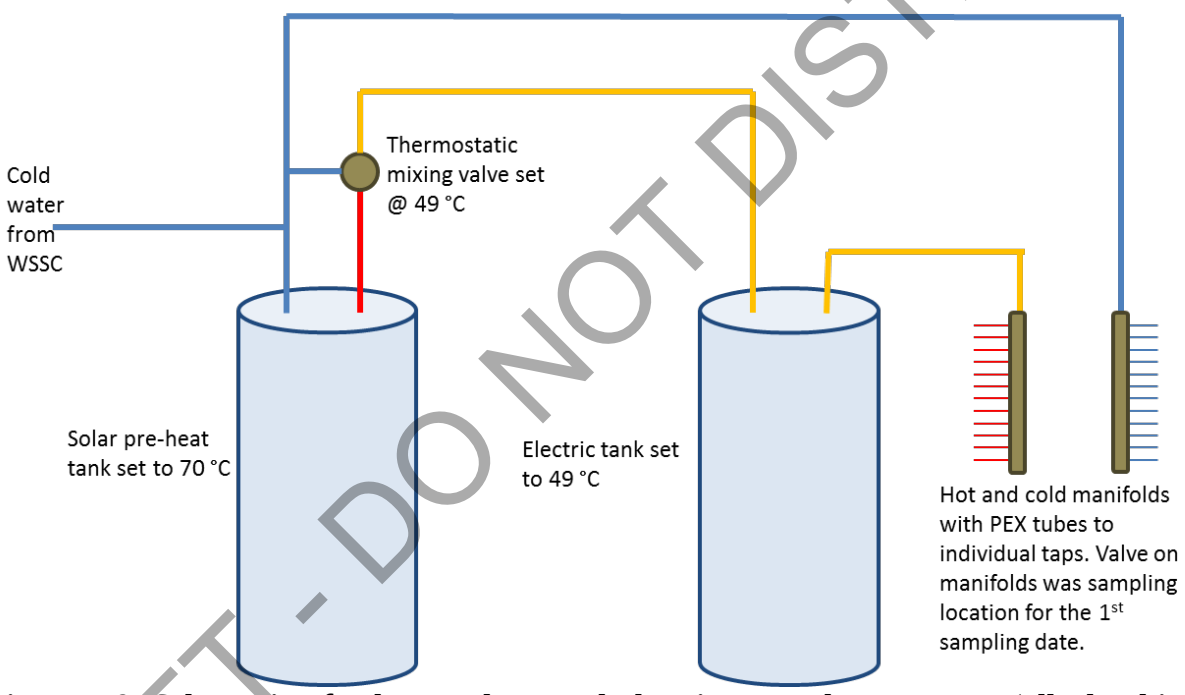

Figure 5.9. Schematic of solar pre-heat and electric water heater setup (all plumbing is copper up to the manifold systems).

5.4.2 Context

After construction was completed in early 2013 and all water systems were tested, they sat stagnant for several months while the research team was outfitting the house with monitoring equipment. In March of 2013, the hot water system was turned back on to begin testing the monitoring equipment associated with the solar pre-heat tank. At that time, a foul (rotten egg) odor was originating from the hot water during flushing. The heaters were increased to 60 °C for several hours and flushed thoroughly, after which the smell was no longer present. The smell was

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attributed to sulfate reducing bacteria growing in the stagnant water, which were remediated by high temperatures and flushing. However, the presence of the 80 gallon preheat storage tank posed additional concerns due to the increased hot/warm water storage and resulting increased water age within the hot water system. The purpose of sampling this building was to assess the extent to which the water storage was increased versus a conventional building and to determine if any risk factors resulted.

5.4.3 Methods

Sampling occurred on two separate dates. During the first date, a profile of the hot and cold water quality in the building before the experiment started was obtained. To accomplish this, flushing from the cold and hot lines were conducted downstream of the water heaters at the cold and hot manifolds. Stagnant and flushed samples were collected and analyzed for metals, major anions, water chemistry (temperature, pH, chlorine, total organic carbon), and selected bacterial and opportunistic premise plumbing pathogens (OPPP). Samples were also collected directly from the bottom of the solar and electric water heaters. After flushing had occurred, temperature recovery times of the electric and solar water heaters were quantified.

During the second day of sampling, the experiment was fully underway with well-defined daily water use patterns (e.g., Table 5.6). To collect samples without interfering with the energy testing associated with using hot water, samples were taken from a tap during the three automated showering events. All water collected during the shower events was tempered to 40 °C. After the three sampling events, additional samples were taken directly from both the solar and electric water heater.

Table 5.6
Timing of water flow events. The three 8.75 gallon events were the simulated showing events sampled during the second sampling visit.

Friday		
Start time	FixtureID	Volume (gallons)
3:33 AM	SinkMastBath	0.52
4:02 AM	SinkMastBath	0.52
6:04 AM	KitchenSink	0.52
6:05 AM	Simulated Shower 1	8.75
6:12 AM	SinkMastBath	0.52
6:25 AM	KitchenSink	0.52
6:32 AM	KitchenSink	0.52
6:33 AM	Simulated Shower 2	8.75
6:39 AM	SinkMastBath	0.52
6:40 AM	KitchenSink	0.52
6:42 AM	SinkMastBath	0.52
6:44 AM	Simulated Shower 3	8.75
6:51 AM	KitchenSink	0.52

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For comparison, samples were collected from a conventional house that has no green features located within the same distribution system. Only hot and cold water samples were taken as a function of flushing from the kitchen sink.

5.4.4 Results and Discussion

After reviewing profiles of hot and cold water during flushing events and comparing these data to a conventional home with no green features, results from the simulated showering events are presented. A final section presents and discusses qPCR results.

5.4.4.1 Cold tap flushing profile. The total chlorine residual in both the net-zero test house and the conventional house verified concerns about effects of storage and water age (Figure 5.10). The conventional baseline house reached a steady residual within three minutes of flushing at 1.5 gpm, whereas it took >20 minutes of flushing to attain a similar residual at the net-zero house at 2 gpm. The net-zero energy house has a longer service line, has newer a service line and pipes, and had stagnant conditions associated with construction prior to sampling, all of which tend to decrease chlorine residuals to the building despite purposeful and very thorough flushing the of lines 1-3 days before sampling.

The pH of stagnant samples was about 0.5 pH units greater than the rest of the flushed of the samples, likely due to the high amount of stagnation in the tap that was sampled. Similarly, ATP, an overall indicator of biomass, was extremely high in stagnant samples vs flushed samples (215 pg/mL vs <2 pg/mL). There were no significant fluctuations in TOC, a basic measurement of the total amount of carbon nutrient potentially available for microbiological growth (range 1.29-1.44 mg/L).

Stagnant samples from this visit indicated there was elevated lead in some samples. For instance the first flush sample for the cold tap had 14.3 μg/L total lead. However, the sample port available was a brass hose spigot on the manifold that was rarely, if ever used. Copper and zinc were also elevated in that sample (0.61 mg/L and 0.29 mg/L, respectively), which is consistent with the notion the stagnant brass sample port caused the high lead. No other inorganic constituents appeared to be elevated or change significantly of the course of flushing.

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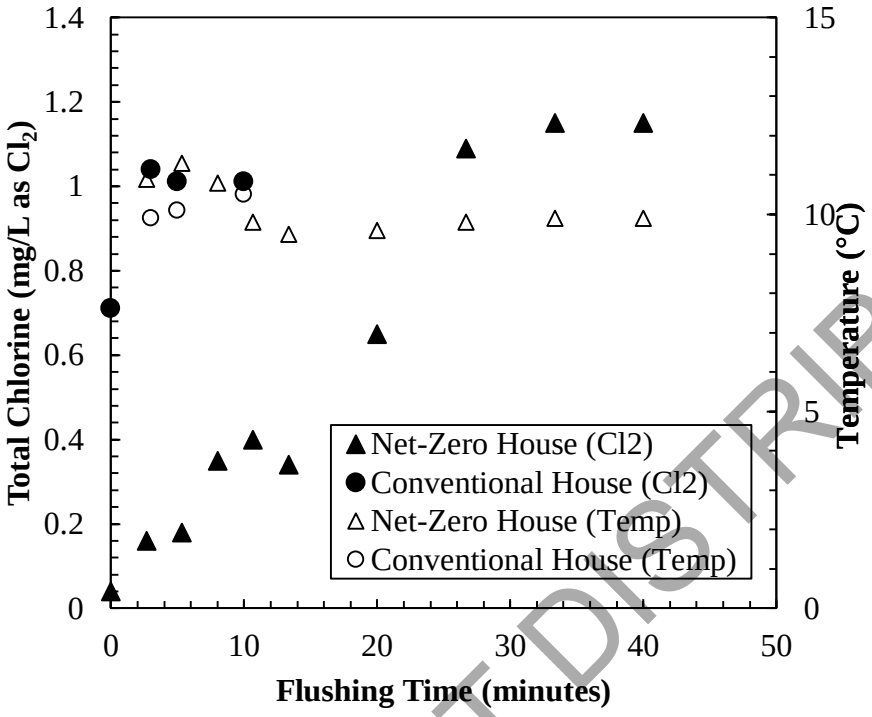

Figure 5.10. Chlorine residual and temperature measurements at cold taps as a function of flushing time for the net-zero energy house and an ordinary household with no green features (all flushing times normalized to 1.5 gpm flow rate).

5.4.4.2 Hot tap flushing profile. The temperature setting of the solar water heater at the net-zero house was different from the temperature setting for the electric water heaters at both the net-zero and conventional houses. At the net-zero house, the solar heater was set to 70 °C, but reportedly never exceeded about 60 °C (personal communication). Water exiting the solar heater and entering the electric water heater is tempered to 49 °C using a thermostatic mixer (Figure 5.9), and the electric heater is set to 49 °C. The conventional household targets 49 °C as well. It is apparent that neither household consistently hits the thermal target (Figure 5.11). The net-zero house water temperature decreased from 50 °C to 35 °C within five minutes of flushing at 2 gpm. The conventional household maintained temperatures in the 40 °C range for approximately 20 minutes at 1.5 gpm, then gradually decreased as more cold water entered the heater, but never reached 49 °C.

After 20 minutes of flushing, chlorine residuals in both systems began to increase markedly. The conventional house chlorine residual increased at a faster rate than the net-zero house, presumably due to the lower overall hot water storage volume (75 gallons vs 160 gallons). It was expected that the net-zero house would require two times the amount of flushing as the conventional house to achieve a chlorine residual comparable to the main distribution system because the storage was doubled. However, both systems reached concentrations of about 1 mg/L as Cl_2 after about an hour of flushing. Because both the solar and electric water heaters at the net-zero house had no disinfectant residual in them at the time sampling began, it would be expected

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that the entire 160 gallons of storage would need to be flushed in order to measure a residual at the hot tap. However, a significant residual (1 mg/L as Cl2) appeared after about 100 gallons of water had been flushed. This suggests that cold water in the solar pre-heat tank might be short circuiting the solar tank volume. In any regard, it seems unlikely that either system has a consistent chlorine residual in it during regular use, given that it took 30 minutes of flushing to obtain significant disinfectant residuals in both systems.

After the system in the net-zero house had been completely flushed such that there was no hot water in the tanks, and water temperatures in both the solar and electric water heaters were similar to temperatures observed of the cold water distribution main (15-17 °C), temperature recovery profiles of the two heaters were examined. One hour after flushing, the electric water heater had recovered to 90% of the initial temperature of 50 °C. The solar water heater temperature did not increase during this one hour period, with a 47% difference between the temperature one hour after flushing and the heater set point. Although the temperature and chlorine residual profiles of the net-zero and conventional household hot water systems were not strikingly different as a function of flushing, the solar water heater did not recover quickly, allowing the system to remain at non-optimal temperatures for controlling pathogen growth.

Similar to the cold water tap, the hot water tap at the net-zero house did not have out-of-the-ordinary chemical profiles. ATP was consistently higher in the hot water samples than the cold water, but only by about 2 pg ATP/mL. The highest concentration of ATP in the hot water flushing profiles was only 3.5 pg/mL, which is well within recommended upper limits of low ATP water (10 pg/mL as defined by LuminUltra, Ontario, Canada). TOC was also slightly elevated compared to the cold water samples (1.51 mg/L vs 1.41 mg/L). Although assimilable organic carbon (AOC) was not measured, levels as low as 10 µg/L have been shown to limit *Legionella* growth (van der Wielen and van der Kooij, 2013). If a fraction of the measured 0.1 mg/L difference was AOC, it has the potential to support bacterial regrowth.

The hot water samples had elevated lead, copper, and zinc. Lead and copper levels were above the action limit of 15 µg/L and 1.3 mg/L, respectively, in first draw samples. As flushing continued, all levels gradually deceased (Figure 5.12). Because there were very strong correlations between lead and copper (Pearson's $R^2 = 0.83$) and lead and zinc (Pearson's $R^2 = 0.98$), it is likely that the high level of inorganic contaminants at this tap was a product of the infrequently used brass sampling port . This conclusion is supported by results presented in the next section, where samples taken from a shower head fixture had lead levels < 3 µg/L.

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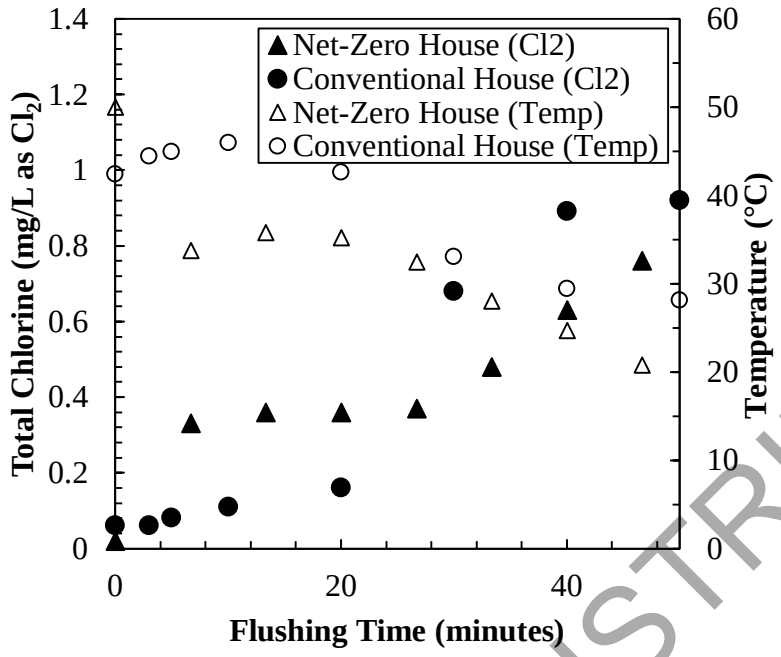

Figure 5.11. Chlorine residual and temperature measurements at hot taps as a function of flushing time for the Net-Zero Energy house and an ordinary household with no green features (all flushing times normalized to 1.5 gpm flow rate).

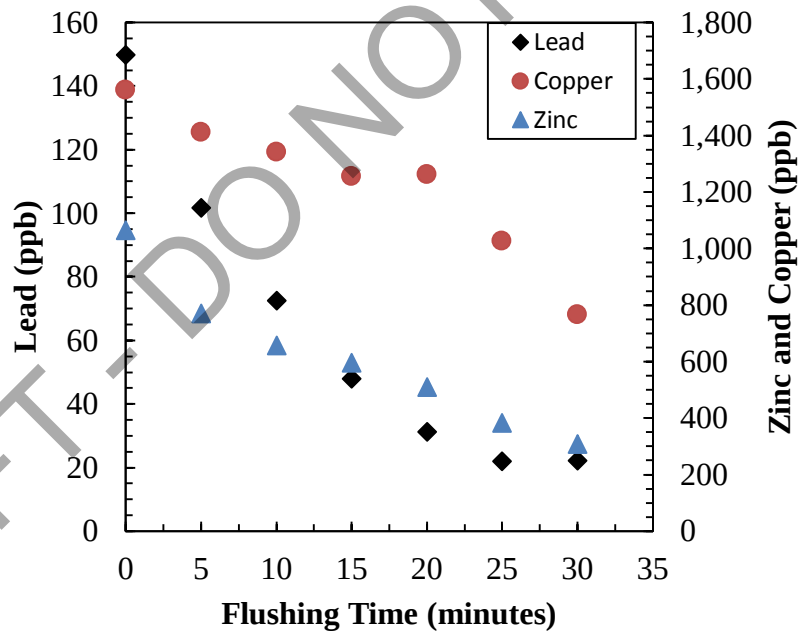

Figure 5.12. Lead, copper, and zinc concentrations as function of flushing at the hot tap

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5.4.4.3 Simulated showering events. The temperature during all three showers was targeted to 40 °C, which is a markedly higher than the maximum temperatures observed during flushing of the hot water tap during the previous sampling visit (33-35 °C; Figure 5.11). However, excluding the first sample at the start of the first shower event, which was <30 °C (probably stagnant water in the line), the thermal target was consistently met (Figure 5.13). The total chlorine delivered to the water heaters never exceeded 0.1 mg/L as Cl_2, which is consistent with expectations based on hot flushing results up to 20 minutes (Figure 15.3). Because these three showering events represent the highest water usage in this experimental home a significant disinfectant residual is never observed in the shower.

With the added hot water storage volume to accommodate the solar preheat tank, the net zero system turns over 3.12 times weekly, as opposed to 6.25 times weekly in the conventional house for the same demand (500 gallons per week). The lower turnover and increased water age decreases the likelihood of maintaining the chlorine residual in distal sites.

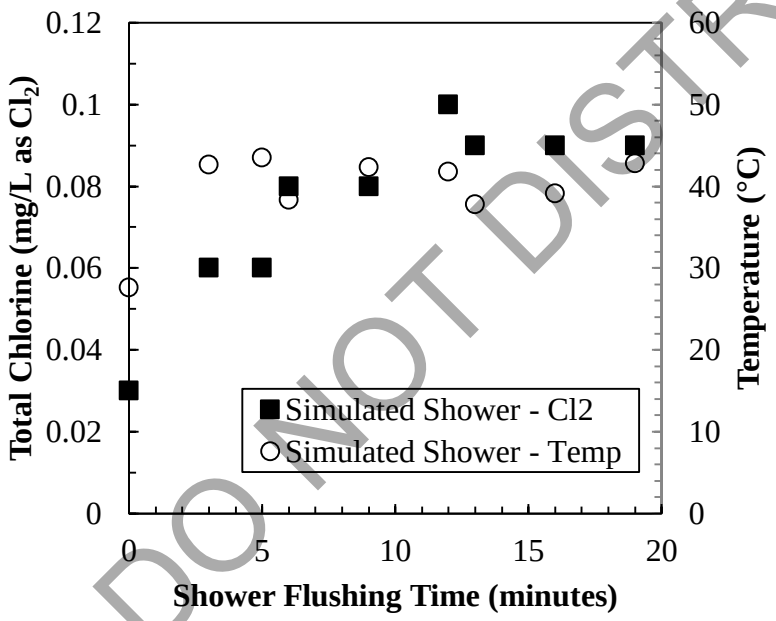

Figure 5.13. Total chlorine and temperature profiles during three simulated showering events (shower #1 from 0-7 minutes of flushing; shower #2 from 7-14; shower #3 from 14-19). Water was turned off and on again between events (refer to Table 5.6)

5.4.4.4 qPCR results. Exploratory biological sampling revealed several insights. First, it appeared there was regrowth within the hot and cold temperature water systems downstream of the water heaters. There was approximately 2 logs more overall bacteria (as measured by 16S rRNA; Table 5.7) and up to a 2 log increase in *Legionella* spp. at the manifold sampling locations, but not in the simulated showering events. This supports the idea presented earlier that the higher water age at these infrequently used sampling ports could be the cause of bacterial regrowth as well as the elevated lead and copper observed at these taps. In addition, there was clear regrowth of *V. vermiformis* within the plumbing system. Samples downstream of the water heaters had higher concentrations (~3 log increase in gene copies/mL) and prevalence of *V. vermformis* than

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the samples taken from the heaters themselves, where samples were consistently below the quantification limit of the assay.

The opposite was true for *Legionella* spp. or *M. avium*. *M. avium* occurred and at a lower frequency than *Legionella* spp. Anecdotally, this supports observations of other researches where water in one system using free chlorine residual was more resistant to *Mycobacterium* growth than *Legionella* growth, whereas the opposite trend was observed when the residual was switched to a chloramine (Moore et al., 2006). It is again noteworthy that the concentrations of *Legionella* spp. were very high as compared to the OSHA standards of 10,000 CFU/L and 100,000 CFU/L. These results, as well as the comprehensive work by the U.S. EPA referenced in Section 1.3.1, highlight the gap between standards and the prevalence and concentration of *Legionella* occurring in practice. (OSHA, 1999; U.S. EPA, 2014).

Table 5.7
Quantitative polymerase chain reaction results for both sampling dates at the net-zero house.

Sample Description	Flushed/ Stagnant	log 16S rRNA (gene copies/mL)	log V. vermiformis (gene copies/mL)	log M. avium (gene copies/mL)	log L. spp. (gene copies/mL)
Cold Manifold Trip 1	Stagnant	7.81	0.50	0.50	4.67
Cold Manifold Trip 2	Stagnant	6.68	3.44	0.50	3.73
Hot Manifold Trip 1	Stagnant	7.59	2.88	3.16	4.30
Hot Manifold Trip 2	Stagnant	7.69	0.00	0.00	5.97
Shower event	Stagnant	5.44	2.86	0.50	3.11
Shower event	Flushed (10 gal)	4.16	2.40	0.50	0.50
Shower event	Flushed (30 gal)	3.60	0.50	0.50	2.57
Water Heater Trip 1	N/A	5.40	0.50	3.11	3.54
Water Heater Trip 2	N/A	5.03	0.00	0.50	0.50
Solar Heater Trip 1	N/A	5.08	0.50	2.98	3.81
Solar Heater Trip 2	N/A	4.18	0.00	0.50	0.50

*A value of 0.5 indicates the genes were detected, but not in quantities above the quantification limit of the method.

5.4.5 Conclusions

- The solar preheat tank doubled hot water storage and water age within the net-zero house.
- The large hot water storage volume likely contributes to the lack of chlorine residuals in the building, though there may be cold water short circuiting during high flow events.
- Exploratory OPPP data reveals regrowth downstream of the water heaters in the infrequently used sample ports, at least with 16S rRNA and *V. vermiformis* assays. In addition, *V. vermiformis* was elevated in the firsts two showering samples, indicating regrowth in the pipes downstream of the manifold.
- Both *M. avium* and *Legionella spp.* were detected at a high frequency at infrequently used taps in both hot and cold water systems.

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- Overall, this case study provides additional evidence that long stagnation events, lack of chlorine residual, and large storage volumes can trigger problems with microbial growth and inorganic contaminants.
- There is a need for recommendations in standards and guidelines that tie specific levels of *Legionella* collected via a defined sampling protocol, with specific remedial actions and responses.

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5.5. FIELD SITE #3

5.5.1 Background

The third field site (FS#3) is a small net-zero energy and net-zero water office building that houses 3-5 full time employees. Rainwater is collected via rooftop (1,000 ft^2) with a first-flush diverter and then stored in a 3,000 gallon cistern for all potable and non-potable uses. To avoid stagnant water within the cistern, solar-powered pumps automatically recirculate 600 gallons of the rainwater in the cistern through the cold water plumbing system, including the treatment system, twice daily. The water treatment system includes a 20 µm filter, a 5 µm filter, and a granular activated carbon (GAC) filter followed by ultra violet light irradiation at 253 nm. At potable taps (in bathrooms and a kitchenette), an additional 1 µm final filter is installed. The filters are changed semi-annually or when there is a high pressure drop through the system as they become clogged. Twice a year the water is treated with a high concentration of bleach (> 50 ppm) and continuously recirculated for 24 hours. After this period the water is drained and the cistern is primed (i.e., filled halfway) with groundwater from a nearby building supplied by local groundwater. Thus, this net-zero building is not actually net zero, because it regularly uses groundwater for recharge and maintenance. In addition, there is some concern that these maintenance practices may cause or facilitate other water quality issues (Table 5.8).

Table 5.8
Potential negative effects of routine maintenance procedures.

Treatment	Potential Issue
GAC filtration	Act as a sink for contaminants such as Pb and metals; Constant supply of dissolved oxygen; Infrequent replacement may facilitate sloughing of biofilm, potential shielding from UV disinfection
UV irradiation	Regrowth potential downstream of UV not addressed
1 µm filter at potable tap	Act as a sink for contaminants
Recirculation of water	Creates completely mixed system; Assists accumulation of contaminants on GAC filters
50 ppm chlorination*	Pitting corrosion in copper pipes; May be ineffective against organisms protected in biofilms; Regrowth potential after reducing biofilm (necrotrophic growth) not addressed

*the facility reduced the concentration of bleach to 10 ppm after the sampling visit

As part of the effort to reduce overall water demand in the building, composting toilets were installed and outdoor irrigation was not installed on the property. All grey water effluent is land-applied to an infiltration field adjacent to the building. In addition, all sink faucets in the

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building are equipped with a low flow restrictor with a 1 gpm flow rate. Half-inch copper pipes supply individual faucets while ¾“ copper pipes are used elsewhere in the system. There were no consumer complaints or other known issues with this water system before sampling. In fact, the water quality was regarded by some users as the highest quality of water they have tasted.

5.5.2 Methods

Stagnant and flushed water samples from hot and cold taps in the men’s restroom, the kitchenette, and a janitor’s closet (not considered potable) were collected to generate a profile of water quality data. In addition, samples were taken directly from the rainwater cistern and directly after the GAC filters and UV tube.

5.5.3 Results and Discussion

After reviewing general information about the use and daily operations of the system, a section on the water quality in the building is presented. A third section discusses qPCR results, followed by general comments on the scalability of this model of water system.

5.5.3.1 Water use. Although there were no water meters on this system to determine the exact demand, the facility estimates that an average of 13,000 gallons is used annually. If this were the case, the 3,000 gallon cistern would be turned over only 4.3 times per year, resulting in an average water age within the system of a little less than 3 months. This water age is unprecedented in convention buildings using municipally supplied tap water. However, upon sampling it was discovered that alkalinity, calcium, and magnesium were much higher than concentrations found in rainwater (~110 ppm as $CaCO_3$, ~12 ppm Mg^{2+}, and ~30 ppm Ca^{+2}) and the water sampled in the cistern was more representative of the local groundwater. The groundwater was pumped into the facility, using on-the-grid electricity, during routine maintenance conducted nearly four months prior to sampling. Based on conversations with facility staff and observations made during sampling, the total annual demand of this facility is probably closer to about 5,000-8,000 gallons, which indicates that 38-60% of total water use in the facility is actually groundwater used for routine maintenance purposes. Indeed, using the calcium and magnesium as a tracer, and assuming that the rainwater have zero hardness and would dilute the groundwater, approximately 40-50% of the water in the cistern at the time of sampling was groundwater. In addition, there is a fire suppressant system that is supplied by the same groundwater and a small firefighting pond located directly adjacent to the building as an on-the-grid emergency backup.

5.5.3.2 Water quality profiles. The pH measured in most of the samples of 7.6 (Figure 5.14) in samples was also inconsistent with typical rainwater levels (pH ~5.5). Stagnant samples from potable taps generally had lower pH, yet a stagnant sample from a janitor’s closet, which was not considered potable water and thus did not have an additional 1 μm filter, did not have a lower pH. It is possible that microbial activity on the 1 μm filters contributed to the decrease in pH, but this was not confirmed with BARTs run that were inconclusive.

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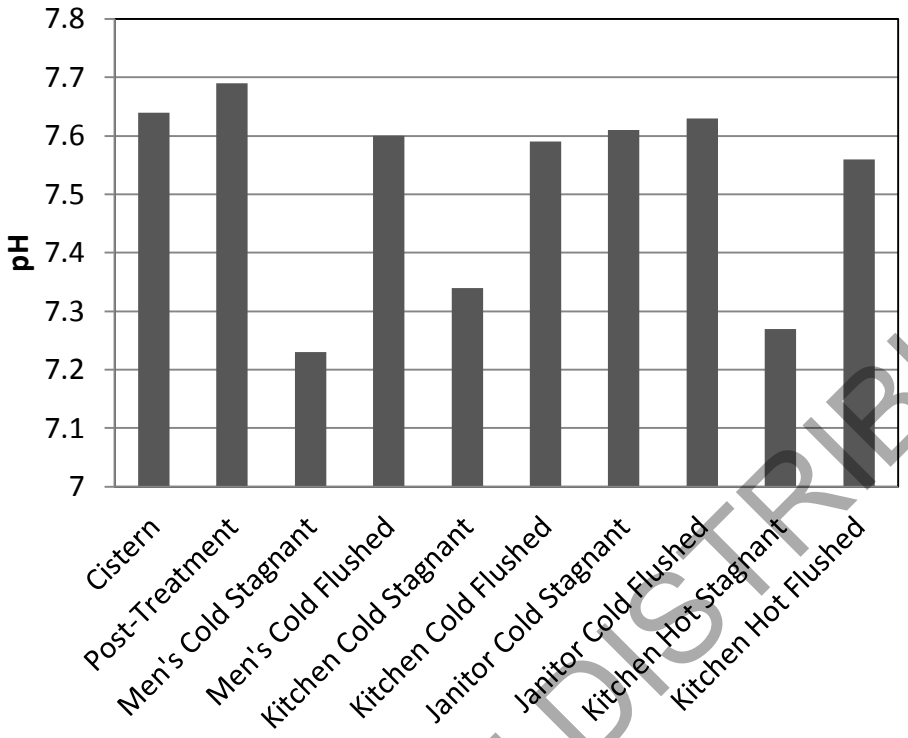

Figure 5.14. pH readings for samples taken at FS#3

In a similar trend, ATP was higher at the potable men's room and kitchenette taps compared to at a non-potable taps and directly downstream of the GAC filters and UV system or the janitor's closet (Figure 5.15). The potable taps had 7 to 17 times more ATP than treated water, again suggesting a high amount of regrowth occurred at or downstream of the1 μm filters.

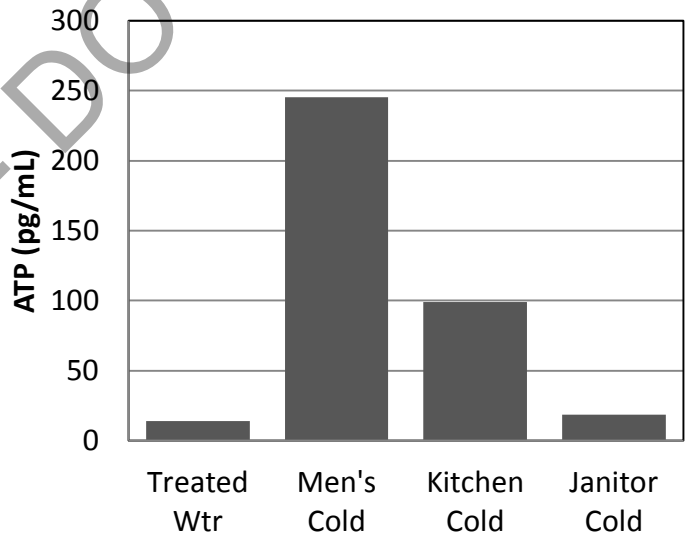

Figure 5.15. ATP concentrations at various locations in the building

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Temperatures in the cold water taps were considerably higher than what is encountered in municipally supplied systems. The temperature in the cistern and in both stagnant and flushed water samples was on average 26.5 °C (standard deviation = 1.3 °C), or indoor room temperature. This was to be expected, however, given that the cistern is effectively indoors. While stagnant samples would likely have elevated temperatures regardless of system type, higher temperatures throughout the system could be problematic. It is suggested that remaining below 20 °C in cold water systems helps to minimize growth of bacteria in general and OPPPs in particular (ASHRAE, 2000). For more conventional systems, periodic flushing may assist with achieving this target; however, water temperatures are dependent on the climate and frequency of flushing.

Metal concentrations in all cold water taps were less than half the U.S. EPA action limits for lead and copper. For example, the ranges for total lead and copper concentrations were 0.1 – 7.7 ppb and 0.02 – 0.57 ppm, respectively. If rainwater was the primary water in the cistern as advertised, the pH and alkalinity would have been significantly lower than the pH and alkalinity measured (pH 7.6 and 110 mg/L as $CaCO_3$) and the water would have been much more corrosive. Since the majority of the water in the cistern was leftover water from the semiannual maintenance, the water is not considered corrosive, and therefore it is not surprising that the amount of lead and copper in the water was not higher. If the system were operated as truly off-the-grid, it is possible and even likely that a higher concentration of lead and copper would be detected. Low pH waters (<6) and low alkalinity (<20 mg/L as $CaCO_3$), similar to typical rainwater quality, would be expected to be the most corrosive (Edwards et al., 1999; Dodrill and Edwards, 1995; Gardels and Sorg, 1989).

Hot water was supplied using 2.5 gallon water heaters with the thermostat set to 50 °C. Although the stagnant water temperatures were at room temperature (25 °C), the thermal target was met within 10 seconds of flushing due to the proximity of the heaters to the taps. Metal concentrations in hot water samples were also well below U.S. EPA action limits (average of 4.2 μg/L for lead and 0.51 mg/L for copper).

5.5.3.3 qPCR results. There were no significant differences in overall bacterial concentrations as measured by 16S rRNA, even directly downstream of the UV treatment (Table 5.9). This is not unexpected, as the qPCR assays pick up both live and dead organisms. No regrowth was observed for *M. avium* or *Legionella* spp. in potable hot and cold water piping and no *L. pneumophila* was detected, but there was nearly a 2-log increase in *V. vermiformis* in both hot and cold taps. Importantly, *V. vermiformis* is an amoeba host for *Legionella*, and it is logical that enhanced growth of this host could sometimes lead to more *Legionella* in some circumstances. *Legionella* spp. was present at very high levels at FS#3 as well.

Table 5.9

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Quantitative polymerase chain reaction results for FS#3.

Sample Description	Flushed/ Stagnant	log 16S rRNA (gene copies/mL)	log V. vermiformis (gene copies/mL)	log M. avium (gene copies/mL)	log L. spp. (gene copies/mL)
Cistern Storage Tank	N/A	6.96	2.60	2.00	4.36
Post-Treatment	Flushed 3 min	6.36	3.43	2.61	4.26
Men's Cold	Stagnant	6.77	4.49	2.73	4.58
Men's Cold	Flushed 3 min	6.51	3.00	0.50	3.48
Men's Hot	Stagnant	6.90	4.20	2.65	4.28
Men's Hot	Flushed 3 min	6.52	2.26	3.32	3.34
Janitor's Cold	Stagnant	6.95	2.93	3.69	3.32

5.5.3.4 Scalability. From a practical standpoint, the facility must routinely monitor for coliform and overall heterotrophic bacterial growth to ensure that the facility is compliant with drinking water quality standards. Instead of sampling and analyzing data on-site, as would any municipal water treatment facility, the building staff collects samples and sends them to a certified national lab for analysis to gather data on heterotrophic plate counts and coliform bacteria. This is time and resource restrictive, and the ability for this approach to be scaled to all private water users that treat their water onsite is low. This suggests that as the practice of treating water on-site for buildings seeking complete or partial water independence gains popularity, methods for monitoring water quality at these locations will have to be rethought.

5.5.4 Conclusions

This case study offers several insights into the net-zero energy and net-zero water building approach to potable water:

- This building is not truly off-the-grid, as it uses on-grid electricity and groundwater for routine maintenance and fire-fighting protection. Because this location is generally supplied by well water, the responsibility for maintaining the water connections is simplified. If this building were located where the municipal water utility provided backup, emergency connections, the situation is more complicated. If the majority or even just a large number of buildings in a municipality seek to be off-the-grid, municipal rate structures would have to be adjusted accordingly to maintain the connections for the backup water supply.
- Calcium and magnesium concentrations of the water in the cistern suggest that 40-50% of the water in the cistern at the time of sampling was groundwater. Therefore, the cistern may have been drastically over-sized for the water demand of this facility.

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- The additional 1 μm filter might be adversely impacting the quality of the water in stagnant samples. Increased levels of OPPPs and their host organisms, as well as higher concentrations of ATP were detected in potable taps with the additional 1 μm filter.
- High levels of OPPPs and host organism *V. vermiformis* were detected in nearly all rainwater samples, despite the routine water recirculation that occurs twice daily. Although long periods of stagnation are avoided by this approach, the overall water age in the facility is likely on the order of months.

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CHAPTER 6: USGBC INSIGHT TECHNICAL REPORT: GREEN BUILDING WATER EFFICIENCY STRATEGIES

6.1 ABSTRACT

This chapter describes compliance paths for projects earning water efficiency credits under LEED for New Construction v2.2. A stratified random sample was taken of all non-confidential certified projects earning these credits under this version of the rating system, and compliance forms for Water Efficiency credits (WEc) 1, 2, and 3 were analyzed. Frequency in use of water efficient landscaping, non-potable water sources, on-site wastewater treatment, and selection of plumbing fixtures and tap fittings were calculated. For WEc1: Water Efficient Landscaping, projects most often avoid permanent irrigation altogether. Rainwater was the most common non-potable water source for those that selected that compliance path. For WEc2: Innovative Wastewater, wastewater reduction was selected over on-site grey- or blackwater treatment. High efficiency toilets and non-water urinals were most often used to meet the high reduction necessary to earn the credit. Dual flush and high efficiency urinals were most often selected for lower (20+% or 30+%) water use reduction needs for WEc3: Water Use Reduction.

6.2 INTRODUCTION

Water use in the built environment is a very important aspect of human civilization. Public supply and domestic use accounts for about 12% of all fresh water withdrawals in the US (Barber, 2009). The energy alone used to run the drinking water and wastewater plants in the US costs about $4 billion each year (Energy Star, 2012). Societally, this water use affects municipal water supply and treatment facility loads. Economically, it affects utility bills and municipal spending. Environmentally, it affects fresh water sources both in terms of volume extracted and pollution added. Because of these impacts, it is beneficial to reduce building water usage rates. There are many different facets of this issue, and many ways of addressing it in buildings, including water efficient fixtures and fittings such as toilets and sinks, collection of non-potable water sources such as rain, and treatment and reuse of wastewater.

The Energy Policy Act of 1992 (EPAct) took a step towards reducing the impacts of building water use by imposing flow restrictions on bathroom fixtures. Since then, many technological advances have been made which can further reduce water impacts while delivering the same level of service expected by building occupants. As a leader in the movement to create built environments that meet the needs of people and life on Earth without sacrificing the long term viability of either, the U.S. Green Building Council has sought to promote these technologies by including their use in the Leadership in Energy and Environmental Design (LEED) rating system for built environments.

In order to achieve certification, applicants must earn credits for inclusion of features in their building that achieve the goals of the rating system. LEED devotes an entire category of credits to efficient water use, covering several aspects of water efficiency. This report aims to describe how projects achieved credits for this category in LEED for New Construction v2.2 through an analysis of compliance paths and choices. Factors investigated include water efficient

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landscaping, non-potable water sources, on-site wastewater treatment, and flush fixture and tap fitting selection.

6.3 METHODOLOGY

6.3.1 Sample

The research team began with the public LEED project directory from the USGBC website, and a list of all non-confidential projects earning Water Efficiency (WE) 1, 2, and 3 credits under LEED NC v2.2. Non-US and confidential projects were not included in the sample. Owner types were obtained from the public database and statistics were generated to describe their distribution. A stratified random sample was then taken of the WE credit-earning projects based on owner type. The result was a sample of 448 projects earning at least one of WE credits 1, 2, and 3. Credits 1 and 3 were earned much more frequently than credit 2 (Figure 6.1).

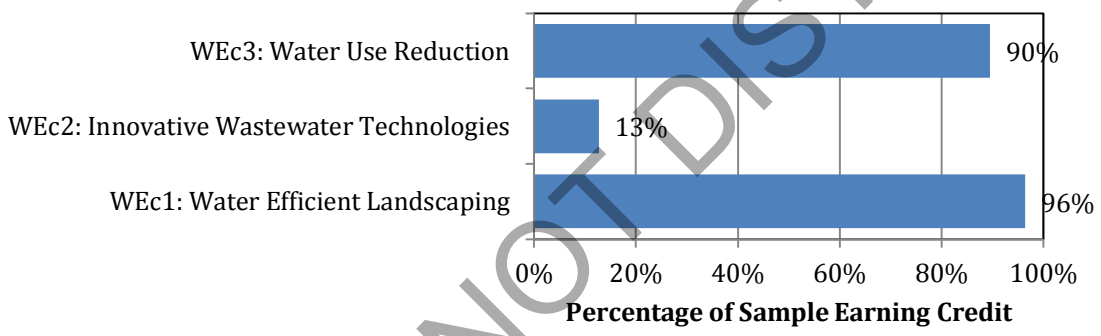

Figure 6.1 Counts of projects earning WEc 1, 2, and 3 in sample

For data validity, credit earning and owner type mentions were analyzed. The percentages of projects earning each credit are approximately equal in the population and the sample. Project teams specified one or more owner types as part of project documentation, and this selection was the basis for owner type classification (Figure 6.2). This stratified random sampling meant that the percentages of projects mentioning each owner type were equal in the population and the sample.

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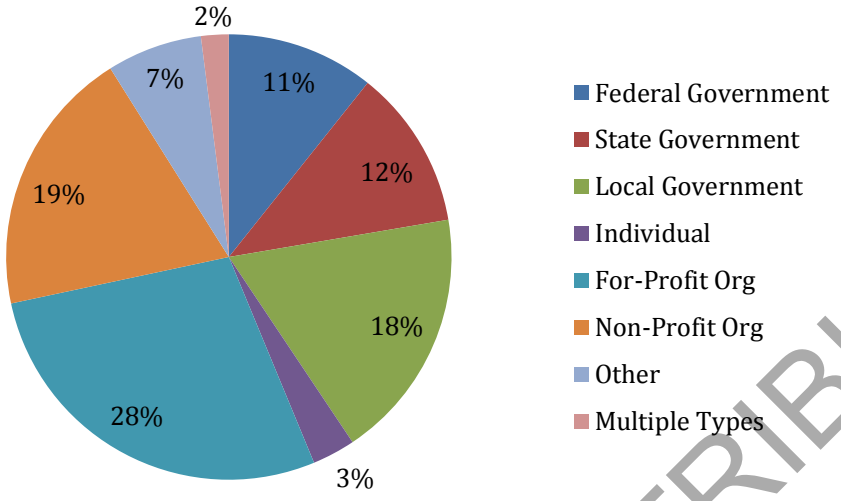

Figure 6.2 Percentages of projects mentioning each owner type

6.3.2 Measures

The data used in this study were drawn from LEED credit submittal forms and from the USGBC list of non-confidential certified projects. LEED credit submittal forms accept input in three different ways: radio buttons, check boxes, and text input fields. Each was treated and displayed differently.

Radio buttons allow a user to select only one of several options. These are presented in this report as pie charts, with data as percentages of projects earning that credit making each selection. This type is used for compliance paths for WEc1 and WEc2.

Check boxes allow a user to select more than one option. Because they are not mutually exclusive, these results are presented as bar charts, with data as percentages of projects with the ability to make a choice selecting each option. This type is used for non-potable water sources in WEc1.

Text field form entry is used to describe and specify flush fixtures and tap fittings in WEc2 and WEc3. Text fields allow manual entry of a description. These are by nature not standardized. The research team generated a list of all unique values, and assigned a standardized value to each. These standardized values are normalized and presented in this report in bar charts, with data as percentages of projects using the flush class of fixtures that used that particular type of fixture, or percentages of tap fittings using a particular flow rate. Projects typically use more than one type of fixture and fitting. For instance, a building might have different types of urinals in different bathrooms. Tap fittings and flush fixtures were categorized by classes and types, as many different brands and flow rates were mentioned. The water closet class included dual flush, high efficiency, compressed air, and composting toilet types. High efficiency toilets are defined as water closets that use a maximum of 1.28 gallons per flush (GPF), which is 20% less water than the current U.S. maximum of 1.6 GPF. Urinal class fixtures were placed in one of two major types: High efficiency and non-water. High efficiency urinals are those that use no more than 0.5 GPF, half of the current U.S. maximum of 1 GPF. Non-water urinals have no flush. Tap fittings include sinks and showers.

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These are categorized by type and flow rate. Flow comparisons for water use reduction towards credit compliance are based on EPAct standards.

6.4 RESULTS

6.4.1 WEc1: Water Efficient Landscaping

This credit covered landscaping water use. 401 out of 448 projects (89.5%) in the sample earned this credit. There were four paths to compliance (Figure 6.3), by some combination of reduced irrigation and non-potable water sources, or by removing permanent irrigation altogether. The most commonly selected option was no permanent irrigation. Reduced irrigation consumption is part of options 1 and 3, and between them the technique almost rivaled the lack of permanent irrigation in popularity.

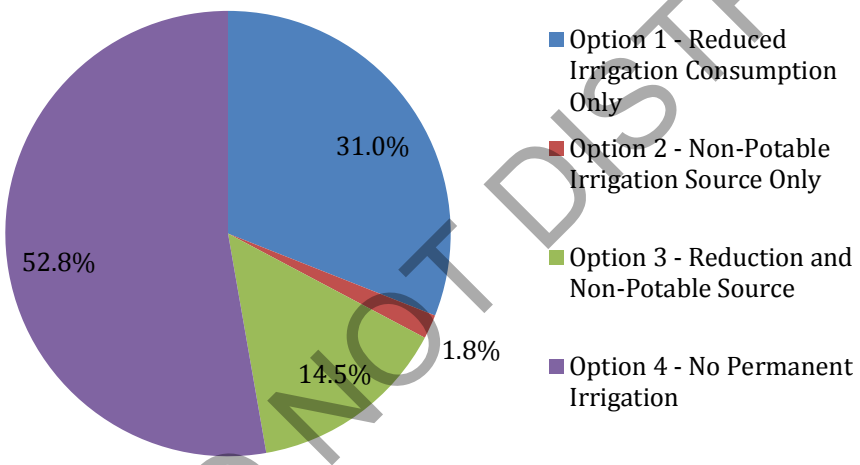

Figure 6.3 WEc1 Compliance path for sample

For those projects selecting option 2 or 3, at least one non-potable water source was listed. Of the 401 projects earning WEc1 in the sample, 65 made this choice. The categories on the forms were rainwater, greywater, wastewater, and publicly supplied non-potable water (reclaimed municipal wastewater that has been treated, but not up to drinking standards), also known as purple pipe. Some projects used more than one source. Rainwater was the most popular choice, followed by public sources (Figure 6.4).

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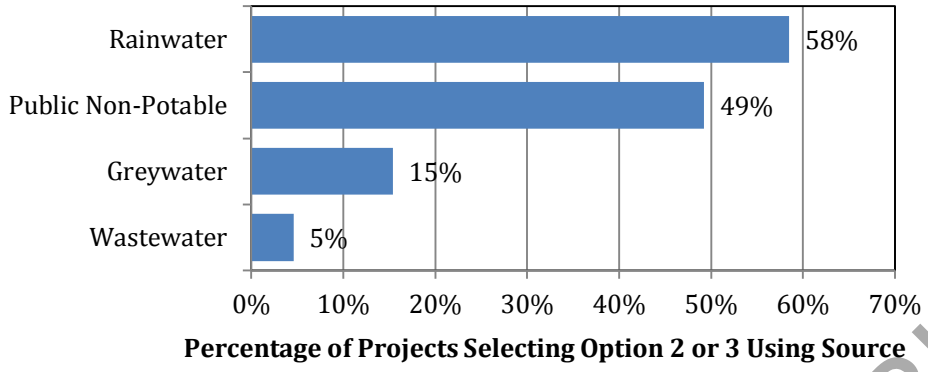

Figure 6.4 WEc1 Non-potable water source for projects selecting option 2 or 3

6.4.2 WEc2: Innovative Wastewater Technologies

This credit addresses generation and treatment of wastewater, and can be achieved either through on-site wastewater treatment or a sewage conveyance water savings of at least 50%, both of which reduce the demand placed on public wastewater treatment facilities by a project. This 50% reduction can be achieved with the use of efficient water closets and urinals. Of the 57 (12.7%) projects in the sample that achieved this credit, most projects selected reduced sewage conveyance based on water savings calculation for their compliance path (Figure 6.5).

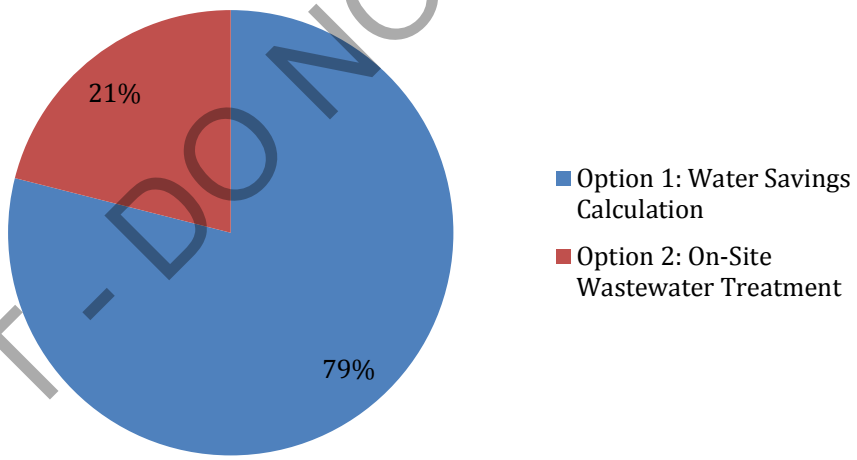

Figure 6.5 WEc2 Compliance path for sample

Although only the projects pursuing the water savings compliance path were required to specify flush fixture types, 54 of 57 (95%) projects achieving the credit provided a description of flush fixtures for the project. Therefore, flush fixtures are given as a percentage of these 54 projects that described flush types (Figure 6.6). Among these, high efficiency toilets and non-water urinals were the most common.

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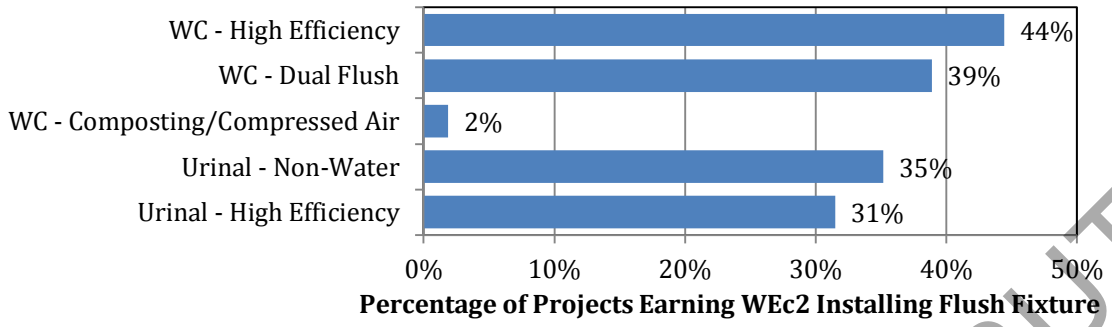

Figure 6.6 WEc2 Flush fixture type usage

6.4.3 WEc3: Water Use Reduction

Water efficiency credit 3 can be earned by reducing water use through efficient tap fittings and flush fixtures to reduce water use in the building by at least 20% for one credit or at least 30% for two credits. These classes are limited to water closets, urinals, lavatory faucets, showers, and kitchen, classroom, lab, or janitor sinks. Projects used some or all of these classes, and some used more than one type within a class. Flush fixture use is given as a percentage of the projects earning WEc3 that used each fixture type for compliance (Figure 6.7). Dual-Flush was the most common type of water closet used, and high efficiency urinals were more commonly used than non-water.

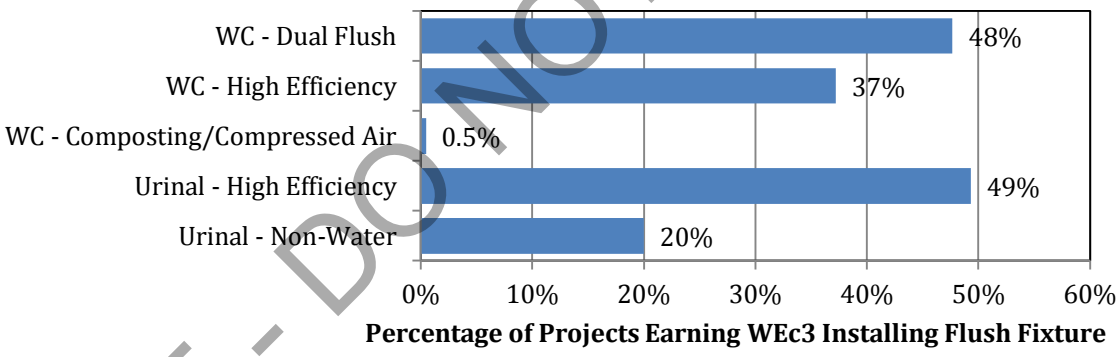

Figure 6.7 WEc3 Flush fixture type usage

Tap fittings described on forms include showers and several classes of sinks. Projects may have multiple taps, so results are presented by type. Use is given as the five most common design flow rates for each fitting type, as a percentage of the type. The average reduction of flow rate from EPAct baseline to design is also given (Table 6.1). The greatest average reduction was in lavatory sinks, at about twice that of the other types.

Tap fitting types were analyzed to find the most common flow rates for each. Projects may have multiple taps, so results are presented by type. Each fitting type had a different distribution of commonly used flow rates (Table 6.2). The most pronounced preference was for 0.5 GPM faucets in lavatory sinks.

Table 6.1

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WEc3 Tap fitting average flow reductions.

Tap Fitting Type	Number of Fittings Examined	Average Percent Flow Reduction
Shower	249	35%
Sink - Lavatory	474	73%
Sink - Kitchen	322	35%
Sink - Janitor	48	34%
Sink - Class/Lab	19	43%

Table 6.2
WEc3 Most utilized flow rates for each tap fitting type.

Tap Fitting Type	Fitting Examined	Most Common Flow Rates (GPM)	Percent of Fittings Using Flow Rate
Shower	249	1.5	43%
		2	15%
		1.8	12%
		1.75	10%
		Other	21%
Sink - Lavatory	474	0.5	78%
		1.5	8%
		1	3%
		2.2	2%
		Other	8%
Sink - Kitchen	322	2.2	32%
		1.5	26%
		0.5	14%
		1.8	8%
		Other	20%
Sink - Janitor	48	2	29%
		2.2	23%
		1.5	17%
		0.5	13%
		Other	19%
Sink - Class/Lab	19	1.5	32%
		0.5	21%
		2.2	16%
		1.6	11%
		Other	21%

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Results were compiled for all sink fittings, and 0.5 GPM faucets were the most commonly used (Figure 5.8).

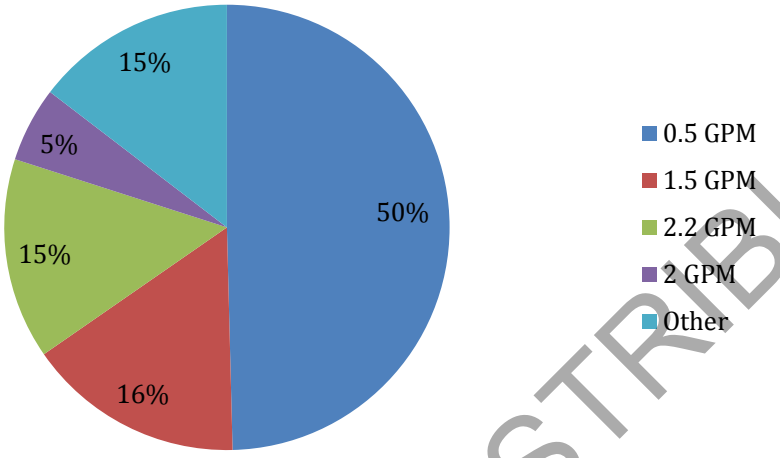

Figure 6.8 WEc3 Most common flow rates for sink fittings

6.5 DISCUSSION

The analysis of WEc1: Water Efficient Landscaping forms showed that non-potable water sources were not used nearly as much as irrigation reduction or elimination. This might be related to the availability of municipal non-potable water, local restrictions on rain or grey water collection, or the simplicity of not having an installed irrigation system. A study of these choices by climate and municipal non-potable availability could be a useful future study. Of the sources mentioned, the heavy skew away from grey and wastewater also bears investigation, perhaps into local ordinance patterns.

With WEc2: Innovative Wastewater Technologies, on site wastewater treatment did not see much use, possibly because the other option of sewage conveyance reduction was partially already covered by flush fixtures used to earn WEc3: Water Use Reduction. This might have provided an easier path to compliance with WEc2 than installing water treatment on-site, as the sewage conveyance reduction was already mostly met for WEc3. There is a difference to be noted between the flush fixture selections, specifically that WEc2, which required a greater wastewater flow reduction, showed majorities for high efficiency water closets and non-water urinals. On the other hand, WEc3, with its lower requirements, tended towards dual-flush water closets and high efficiency urinals. This could indicate that non-water urinals and pure high efficiency water closets are less desirable than the other options when water use restrictions are not as high.

6.6 CONCLUSIONS

While it is true that projects employ many different techniques to earn each water efficiency credit, it is clear from the results of this study that some are much more common than others. WEc1 earners tended towards removing permanent irrigation altogether, and when non-potable

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water sources were used, they preferred rainwater and public non-potable sources. WEc2 earners tended to avoid on-site wastewater treatment in favor of conveyance reduction, and used non-water urinals and high efficiency water closets to that end. WEc3 earners selected high efficiency urinals over non-water urinals, and tended to select dual-flush water closets over high efficiency water closets. Efficient tap fittings were most commonly used in lavatory sinks, and typically used 0.5 GPM faucets.

As the use of water efficiency techniques in the built environment becomes more common, it becomes even more important to study how it is being achieved by projects. By doing so, practices can be analyzed and improved. This report provides a starting point for future research, pointing to the most commonly used techniques on LEED projects. In this way, research can be directed towards the most useful questions first. Why is rainwater the preferred non-potable water source? What makes projects select dual flush toilets over low-flow? Why are waterless urinals less used than low-flow? Answering these questions could make it easier for future builders to make selections of their own, and for more projects to include water efficient features.

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CHAPTER 7: CLIMATE FACTORS

7.1 ABSTRACT

The variation of water efficiency measures in green buildings as a function of climate regions was quantified using project certification documents from the Leadership in Energy and Environmental Design (LEED) for New Construction v2.2 system. These documents included design decisions about landscape irrigation and toilet selections. The distributions of decisions were compared across two climate region classification systems: those used by the National Oceanic and Atmospheric Administration (NOAA) and the US Department of Energy's Energy Efficiency and Renewable Energy (EERE) office. Significant differences were demonstrated in several decisions, including landscape irrigation water reduction choices, which varied in both systems. Water closet choices showed some difference, with dual flush toilets being selected significantly more in the EERE Marine and NOAA Northwest region. High efficiency toilets were selected significantly less in the EERE Marine and NOAA Northwest regions than at least one other region. High efficiency urinals showed differences in only one climate classification system, being selected significantly more in the EERE Marine region than in the Hot-Dry and Mixed-Humid regions. Non-water urinals showed no significant differences.

7.2 INTRODUCTION

Water use in buildings accounts for about 11% of fresh water withdrawals in the US (Barber 2009). Utility scale water extraction, treatment, and distribution are all major operations with significant environmental and public health impacts. To make the most of scarce water resources, a number of strategies have been employed over the years in the building industry.

The Energy Policy Act of 1992 (EPAct) took a step towards reducing the impacts of building water use by imposing federal flow restrictions on new bathroom fixtures. Since then, many technological advances have been made which can further reduce water impacts while delivering the same level of service expected by building occupants.

More recently, policy and habits in environmentally conscious construction and maintenance have been influenced by green building rating and certification systems, such as the US Green Building Council's (USGBC's) Leadership in Energy and Environmental Design (LEED) program. The LEED certification system has been adopted by some of the largest agencies in the US Federal Government, including the General Services Administration (US General Services Administration, 2013), and is by far the most used building certification system that includes water issues in the US with over 25,000 certified projects (US Green Building Council, 2014). LEED promotes water efficiency by giving projects credits toward certification through several avenues, including efficient toilets, sinks, and landscape irrigation strategies.

There are a number of rating systems within LEED, designed to cover different types of construction, renovations, or operations. This paper focused on the version designed for new construction. In order to achieve LEED certification, projects earn credits for including sustainable features and practices in their designs. To earn these credits, they must submit documentation describing design details related to whichever credits are being sought.

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The first few iterations of LEED were meant to be broadly applicable to encourage participation, and as such did not have any region or climate specific guidelines. They did, however, allow participants freedom in selection of options for reduction of water use. Water issues vary markedly by region in the U.S., with very high stress in deserts and little stress in less populated and high rainfall regions. Projects therefore had the ability to be climate specific in their selections, but had no explicit incentive or suggestion in the certification system to do so. Starting in LEED version 3, regional priority credits were included to promote this behavior, and water use reduction became mandatory.

The USGBC has published information about trends in LEED participation in its Green Building Information Gateway (GBIG) project (US Green Building Council, 2013)as well as a number of details about the size, location, and function of individual projects. GBIG provides a credit-level resolution, showing what goals have been achieved by projects. However, for confidentiality reasons, it is not able to provide details about how credits are earned, i.e., with which specific technologies or practices conservation is achieved. For this investigation, the USGBC provided data that are not part of the GBIG. This was possible because the results are presented in aggregate. Before this investigation, the only precedent for analysis of USGBC data at this resolution was a report relating green building design goals and energy performance to technology selection (Brennan, 2012).

Prior to this investigation, no studies had been done on LEED water efficiency credits at a resolution that showed what technologies were employed to earn them. The first stage of this investigation was a study published as a report on the USGBC website that described design choices made by projects to earn water efficiency credits (Chambers et al., 2013). The project data from that study were used to perform the study presented in this paper. The goal of this research was to identify the differences in the types of technologies (in the case of toilets and urinals) and strategies (in the case of landscape irrigation) used to achieve LEED water efficiency credits across different climate regions in the continental United States.

7.2.1 Research Scope

The researchers selected LEED NC v2.2 for study because it had the largest number of projects and date range at the time of sample selection, and because the data format and content of project documentation for this version was most suitable for the type of analysis sought. This study examined certification documents for Water Efficiency credits 1 and 3 from this version of LEED. These certification documents describe how projects intend to comply with LEED requirements. The first credit examined was WEc1: Water Efficient Landscaping. It requires projects to reduce the use of potable water in landscaping, either by reducing the need for water or by using non-potable sources. This study compared the four basic options for compliance: reduced irrigation consumption only, non-potable irrigation source only, reduction and non-potable source, and no permanent irrigation. The other credit examined was WEc3: Water Use Reduction. It requires projects to reduce the use of water within the building through efficient plumbing fixtures and fittings within structures. This study compares the use of the most common categories of toilets in LEED NC v2.2 buildings: high-efficiency and dual flush water closets, and high efficiency and non-water urinals (Chambers, 2013). High-efficiency is defined for water closets as 1.28 gallons per flush or less and 0.5 gallons per flush or less for urinals. WEc2: Innovative Wastewater Technologies was omitted from this study because of the relatively low number of projects earning

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it (13% of the sample), and because the most common means of compliance is the use of efficient toilets, which overlaps with WEc3.

Within the framework of these data, the question became: For projects achieving LEED NCv2.2, how did landscape irrigation choices used to earn WEc1 and flush fixture choices used to earn WEc3 vary by climate region?

7.3 RESEARCH METHODOLOGY

Water use reduction choices for a sample of LEED certified projects earning water efficiency credits under LEED for New Construction v2.2 were analyzed for differences using two climate classification schemes. LEED credit application forms were provided by USGBC. Researchers cleaned and compiled choices on these forms indicating irrigation schemes and toilet and urinal types. Contingency and pairwise statistical tests were used to find significant differences in choices on the forms between climate regions.

7.3.1 Sample Selection

Green buildings were defined as structures intended to be environmentally responsible. There are multiple sets of guidelines and certification programs used to help designers achieve this goal, but not all projects are actually registered with the programs. As such, it is difficult to determine how many such buildings exist. The USGBC was selected as a large source of project information, with over 12,000 projects certified at the time of sample selection. Within the USGBC's LEED program, one specific rating scheme was selected for comparison, LEED for New Construction v2.2. This version was chosen because of the number of projects earning it and because its certification data formatting was in an easier form than the other versions offered. The USGBC provided a list of all non-confidential projects earning Water Efficiency (WE) credits 1 and 3 under LEED NC v2.2 in the continental United States.

Certification data were provided by USGBC using a stratified random sampling approach, wherein the sample has a distribution of a characteristic that is similar to that of the population. Sampling was stratified based on owner type for projects. This was done to evenly represent the different decision making strategies in different types of organizations. The opportunity to stratify by location was not available. The result was a sample of 448 projects earning at least one of WE credits 1 and 3, including 391 WEc1 projects and 422 WEc3 projects. The USGBC provided completed certification forms for these credits from these projects, which contained the information used in this study.

Due to confidentiality requirements, nothing that might be used to identify specific projects used in the study can be disclosed. Therefore, only very low resolution information about project locations (i.e., their climate region) is included in this paper.

7.3.2 Water Efficiency Choices

Within WEc1, the certification documents covered potable water use in landscaping. This was shown through the ability to select one of four options:

- A: Reduced Irrigation Consumption Only

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- B: Non-Potable Irrigation Source Only
- C: Reduced Irrigation and Non-Potable Irrigation Source
- D: No Permanent Irrigation

Credit documentation forms also offered some additional details describing water quantities and non-potable sources, depending on the design team's selections. These details were given as annual volumes of water use and check boxes for a list of different non-potable sources. The design team's choice of option was the best indicator of landscape irrigation water efficiency techniques employed in the project, and the only characteristic given for all projects, so it was selected as the WEc1 data field to analyze.

To earn WEc3, projects were asked to describe a number of details about fittings and fixtures. These included product types, makes, models, and flow rates, as well as information about intended user types and genders. The ubiquitous use of toilets and urinals to earn this credit, the common classification of each in two main categories, and the nature of the data led to their selection as the characteristics from WEc3 to analyze. The toilet types examined were dual flush toilets and high efficiency toilets, while the urinal types selected were high efficiency urinals and non-water urinals.

It should be noted that due to the nature of this version of LEED, these data represent design intent only. As-built data were not available, as their collection was not a part of the certification process for LEED NCv2.2.

7.3.3 Climate Regions

Two separate climate classification systems were examined to relate LEED water saving features to climate, including a system used by the National Oceanic and Atmospheric Administration (NOAA) (Figure 7.1a) and a system used by the US Department of Energy's Energy Efficiency and Renewable Energy (EERE) office for their Building Technologies program (Figure 7.1b). The NOAA system is based on research done by the National Climatic Data Center (Karl and Koss 1984), and consists of nine groups of states. The EERE system is based on heating degree days, average temperatures, and precipitation (US Department of Energy, 2010). It divides the continental United States into five regions and two sub-regions, with boundaries following county lines.

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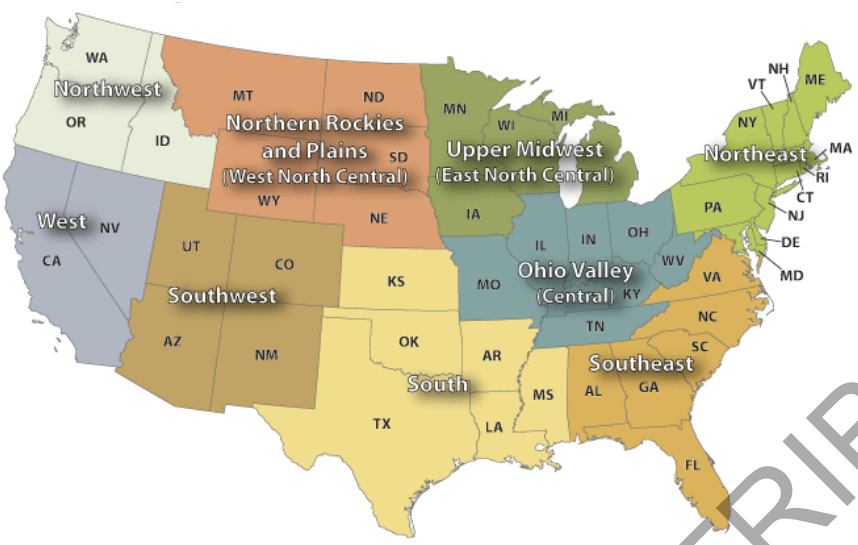

Figure 7.1a NOAA Climate Regions (National Oceanic and Atmospheric Administration, 2013)

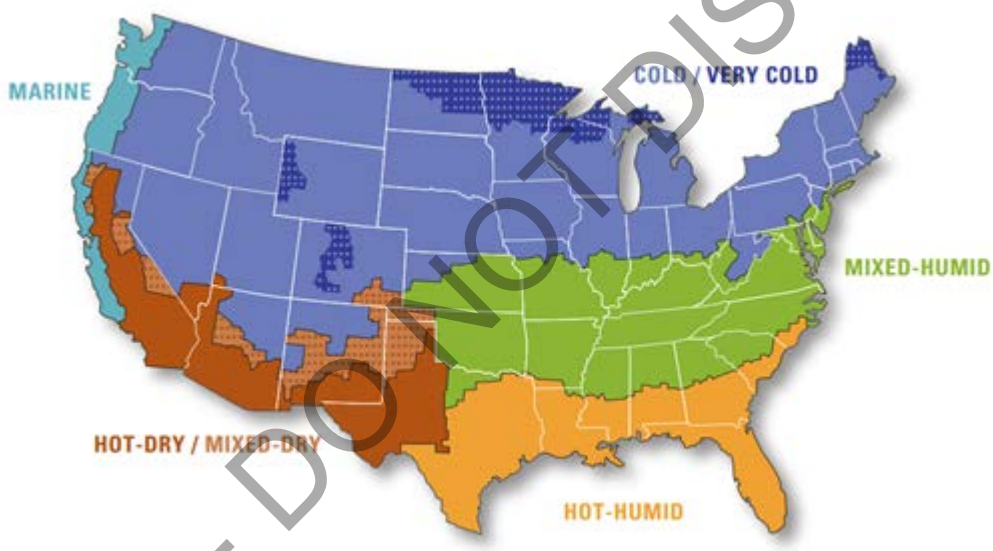

Figure 7.1b EERE Climate Regions (U.S. Department of Energy, 2010)

7.3.4 Data Analysis

To verify sample representativeness, credits earned and owner types were analyzed. The percentages of projects earning each WE credit were approximately equal in the population and the sample. The stratified random sampling by owner type was verified with the percentages of projects mentioning each owner type being equal in the population and the sample.

The data source was forms filled out by project representatives. These documents only indicate design choices, and so represent the intentions that are the focus of this study. The design of the forms allowed for the flexibility in compliance that the USGBC intended, by giving text boxes for the representative to fill out describing the technologies used. As a consequence of this

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flexibility, there was significant variability in how technologies used to achieve compliance with WEc3 were described on the forms. Information about such things as type, make, model, and flow rate had spaces for input, but these spaces were not always used. For example, one form might have been filled out with "High Efficiency Toilet, [Brand], [Model], 1.28 GPF" while another might just have said "Dual Flush".

Where possible, toilet makes and models as described were used as the defining characteristic for these fixtures, and fixture types and flush rates entered on the forms were standardized, verified, and updated as necessary to achieve consistency with product specifications for the models on the forms. When no make or model was provided, provided fixture types and flow rates were taken as correct. WEc1 did not have this problem for the characteristic examined, as it allowed projects to select one of four mutually exclusive options on the form indicating a reduction in potable water use, a non-potable water source, a combination of the two, or no permanent irrigation whatsoever.

In order to assign climate regions, project presence in each had to be determined. Locations in the USGBC project database are entered by project representatives. They provide cities and states for each project. The cities were given county designations by geographical locations using ArcGIS, and these counties along with state designations were used to assign climate regions from NOAA and EERE classification systems.

Contingency analysis was performed on the data, to determine whether differences existed in distributions for each characteristic across climate regions under each system. Where significant differences were found, Tukey pairwise comparison was performed for that characteristic and climate classification system to determine which regions differed from each other under a rigorous test. This test identified groups of regions that were not statistically different from each other, and assigned regions to all groups that they fit into. For all tests, an alpha of 0.05 was used for a confidence of 95%.

7.4 RESULTS

The tests of characteristic variations within each climate region classification system indicated that significant differences likely existed for all but two cases (Table 7.1), non-water urinals in the EERE system and high efficiency urinals in the NOAA system. Details for each characteristic examined are presented below. Tukey's pairwise analysis was performed for a rigorous test of characteristic-region combinations. These tests show which regions differ from each other for each characteristic.

Table 7.1
Results of statistical analysis of differences within each climate region classification system

Characteristic	EERE		NOAA	
	Result	**P-Value**	**Result**	**P-Value**
WEc1				
Option	Difference	<0.0001	Difference	<0.0001
WEc3				
Urinal - High Efficiency	Difference	0.0473	No Difference	0.3582
Urinal - Non Water	No Difference	0.2612	Difference	0.0413
WC - Dual Flush	Difference	0.0005	Difference	<0.0001

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WC - High Efficiency	Difference	0.0379	Difference	0.0031

Figures 7.2-7.6 are mosaic plots. In these plots, the X-axis shows the proportion of the total sample in each climate region. The width of each bar, therefore, represents how much of the total sample was in that region. The Y-axis shows the percentage of projects in that particular region that selected the toilet, urinal, or irrigation type presented in that plot. These mosaic plots allow for visual examination of the data. Where one bar is much taller or shorter than the others, there are often, but not always, statistically significant differences. The statistical methods used identified these statistically significant differences where they existed.

7.4.1 WEc1: Option for Water Efficient Landscaping

The analysis showed that option selection differences between climate regions in both classification systems were statistically significant (Table 7.1). Mosaic plots (Figure 7.2 a, b) were generated to illustrate this graphically. Pairwise analysis (Table 7.2 a, b), which compares two regions to each other at a time, proves this with most comparisons showing a p-value below 0.05, indicating a greater than 95% confidence in the result. Differences were shown to exist between all EERE regions, and most NOAA regions.

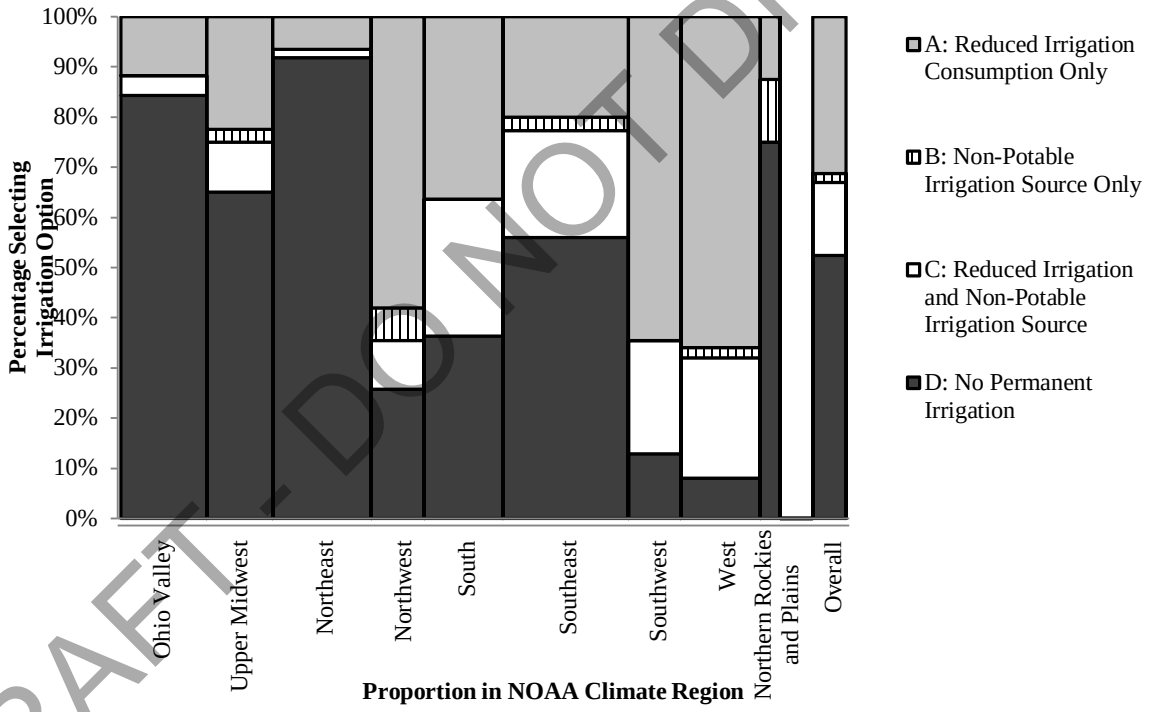

Figure 7.2a NOAA Irrigation Option Mosaic Plot

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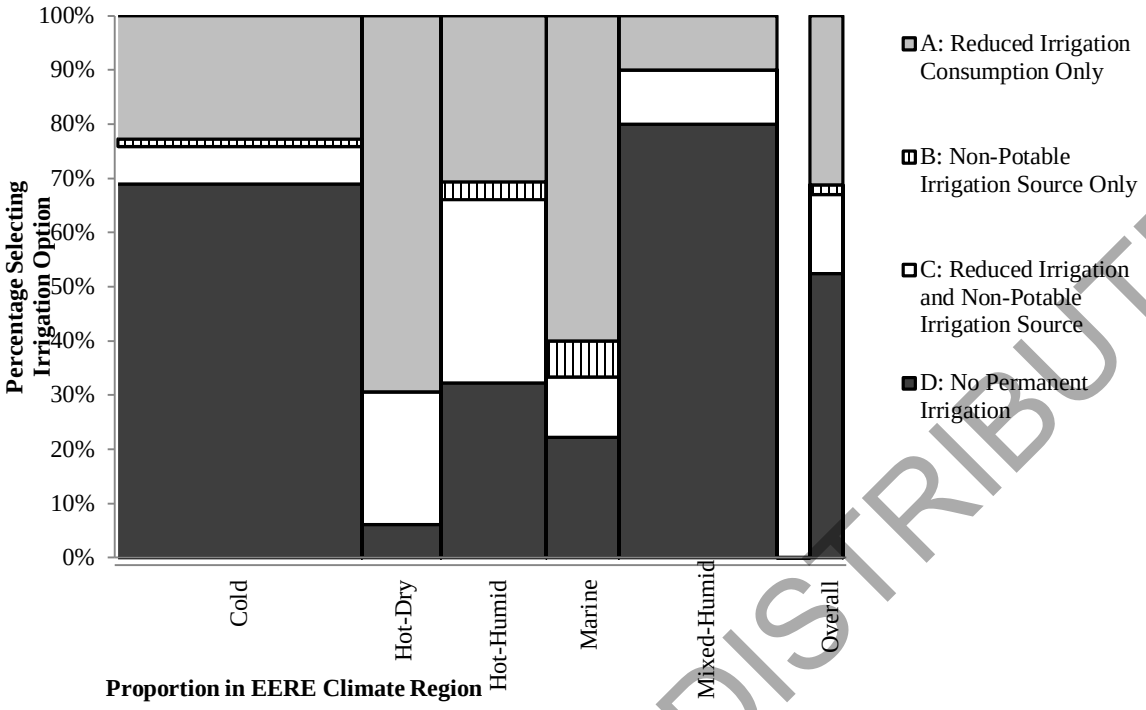

Figure 7.2b EERE Irrigation Option Mosaic Plot

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Table 7.2a
NOAA Irrigation Option comparison p-values

	East North Central	Northeast	Northwest	South	Southeast	Southwest	West	West North Central
Central	0.1346	0.4583	<0.0001	<0.0001	0.0022	<0.0001	<0.0001	0.1988
East North Central		0.0070	0.0060	0.0206	0.4676	<0.0001	<0.0001	0.3773
Northeast			<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.1660
Northwest				0.0277	0.0009	0.1175	0.0586	0.0320
South					0.0632	0.0270	0.0021	0.0104
Southeast						<0.0001	<0.0001	0.1602
Southwest							0.6961	0.0004
West								<0.0001
Key:	>99.99% Confidence	>95% Confidence						

Table 7.2b
EERE Irrigation Option comparison p-values

	Hot-Dry	Hot-Humid	Marine	Mixed-Humid
Cold	<0.0001	<0.0001	<0.0001	0.0294
Hot-Dry		<0.0001	0.0362	<0.0001
Hot-Humid			0.0049	<0.0001
Marine				<0.0001
Key:	>99.99% Confidence	>95% Confidence		

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7.4.2 WEc3 Characteristics

Some differences in WEc3 existed between regions in both climate systems (Table 7.3), but these were not as pronounced as within WEc1. Within the NOAA system, only the water closets showed some inter-regional differences. The Northwest region showed this the most, differentiating itself from all but the Northeast and Southwest regions with dual flush water closets. The Northwest also differed to a lesser extent with high efficiency water closets, showing differences only with the Southeast and West North Central regions. Within the EERE system, more differentiation was shown. The Marine region differed from all others with dual flush water closets. With high efficiency water closets, the Marine and Hot-Humid regions differed only from each other. This system, unlike the other, showed some difference in high efficiency urinals, with the Hot-Dry region differing from the Mixed-Humid and Marine regions.

Table 7.3a
Summary of groupings from pairwise analysis in NOAA regions

Feature Selection	**Statistically Significant NOAA Region Differences**		
	Selected Feature	**More Than**	**Selected Feature**
Toilet - Dual Flush	Northwest	>	Ohio Valley
		>	Upper Midwest
		>	South
		>	Southeast
		>	West
		>	Northern Rockies & Plains
Toilet - High Efficiency	Southeast	>	Northwest
	Northern Rockies & Plains	>	Northwest
Urinal - Non Water	(None)		
Urinal - High Efficiency	(None)		

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Table 7.3b
Summary of groupings from pairwise analysis in NOAA regions

Feature Selection	Statistically Significant EERE Region Differences		
	Selected Feature	**More Than**	**Selected Feature**
Toilet - Dual Flush	Marine	> > > >	Cold Hot-Dry Hot-Humid Mixed-Humid
Toilet - High Efficiency	Hot-Humid	>	Marine
Urinal - Non Water	(None)		
Urinal - High Efficiency	Hot-Dry	>> >	Marine Mixed-Humid

7.4.3 WEc3: Water Closet – Dual Flush

Contingency analysis (Table 7.1) showed that dual flush water closet use differs between NOAA climate regions, as well as between EERE climate regions. Mosaic plots (Figure 7.3 a, b) present this visually. Pairwise analysis identified differences. For the NOAA system, the Northwest region had the highest inclusion rate, and showed statistically significant difference from all but the Northeast and Southwest regions (Table 7.3). Other differences existed, such as the low selection rate in the West North Central region, but these were not statistically significant. For the EERE system, the Marine region was shown to differ from the rest, using dual flush water closets more than the other regions (Table 7.3).

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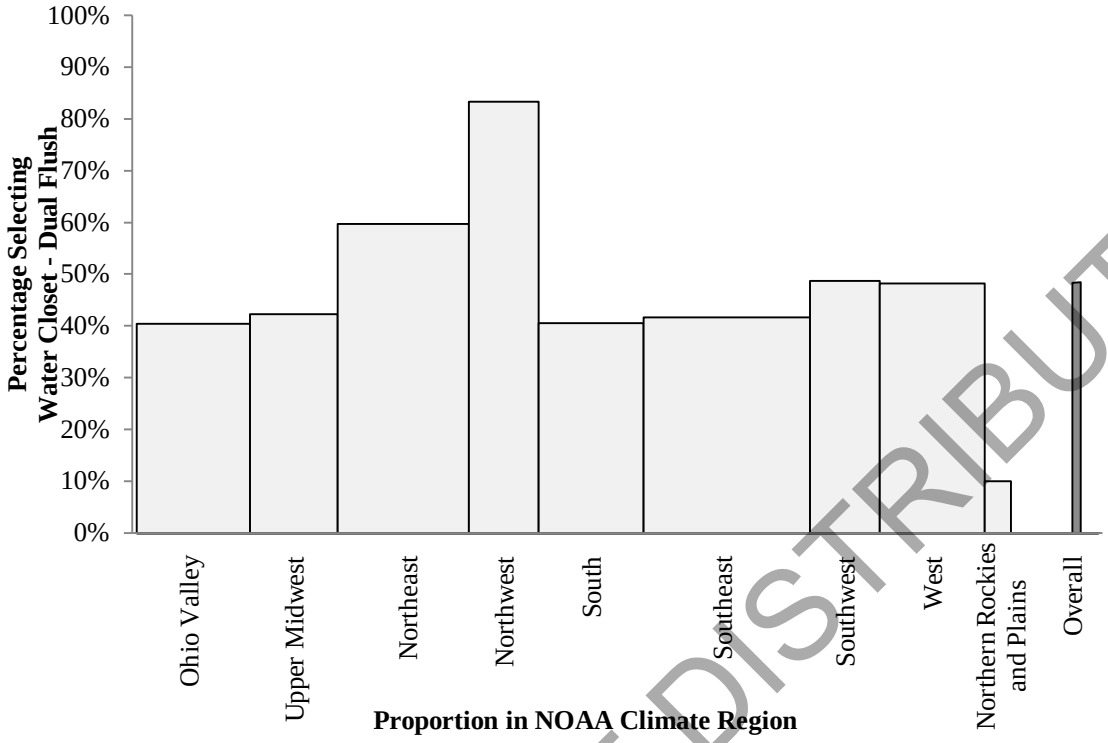

Figure 7.3a NOAA Dual Flush Water Closet use

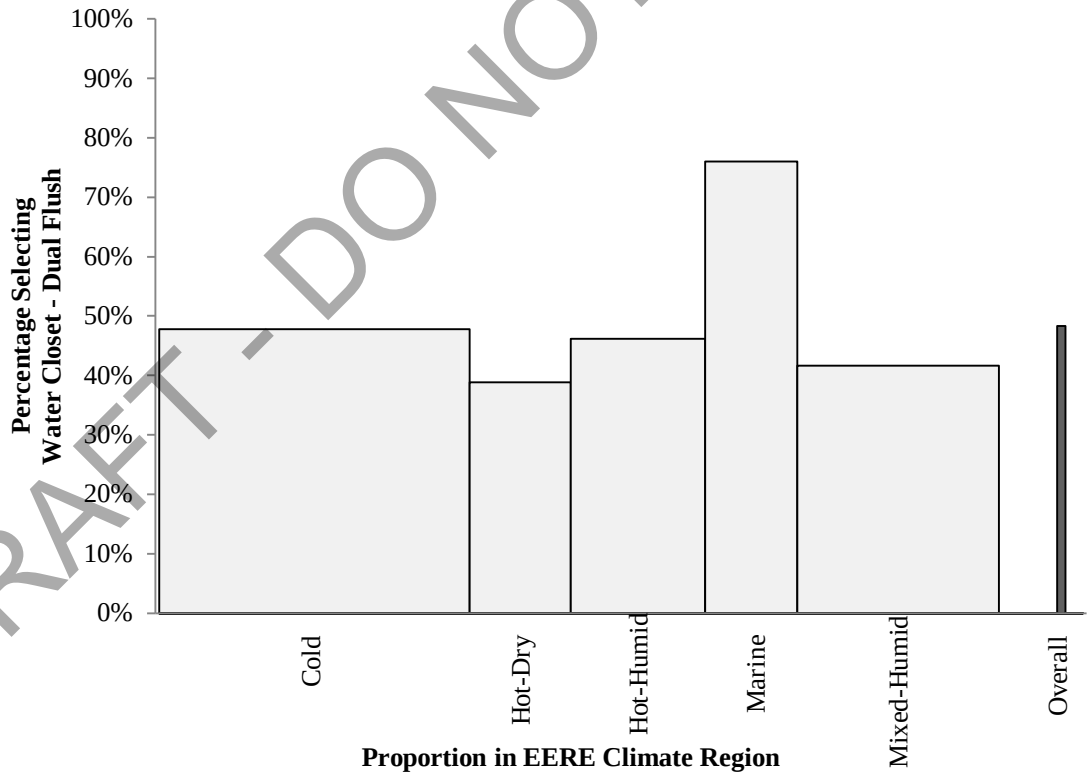

Figure 7.3b EERE Dual Flush Water Closet use

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7.4.4 WEc3: Water Closet – High Efficiency

Contingency analysis (Table 7.1) showed that high efficiency water closet use differs between NOAA climate regions, as well as between EERE climate regions. Mosaic plots (Figure 7.4 a, b) represent this visually. Pairwise analysis identified the differences. For the NOAA system, the Northwest region selected these features significantly less than the Southeast and West North Central regions, but did not differ in a statistically significant degree from the other regions (Table 7.3). The EERE system showed differences between the Hot-Humid region's high selection rate and Marine region's low selection rate.

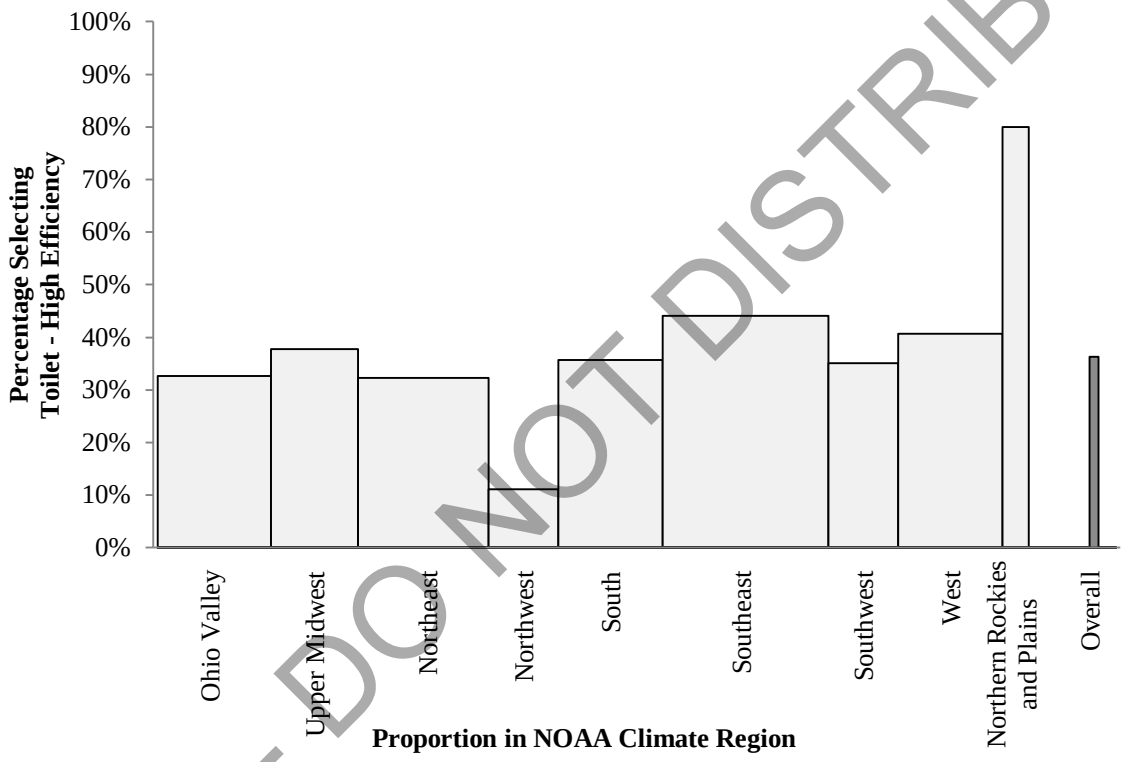

Figure 7.4a NOAA High Efficiency Water Closet use.

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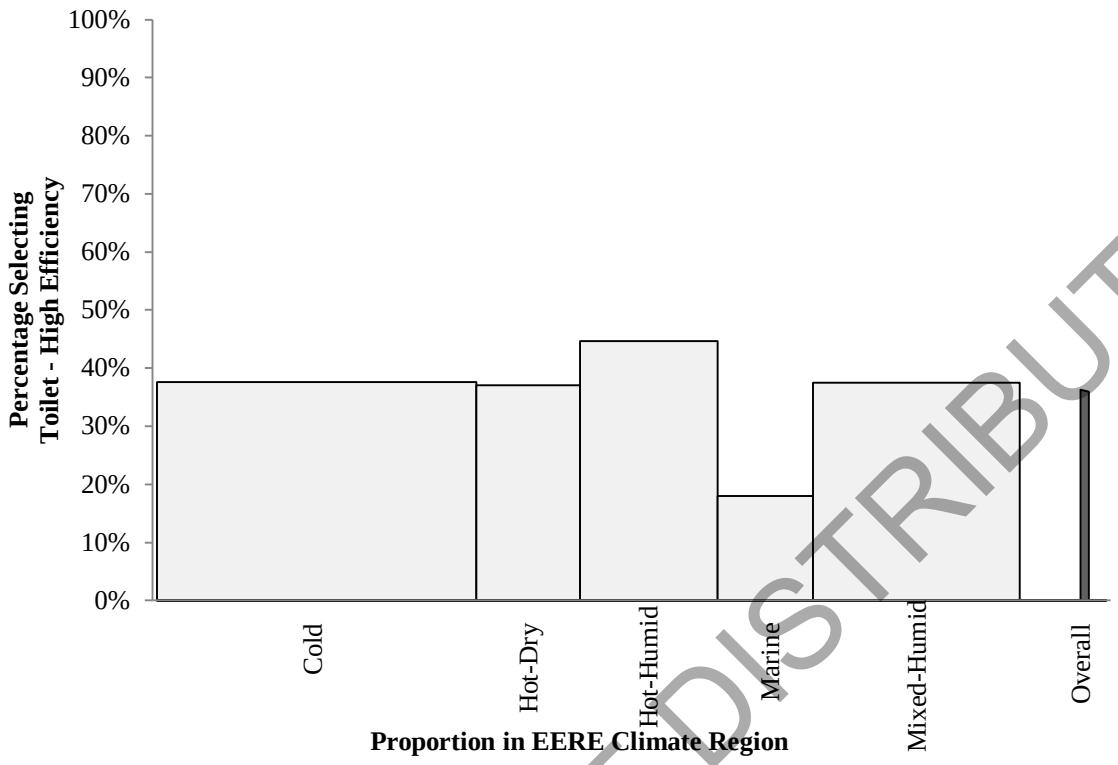

Figure 7.4b EERE High Efficiency Water Closet use.

7.4.5 WEc3: Urinal – High Efficiency

Contingency analysis (Table 7.1) showed that high efficiency water closet use differs between EERE climate regions but not NOAA regions. Mosaic plots (Figure 7.5 a, b) represent this visually. Pairwise analysis identified the differences in the EERE system (Table 7.3) but found none in the NOAA system. The Mixed-Humid and Marine regions showed statistically significant difference from the Hot-Dry region.

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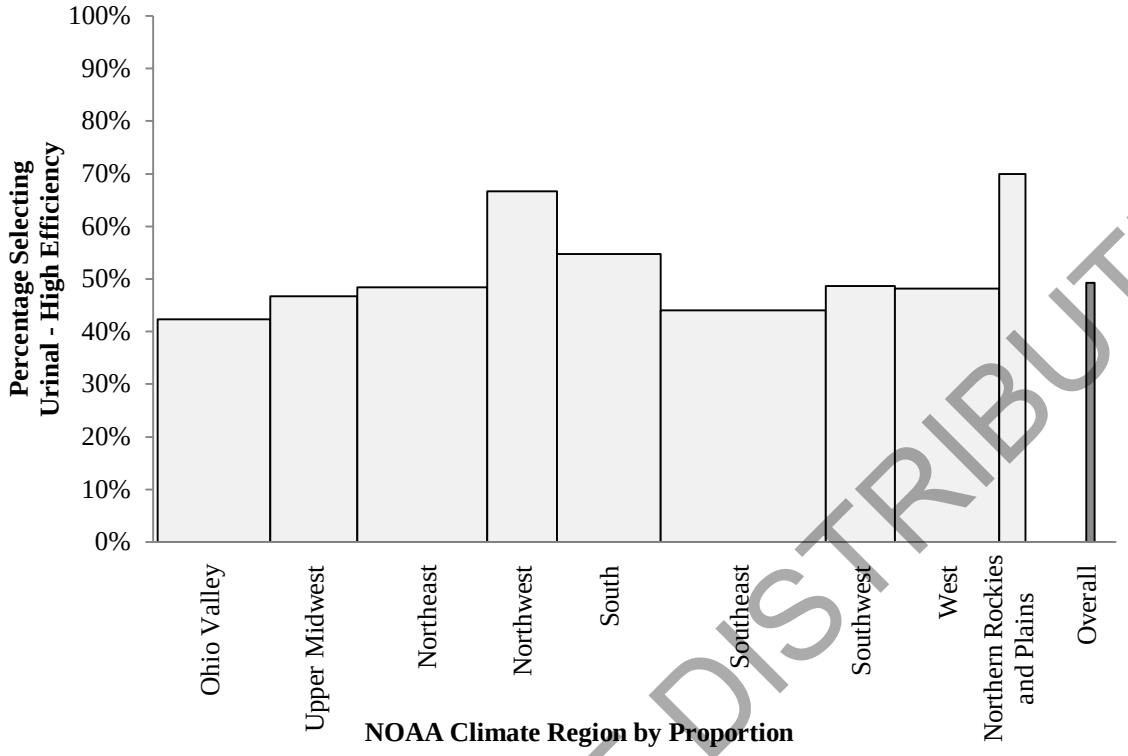

Figure 7.5a NOAA High Efficiency Urinal use

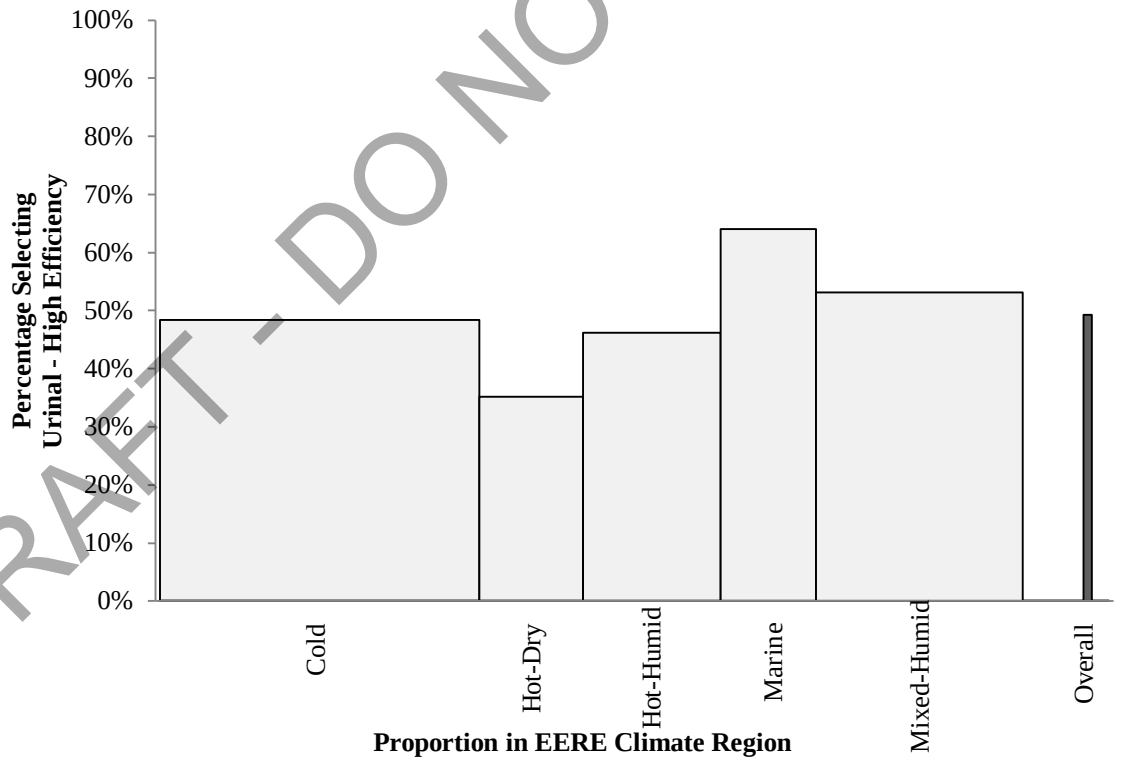

Figure 7.5b EERE High Efficiency Urinal use.

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7.4.6 WEc3: Urinal – Non Water

Contingency analysis (Table 7.1) suggested that high efficiency water closet use differs between NOAA climate regions but not EERE regions. Mosaic plots (Figure 7.6 a, b) represent this visually. The more conservative pairwise analysis (Table 7.3) did not identify differences, indicating that this conclusion about differences in NOAA regions is not strong enough to call significant under a rigorous test. The lack of significant difference in EERE regions is repeated under the pairwise test.

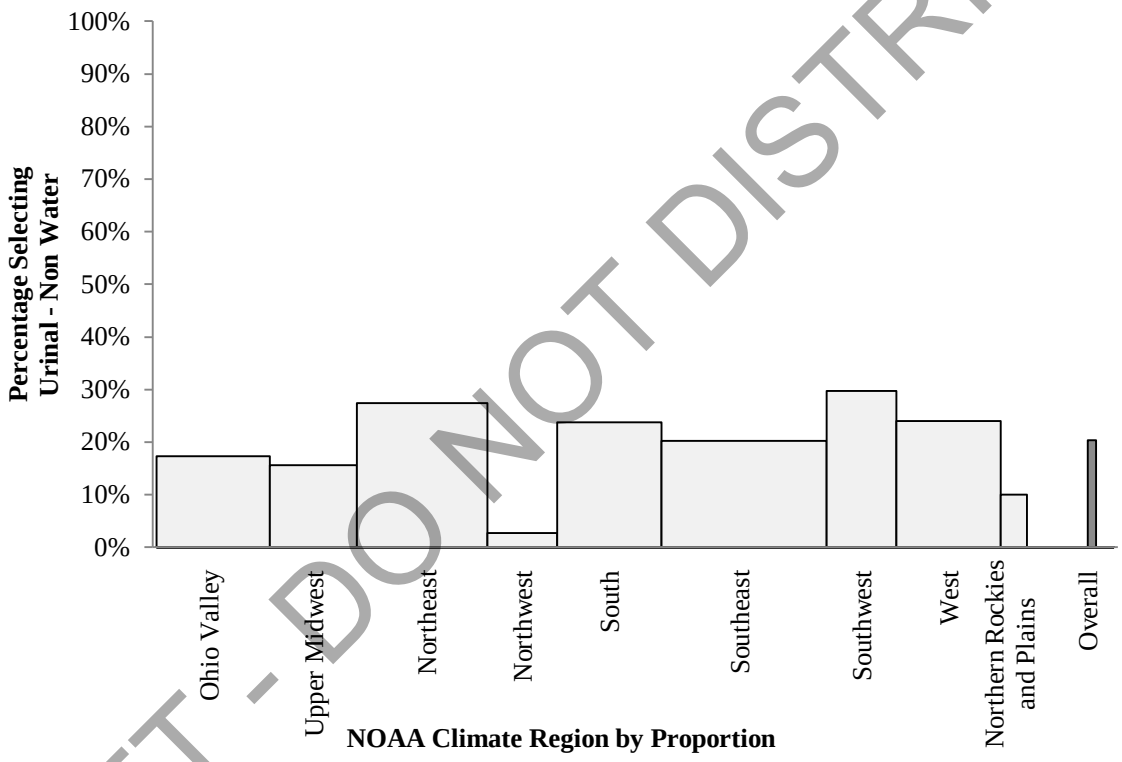

Figure 7.6a NOAA Non Water Urinal use.

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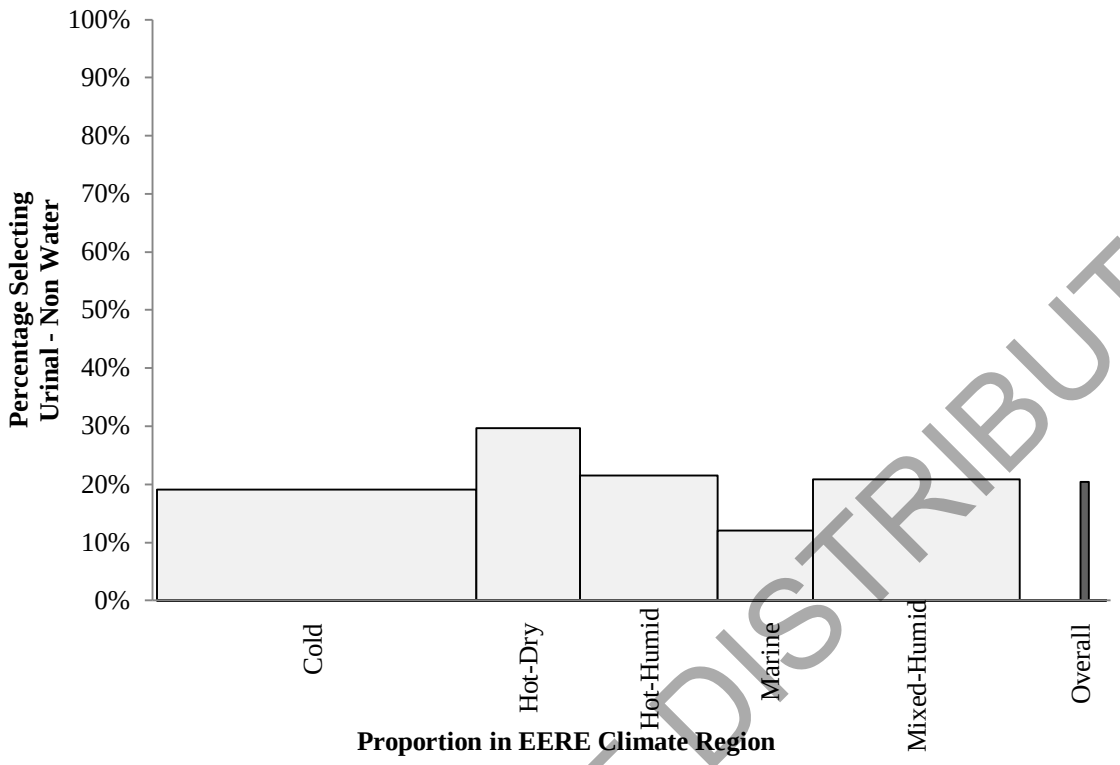

Figure 7.6b EERE Non Water Urinal use.

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7.5 CONCLUSIONS

These results support the hypothesis that landscape water use design decisions for LEED NC v2.2 projects vary between climate regions. This may have to do with practices already in place in those regions, or because the impact of regional rain water availability is most visible outside in the landscaping.

While irrigation selections showed differences between most regions under both climate systems, it should be noted that the choice of no permanent irrigation was least used in the Hot-Dry EERE region and three western NOAA regions. This may be related to societal expectations for landscaping that require more water than is naturally available in that region, or it may be because of the availability of rain reducing the need for these features in other regions.

Toilet and urinal type selections showed differences between fewer regions than did irrigation selections, and in fact were not significant in non-water urinals. The higher selection rates of dual flush water closets and lower selection rates of high efficiency water closets in the NOAA Northwest and EERE Marine environments suggests that in these water rich regions, there is a preference for dual flush toilets. With non-water urinals, the name clearly indicates lower water usage, so one might expect them to be significantly more popular in water-sensitive regions. The distribution graphs indicate that they are included in designs in the hot-dry climate region more often than other EERE regions, but the difference is not statistically significant.

These results indicate that while some LEED v2.2 water efficiency design decisions were different between climate regions, there was still room for further climate specificity. The inclusion of climate specific guidelines within the newer green building rating systems could make climate specificity more prevalent in green building water efficiency strategies, especially with regard to plumbing fixtures.

7.6 FUTURE RESEARCH

This research demonstrated that differences existed in some water efficiency design choices, but the data examined did not include any information about why these design choices were made. Future research is needed to identify these reasons. Some possible influences to investigate are the input of various stakeholders in the design process, local and regional water efficiency legislation, and local water sensitivity related to non-climate factors such as demand.

Another limitation of this study was that no comparison was made with projects where regional climate needs were mentioned in the rating system. As climate specificity is implemented in green building guidelines and certification programs, it would be interesting to learn whether projects are actually making a point of selecting water efficiency measures appropriate for the climate and the region's water resource sensitivity.

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CHAPTER 8: GREEN BUILDING SURVEY

8.1 ABSTRACT

An internet survey was developed to synthesize experiences of green building professionals with water conservation related innovations. The survey was distributed by the US Green Building Council and other venues, including LinkedIn and several mailing lists. Participants rated their experiences with 33 types of innovations, and indicated problems they had experienced. Participants were also asked to check off experiences from a short list of common issues. The most common problems were due to pipe leaks and clogs, insufficient hot water, premature system failure, and complaints about taste, odor, or coloration. A majority of respondent ratings were not negative (i.e., positive or neutral). Green landscaping innovations were overwhelmingly positive in all categories. Non-water urinals and toilets had the most negative response distributions, followed by blackwater and greywater recovery systems. Payback expectations were different from outcomes in both positive and negative directions for many of the innovations examined.

8.2 INTRODUCTION

Many green buildings utilize innovations that reduce dependency on external resources by reducing the use of potable water or limit the production of wastewater. Multiple environmental, ethical, and financial factors are involved in implementation of such systems, but an important incentive is criteria for green building certifications such as the US Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED) program, which has certified over ten thousand projects in the United States (US Green Building Council, 2013).

The paths to compliance in contemporary green building rating systems typically allow for a wide range of techniques and technologies to be employed in a project. Because the requirements for water use in these green buildings are different from traditional buildings, the water solutions used may of necessity be atypical or new innovations.

The reactions of early adopters to these innovations can greatly influence public opinion and future adoption of the innovations (Rogers, 2003). Anecdotal evidence exists to support the conclusion that some systems are creating negative experiences. These include pipe corrosion and bad smells associated with non-water urinals (Guevarra, 2010; Shapiro, 2010), increased water usage from long showers (Walker, 2009), and site inappropriate system installation (Bray and McCurry, 2006). Some technologies have been studied systematically, especially with regard to opportunistic pathogens in water heater systems (Bagh et al., 2004; Brazeau and Edwards, 2012; Codony et al., 2002; Mathys et al., 2008). However, a review of the literature yields no comprehensive study of water systems in green buildings or any scholarly synthesis of water system experiences and satisfaction.

This research addressed this issue by collecting green building professionals' perceptions of innovations related to water conservation in buildings through an internet survey. Participation was open to any green building professional that had experience with water conservation related systems. The USGBC's network of these professionals was initially utilized, and several other professional and government organizations were added to increase participation.

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Innovations considered included anything intended to assist in water conservation in green buildings. A comprehensive list of innovation types was created by the researchers, in order to help participants describe their experiences. The survey identified which of these innovation types were generating positive and negative experiences, as well as the most common problems.

8.3 RESEARCH METHODOLOGY

An internet survey queried adopters about known problems, gave participants the opportunity to rate their satisfaction with various systems, and allowed them to describe these experiences.

8.3.1 Distribution

The survey was initially distributed by the US Green Building Council (USGBC) through several of their internet-based social networking tools (USGBC Yammer, USGBC Chapter Newsletters, USGBC Education Portal, USGBC National Newsletter), as well as through their contact for an official post at LEEDUser.com. To gather additional responses, several contacts were used to distribute the survey to a list of federal facility managers through the US General Services Administration, the US Department of Energy, and the US Interagency Sustainability Working Group. Distribution was also made through the Society of Building Science Educators listserv, the Water Research Foundation mailing list, the Green Building Alliance newsletter, and direct email to a list of members of the Associated General Contractors (AGC). Several postings were also made to LinkedIn on various green building boards. It is impossible to know how many individuals saw or received the invitation, as membership in most of these mailing lists is confidential, as is the number of reads the pages receive. What is known is that the AGC mailing list used was 4008 members strong, and that the USBGC and LinkedIn forums are active. The survey link was opened by 166 distinct IP addresses.

8.3.2 Survey Content

Because of the length and breadth of the survey, respondents were first taken to a 'short' overview page, where they were asked whether they had experienced any of the problems that researchers suspected might be most common. These known problems were based on the literature and the experiences of the researchers. Nine general issues were described (Table 8.1).

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Table 8.1
Known problems asked about on survey

One or more water-related systems have had to be replaced before the end of their design life.
There have been user complaints about water taste, odors, or coloration.
There have been user complaints about water temperature.
There have been complaints about insufficient hot water.
A significant number of building users drink bottled water instead of tap water.
There have been leaks or clogging of pipes.
There have been capacity problems, including inability to handle water demand or undesired accumulation/diversion of wastewater/stormwater.
Building occupants have perceived illness (or other health concerns) as being related to green water systems.
Water tests show contamination.

To get the breadth of water conservation related innovations, a comprehensive list of innovation types was created (Table 8.2). This list contained 33 innovations, divided into 9 categories. The list was based on facility features mentioned in LEED documentation and the professional experience of the research team.

8.3.3 Survey Format

In order to gather information on professional experiences with water systems in green buildings, an internet survey was created using the tools provided by Qualtrics. The survey was broken into several sections, with a 'short form' at the beginning asking about the known problem types (Table 8.1), to help with classification of negative experiences. Respondents were asked to check boxes for each problem experienced, and were given an opportunity to describe other problems. This was followed by questions about the 33 innovations (Table 8.2), with a page for each of the nine categories. Respondents were asked to rate experiences with innovations in each category on a five point Likert scale, with the options Extremely Disappointing, Somewhat Disappointing, Indifferent, Satisfying, and Far Exceeded Expectations. Respondents were able to select more than one rating for each innovation in case they had varied experiences. Negative responses were followed with open ended questions about the types of innovations, the problems, and their resolution. Responses of Far Exceeded Expectations were followed with open ended questions about the types of innovations and their success.

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Table 8.2
Categories of innovations included in user satisfaction portion of survey

Category	Innovation
Toilet and Urinal	Water Conserving Toilets Non-Water Toilets Non-Water Urinals Alternative Flushometer Valves
Shower and Faucet Fixtures	Low Flow Fixtures Alternative Controls Self-Powering
Plumbing	Alternative Piping Manifold Distribution Cured-in-Place Pipe Lining High Performance Epoxies
Water Heating	Recirculation On-Demand Solar Heat Recovery
Appliances	Water-Efficient Dishwashers Water-Efficient Clothes Washers Water-Efficient Icemakers
Alternative Water Sources	Rainwater Harvesting Greywater Reuse Blackwater Reuse Process Water Recycling/Reuse Condensate Recovery Municipal Nonpotable
Landscaping	High Efficiency Irrigation Water Conserving Plant Selection Green Stormwater Retention and Infiltration Grey Stormwater Retention and Infiltration
Performance Monitoring	Water Audits Sub-Metering
User Education	Feedback on Water Use Signage and Educational Materials Behavioral Policies and Incentives

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8.4 RESULTS

The survey link was opened by a total of 166 distinct IP addresses. Of those that opened the link, 95 individuals went past the introductory pages to report problems with green water systems, and 76 of those continued on to respond to some or all of the remaining innovation ratings

pages. Response counts are provided in the data summary section. The predominant professional roles of respondents are presented in Table 8.3. Professional experiences with green building water systems are presented in Table 8.4.

Table 8.3
Predominant professional roles of the 95 respondents

Role	Percentage
Constructor	3%
Designer	34%
Educator	13%
Facility Manager	5%
Inspector	7%
Occupant/User	4%
Operator/Maintainer	3%
Owner	4%
Planner	3%
Product Manufacturer	3%
Utility Service Provider	3%
Other	18%

Table 8.4
Experience questions

Question	**% Yes**
Are you involved in building operations or maintenance?	38%
Have you ever been involved in the design, construction or operation of a building utilizing green water innovations?	84%
Have you ever been an occupant of a building utilizing green water technologies?	76%

8.4.1 Known Problem Types

Of the 95 respondents summarized in this report, nine did not provide any answers after the demographics page, suggesting that their responses should be omitted. However, other respondents did not indicate experience with any of the known water problems, but did share other experiences later. For this analysis it is assumed that the nine respondents did not experience the known water problems, and thus they are included in the total for this section. These responses for known water problems are collected below (Table 8.5). Problems with leaks or clogging of pipes were most reported, followed closely by complaints about hot water supply, early failure of systems, and complaints about water taste, odors, or coloration. Very few respondents reported occupants perceiving health concerns as related to green water systems, and fewer reported contamination in water tests.

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Table 8.5
Known problem type results

Problem Description	Percentage (of 95)
There have been leaks or clogging of pipes.	32%
There have been complaints about insufficient hot water.	31%
One or more water-related systems have had to be replaced before the end of their design life.	29%
There have been user complaints about water taste, odors, or coloration.	29%
A significant number of building users drink bottled water instead of tap water.	22%
There have been user complaints about water temperature.	21%
There have been capacity problems, including inability to handle water demand or undesired accumulation/diversion of wastewater/stormwater.	14%
Building occupants have perceived illness (or other health concerns) as being related to green water systems.	6%
Water tests show contamination.	2%
Other	18%

8.4.2 Innovation Ratings

When asked to describe their experiences with specific water-related innovations in buildings, respondents reported a variety of satisfaction levels and experiences. The nine categories of innovations are presented separately here, with charts describing the distribution of ratings for each innovation type. Not all respondents had experience with each innovation, so some innovations had relatively low rating counts. The count of ratings for each type is provided in the charts with type titles, as well as the number of respondents that viewed the category. There were 19 instances where a responder gave two ratings for a particular innovation. In line with the survey instructions, these were treated as separate experiences. Summaries paraphrasing free response data are also included to illustrate the experiences respondents had. Explanations of innovation types which were provided through mouse-over text on the surveys are also included in the summary tables.

8.4.2.1 Toilets. The Toilet category contained classes of toilets, urinals, and flushometer valves. Toilet responses (Figure 8.1) show a large share of negative experiences for non-water options, with 46% for non-water toilets and 58% for non-water urinals. Results were generally positive for water conserving toilets, as well as alternative flushometer valves.

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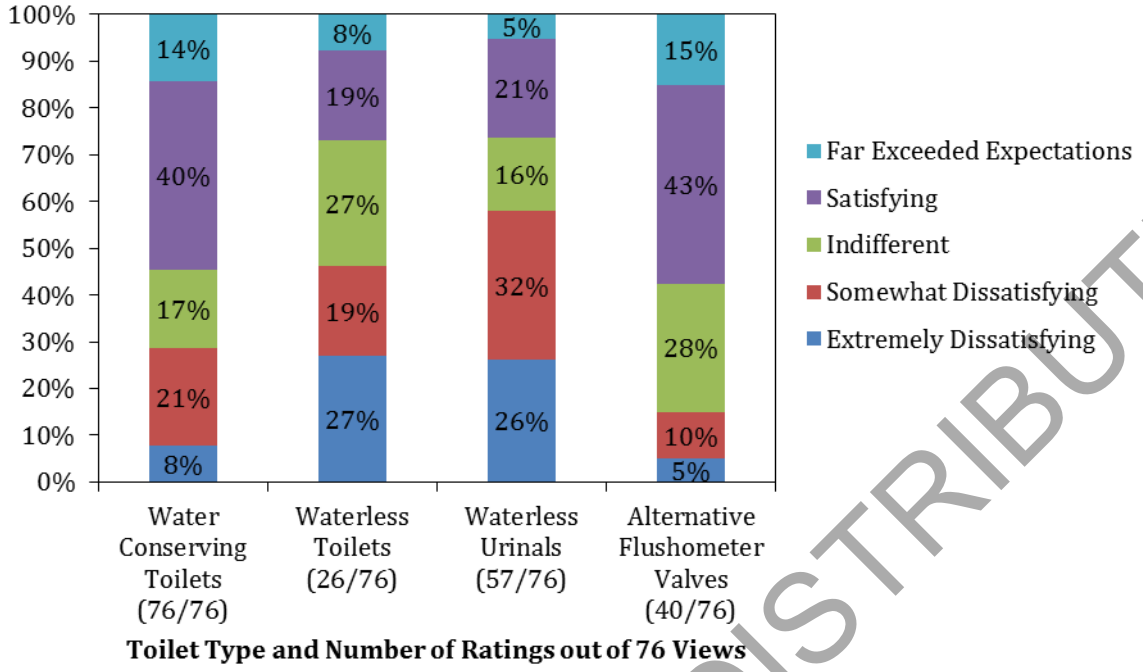

Figure 8.1 Response breakdown for Toilet category

With toilet innovations, positive experiences reported by respondents focused mainly on effective function of the innovation in saving water (Table 8.6

Table 8.6). Those that described them said they were pleased that the toilet worked well or as intended, and that they were happy about their ability to save water. Negative experiences were slightly more varied. Some respondents said that their water conserving toilets did not have sufficient flow to clean the bowl, or to carry waste through the lines, and required multiple flushes. Non-water options received negative responses related to odor, cleanliness, and difficult maintenance. Non-water urinal negative responses reported maintenance staff being unable or unwilling to deal with maintenance procedures. Clogging from salts was also reported. Alternative flushometer valves also received complaints. Respondents perceived that dual-flush valves were often used on the higher volume flush when a low volume would suffice, either through habit or ignorance. Automatic flush valves were triggered by mistake, either from poorly calibrated sensors or non-elimination uses of stalls, such as changing clothes.

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Table 8.6
Experiences described for toilet category

Type & Alt Text	Positive Experiences	Negative Experiences
Water Conserving Toilets Low-flow, high efficiency toilets (HETs), dual-flush toilets, pressure-assisted toilets, etc.	• Worked well or as intended • Easy way to conserve water	• Insufficient flushing power to clear bowl • Insufficient water for line carry
Non-Water Toilets Composting, incinerating, foam-flush, vacuum-flush, etc.	• Worked well or as intended	• Odor • Difficult to maintain • Cleanliness
Non-Water Urinals	• Worked well or as intended • Water conservation	• Improperly trained maintenance staff led to failures • Odor • Line clogging from salts • Cleanliness
Alternative Flushometer Valves Dual-flush, automated flush, self-powered, timed, solar-powered, etc.	• Worked well or as intended • Water conservation	• Automatic flush sensors are triggered more than necessary • Dual flush valves often used on the wrong flush option

7.4.2.2 Shower and faucet fixtures. The Shower and Faucet Fixtures category included low flow fixtures, as well as controls and self-powering control mechanisms. Responses for shower and faucet fixtures (Figure 8.2) show similar degrees of positivity for each type. Low flow fixtures showed 33% dissatisfaction, with about twice as many ratings given as the other two types in this category. Alternative controls were met with 45% indifferent ratings.

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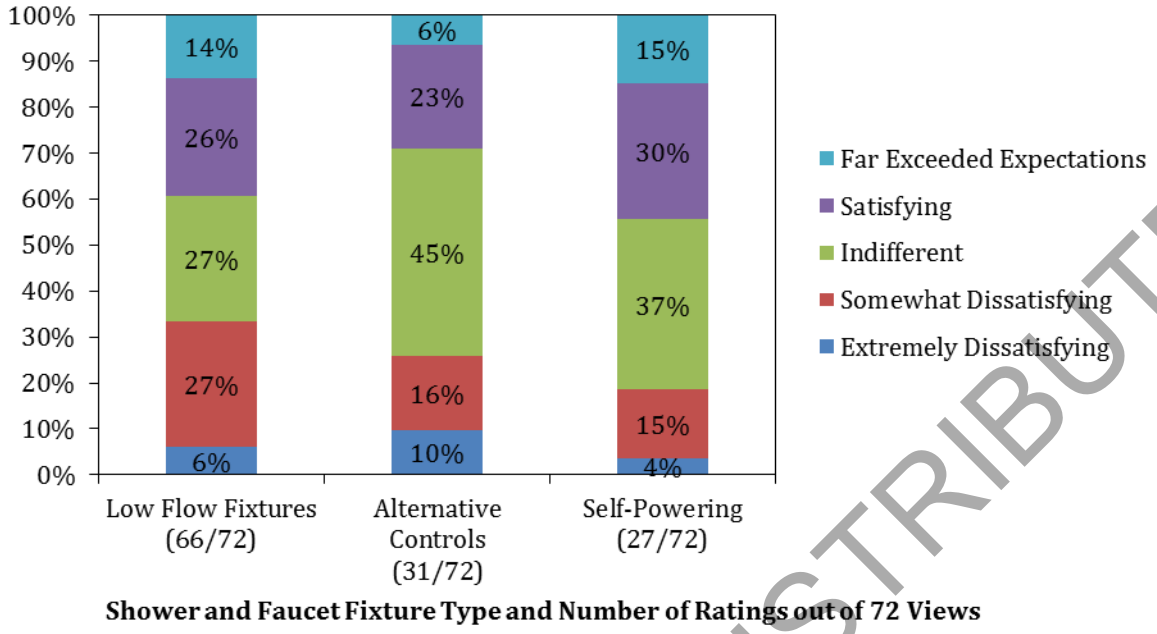

Figure 8.2 Response breakdown for Shower and Faucet Fixture category

With low flow shower and faucet fixtures, positive experiences described mostly involved the fixtures working well, and pleasure at the ability to easily conserve water (Table 8.7). One respondent was happy to note that their customers did not notice a switch to high efficiency bathroom sink faucets. Negative experiences involved inconsistent or too little flow, and extended waits for hot water. Respondents also indicated that the lower flow can be insufficient to clear and clean the drain pipes. In buildings requiring high water pressure or fire suppression systems, there were complaints about excessive splashing. Positive alternative control experiences involved the controls working well, and users being happy to not touch controls in public bathrooms. Complaints were about cycle length and sensor mechanisms that were difficult to trigger. For self-powering fixtures, positive experiences given only described fixtures working well. Negative experiences involved early battery failures.

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Table 8.7
Experiences described for shower and faucet fixture type

Type & Alt Text	Positive Experiences	Negative Experiences
Low Flow Fixtures Restricted, aerated, laminar flow, etc. Better than code requirements	• Worked well or as intended • Users did not notice switch • Water conservation	• Increased hot water delivery time • Too little flow in shower • Inconsistent flow • Splashing in buildings that maintain high water pressure for fire suppression system • Insufficient water for line carry
Alternative Controls Metered, timed, trickle valves, sensor-activation, foot activation, etc.	• Worked well or as intended • Enjoyed not having to touch controls	• Cycle too short • Automatic sink sensors difficult to trigger or keep triggered
Self-Powering Microturbine powered, solar powered, etc.	• Worked well or as intended	• Early battery failures

8.4.2.3 Plumbing. The plumbing category included alternative piping materials, manifold distribution, cured-in-place pipe lining, and high performance epoxies for joints and sealing. The lining and epoxies types had the lowest number of ratings of any innovation type in this study. Plumbing responses (Figure 8.3) were largely positive or indifferent for alternative piping and manifold distribution, with all types having over 40% indifferent responses. Very few respondents reported experience with cured-in-place pipe lining or high performance epoxies.

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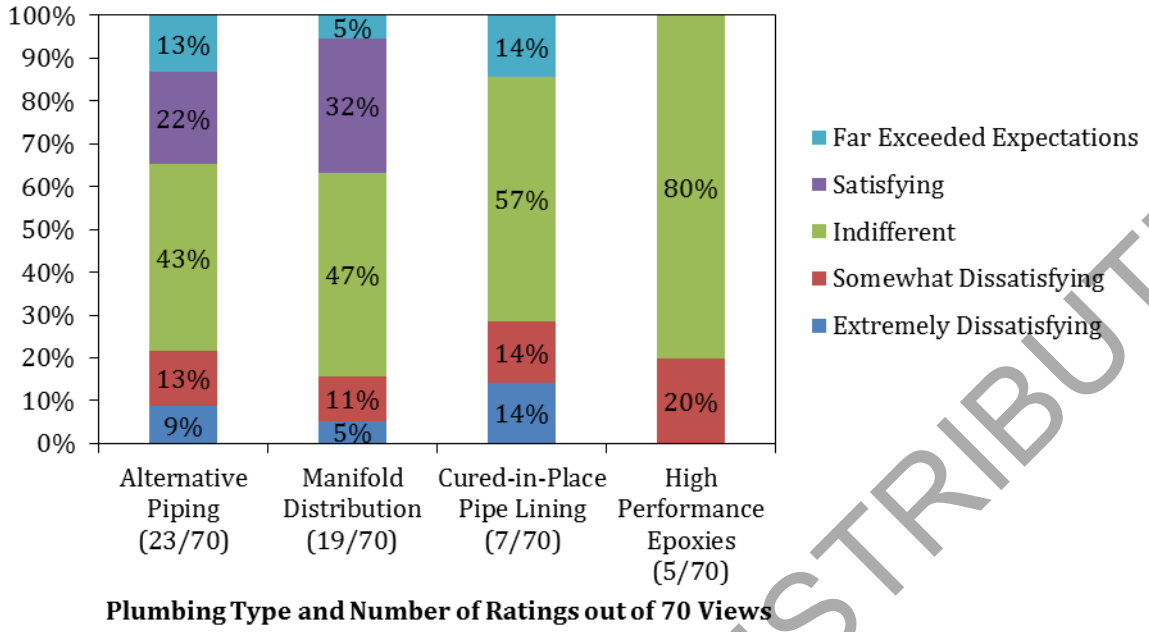

Figure 8.3 Response breakdown for Plumbing category

For alternative piping (Table 8.8), all experiences described were about PEX. Respondents indicating positive experiences described PEX as having improved pressure and flow over copper, and respondents were pleased with the ease of installation and repair. One respondent reported leaking in their PEX piping, and another complained of air and dirt pockets forming from slag in their PEX piping. Manifold distribution was perceived as easy to install, manage, and repair. One respondent complained of leaking. Positive reports said cured-in-place pipe lining was more durable and had better flow than the original pipes. The negative experiences involved an epoxy lining project being expensive and lacking quality control. No experiences were described for high performance epoxies.

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Table 8.8
Experiences described for plumbing type

Type & Alt Text	Positive Experiences	Negative Experiences
Alternative Piping PEX, Aluminum-Plastic composite, Recycled PVC, fused polypropylene, etc. Also includes alternative types of pipe insulation	• PEX had better pressure and flow than copper. • PEX easy to install and repair	• PEX with slag creating air and dirt pockets • PEX leaking
Manifold Distribution	• Easy to install and manage	• Leaking
Cured-In-Place Pipe Lining	• Improved durability and flow characteristics over original pipe	• Lining for copper pipe was expensive and lacked quality control
High Performance Epoxies	• None given	• None given

8.4.2.4 Water heating. The Water Heating category included recirculating systems, on-demand (instant) heating, solar heating, and heat recovery systems. Responses for water heating innovations were very positive across the board (Figure 8.4).

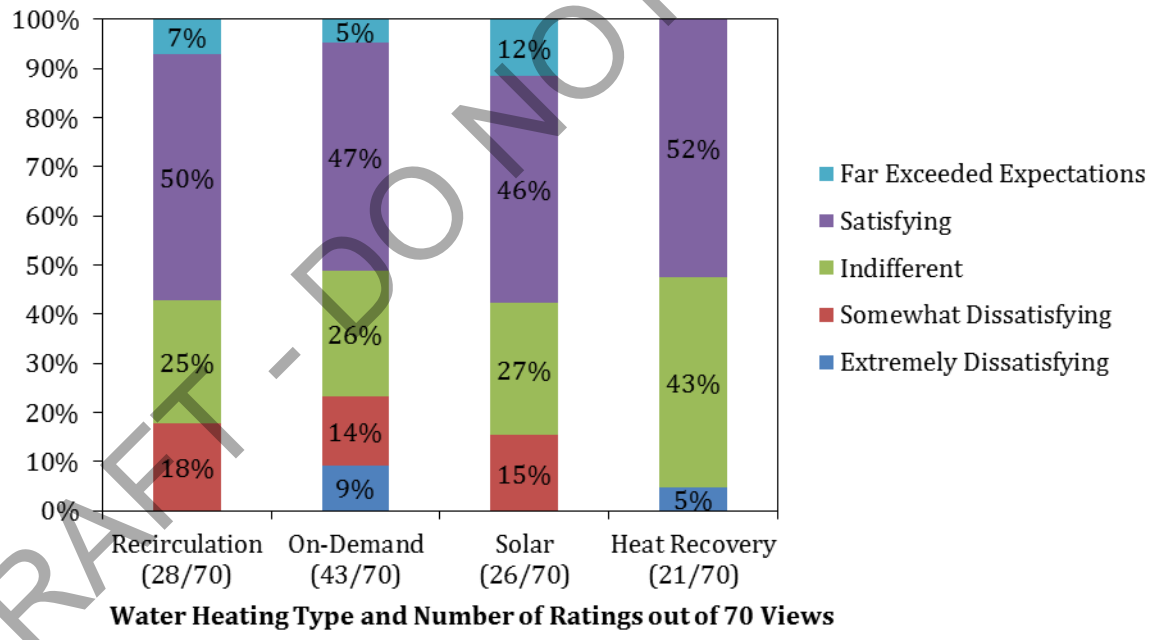

Figure 8.4 Response breakdown for Water Heating category

Positive experiences with recirculation systems (Table 8.9) included installations that worked well or as intended, with users happy not to have to wait for hot water. In one case, pipe leaks due to cavitation occurred possibly because of the constant flow. Positive experiences with

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on-demand water heating systems described respondents pleased by quick supplies of hot water that did not run out. The negative experiences involved insufficient heating capacity, which forced users to choose between heat and flow rate. Systems in cold environments, such as basements, were reported to be excessively noisy when coming up to temperature. Positive solar water heating experiences involved systems working well, or as intended. The short payback period was also mentioned. Negative experiences involved expense and long payback periods for the larger, more advanced systems.

Table 8.9
Experiences described for water heating type

Type & Alt Text	Positive Experiences	Negative Experiences
Recirculation Hot water recirculation systems	• Worked well or as intended • No wait for hot water	• Pipe leaks due to cavitation
On-Demand Centralized or point of use, instantaneous	• Worked well or as intended • Quick supply of hot water • Hot water does not run out	• Insufficient heating capacity • Inconsistent temperature • Excessive noise in cold environments
Solar Solar water heating	• Worked well or as intended • Short payback period	• Long payback period
Heat Recovery Water heat recovery systems, from greywater, geothermal, HVAC, etc.	• Worked well or better than intended • Energy savings	• Hot water demand and wastewater generation not always synchronized

8.4.2.5 Appliances. The Appliances category included dishwashers, clotheswashers, and icemakers. Icemakers had the third lowest number of ratings in this study. Responses for appliances were largely positive or indifferent (Figure 8.5).

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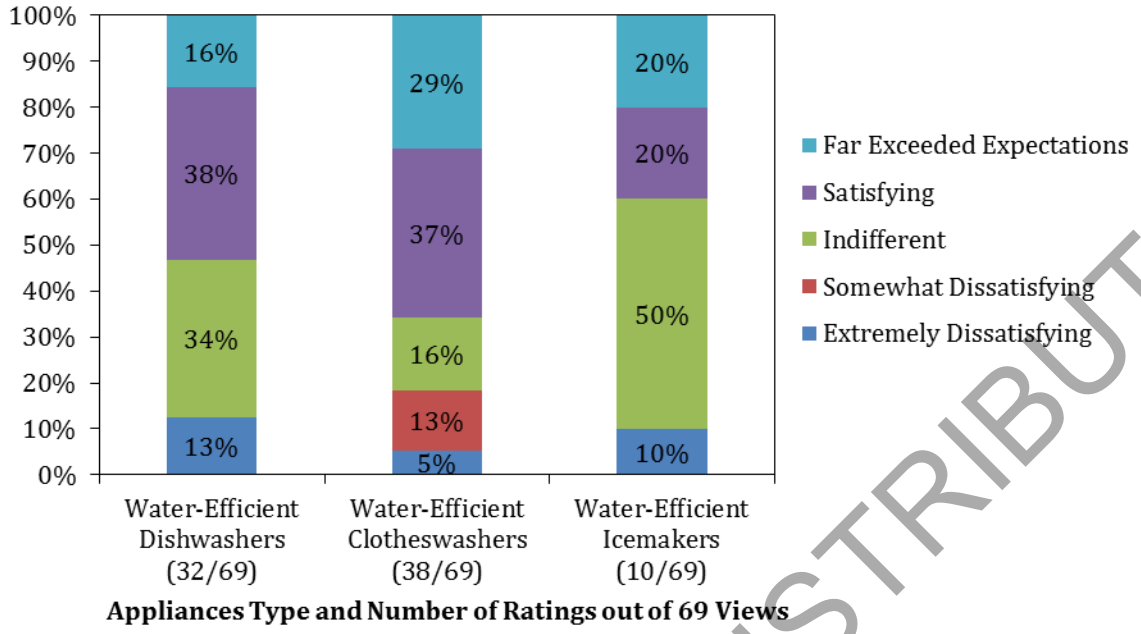

Figure 8.5 Response breakdown for Appliances category

For all appliance types, respondents were pleased with the savings that they experienced (Table 8.10). Positive experiences for water-efficient dishwashers mostly said that the dishwashers worked well and were quiet. The negative experiences were with dishwashers that failed to properly wash dishes. Water-efficient clothes washers worked well or better than expected for positive responders. Negative experiences included user error with front loading machines, where clothes were dropped. Respondents indicated that some machines did not wash clothes well, and developed a mildew odor, likely due to inadequate rinse and draining. Water efficient icemakers created positive experiences with better taste than respondents were used to, though there was a complaint about lengthy ice-making cycles.

Table 8.10
Experiences described for appliances type

Type & Alt Text	Positive Experiences	Negative Experiences
Water-Efficient Dishwashers	• Worked well or as intended • Water and energy savings • Quiet	• Dishes not washed well
Water-Efficient Clothes Washers	• Worked well or better than intended • Water and energy savings	• Mildew odor from inadequate rinse or draining • Clothes fell to floor out of front-loading machine • Clothes not washed well
Water-Efficient Icemakers	• Better taste than conventional • Energy savings	• Lengthy cycle

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8.4.2.6 Alternative water sources. The Alternative Water Sources category covered sources of non-potable water, including rainwater, greywater, blackwater, process water, condensate, and municipal supply. Responses for alternative water sources varied somewhat, but were largely satisfactory (Figure 8.6). Municipal nonpotable sources met with a large amount of indifference. Process water and condensate recovery were very well liked, with 77% and 73% positive responses, respectively. Greywater and blackwater reuse both had 15-25% proportions of strong responses on both ends of the spectrum.

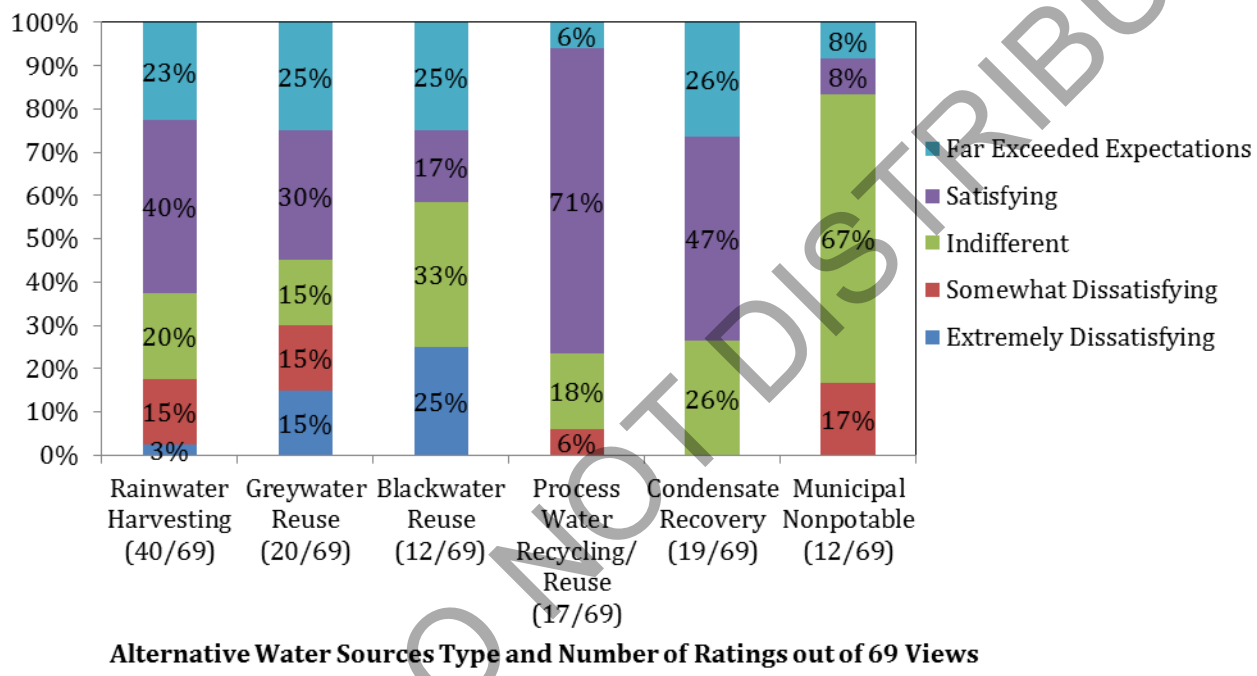

Figure 8.6 Response breakdown for Alternative Water Sources category

Positive experiences reported for alternative water sources often included mention of water savings, and systems performing well or better than intended (Table 8.11). Negative experiences with rainwater harvesting included expensive maintenance and treatment, freezing failures, the difficulty of finding turnkey systems, and issues where the lack of pressurization required addition of pumps, sometimes post-installation. Negative experiences with greywater reuse revolved around poor designs and bad filters that caused odors, sepsis, and complete system failure. Blackwater reuse was seen very positively by respondents whose systems were automated or remotely controlled by the installer. Negative experiences indicated high costs and poor process design. Chlorine treatment was also reported to cause pipe failures due to treatment process design flaws. Process water use gave positive experiences with water savings and a reduced need for chemical treatment. Condensate recovery gave positive experiences for similar reasons, by providing users with very clean water. Negative experiences with municipal non-potable water sourcing included the necessity of polishing on site, as well as complaints about the cost of infrastructure installation.

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Table 8.11
Experiences described for Alternative Water Sources type

Type & Alt Text	Positive Experiences	Negative Experiences
Rainwater Harvesting Rainwater and stormwater collection	• Water savings • Worked well or as intended	• Expensive to maintain • Lack of pressurization required addition of pumps • Freezing related failures • Hard to find turnkey systems
Greywater Reuse Greywater treatment and reuse	• Worked well or better than intended	• Systems went septic quickly • Bad filters • Odors
Blackwater Reuse Blackwater treatment and reuse	• Automated and remotely controlled systems make life easy • Worked well or better than intended	• Water treatment causes pipe failures elsewhere in building • High operating costs • Poor process design
Process Water Recycling/Reuse Industrial process water	• Water savings • Reduced need for chemical treatment	• None given
Condensate Recovery HVAC condensate recovery	• Water savings • Cleaner water	• None given
Municipal Nonpotable Municipal Nonpotable sources (purple pipe)	• None given	• Cost of infrastructure • Required polishing

8.4.3 Landscaping

The Landscaping category included efficient irrigation, plant selection, and green and grey (living and non-living) stormwater management. Landscaping innovations were very well received at 75% or more positive responses (Figure 8.7). Only green stormwater retention and infiltration had any dissatisfying experiences reported, with 6% of responses.

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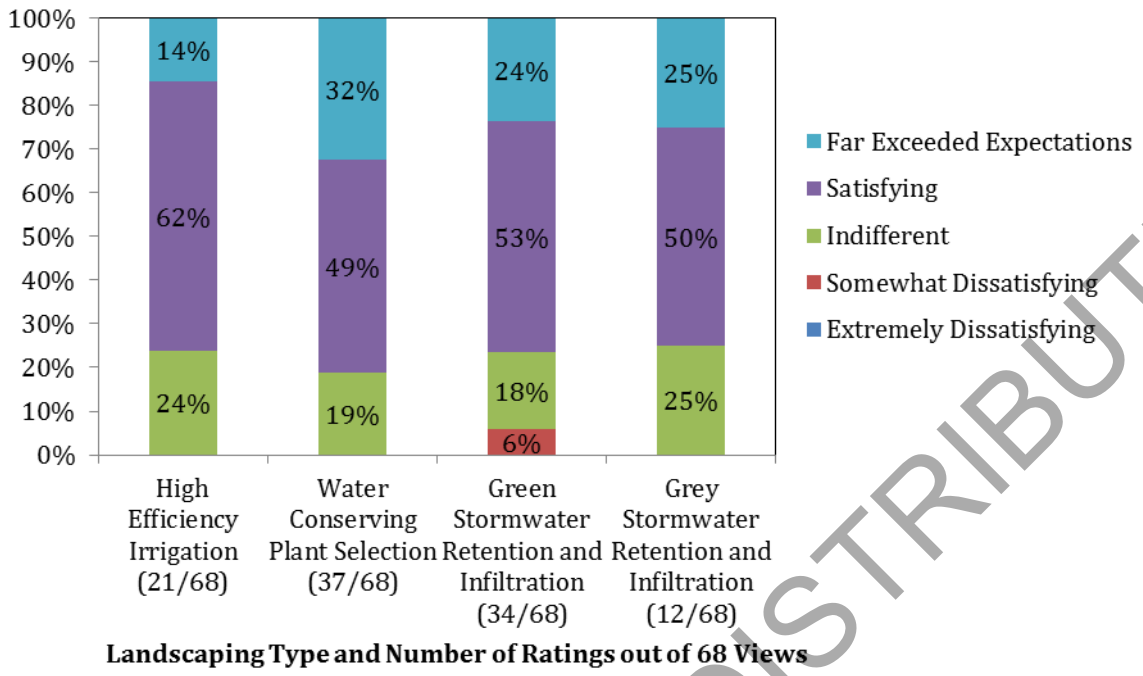

Figure 8.7 Response breakdown for Landscaping category

Landscaping innovations were very positively received (Table 8.12). High efficiency irrigation created positive experiences by saving water, and also improving the perception of landscape management by not watering areas that don't need water, like sidewalks. Positive experiences with water conserving plant selection involved water savings, minimal upkeep, and excitement at the use of native plants. Green stormwater management created positive experiences associated with low maintenance and aesthetics, and by working well. This is the only landscaping type to mention negative experiences, which resulted from water gardens often being built incorrectly by unqualified contractors. Grey stormwater management systems were positively perceived for working well, and because respondents enjoyed watching porous pavement drain.

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Table 8.12
Experiences described for landscaping type

Type & Alt Text	Positive Experiences	Negative Experiences
High Efficiency Irrigation Alternative controls, high efficiency distribution, tailwater reuse, etc.	• Water savings • Reduced perception of wasted water by not spraying sidewalks, etc.	• None given
Water Conserving Plant Selection Native plants, xeriscaping, etc.	• Water savings • Minimal upkeep • Native plants	• None given
Green Stormwater Retention and Infiltration Biological systems such as vegetated roofs, Bioswales, rain gardens, infiltration basins, etc.	• Low maintenance • Aesthetically pleasing • Worked well or as intended	• Water gardens often built incorrectly by non-experts
Grey Stormwater Retention and Infiltration Non-biological systems such as pervious paving, storage, etc.	• Porous pavement fun to watch drain • Worked well or as intended	• None given

8.4.3.1 Performance monitoring. The Performance Monitoring category included water audits and sub-metering of water use. Performance monitoring innovation experiences were mostly rated as satisfying or indifferent (Figure 8.8), with under 20% negative experiences for both types.

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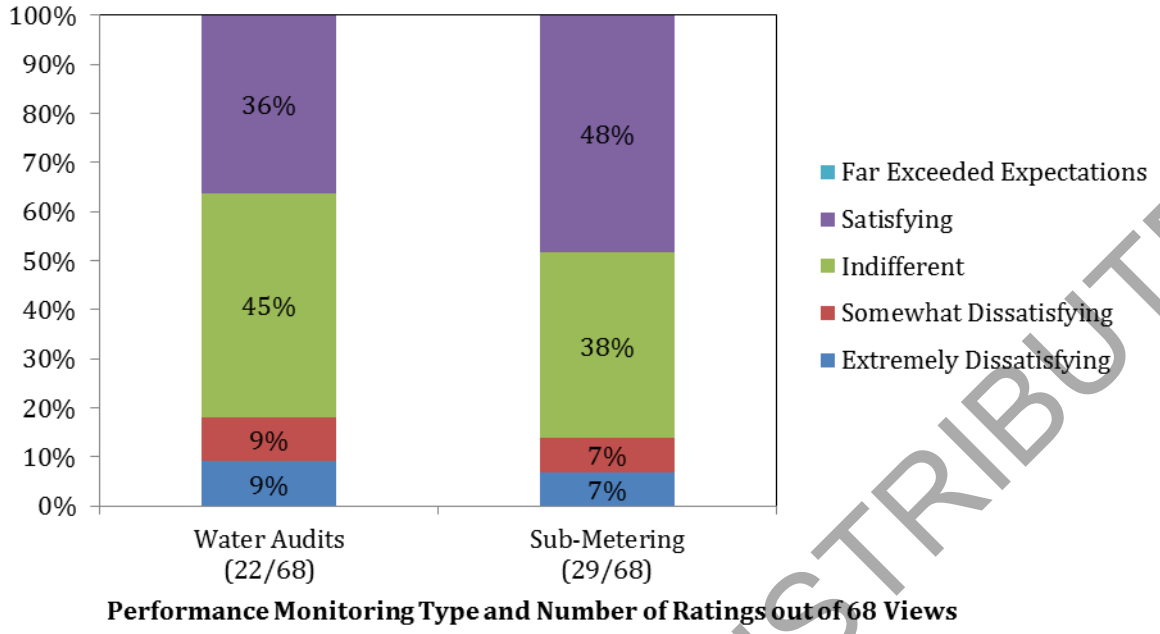

Figure 8.8 Response breakdown for Performance Monitoring category

Positive experiences described for water audits involved good return on investment, and a sense of becoming informed (

Table 8.13). In one case, a dissatisfied respondent had an audit with very poor return on investment. Sub-metering created positive experiences where demand was reduced, and firm documentation was available for questions of use and billing. The complaints included a high initial cost and difficult installation.

Table 8.13
Experiences described for performance monitoring type

Type & Alt Text	Positive Experiences	Negative Experiences
Water Audits Audits of building water use, water bill analysis, etc.	• Informative about waste • Good return on investment	• Poor return on investment
Sub-Metering Sub metering of occupants and rooms for detailed usage data	• Reduced demand • Firm documentation for use and billing	• High initial cost • Difficult installation

8.4.3.2 User education. The User Education category included feedback, signage and educational materials, and behavioral policies and incentives. User Education innovation experiences were mostly described as satisfying or indifferent (Figure 8.9).

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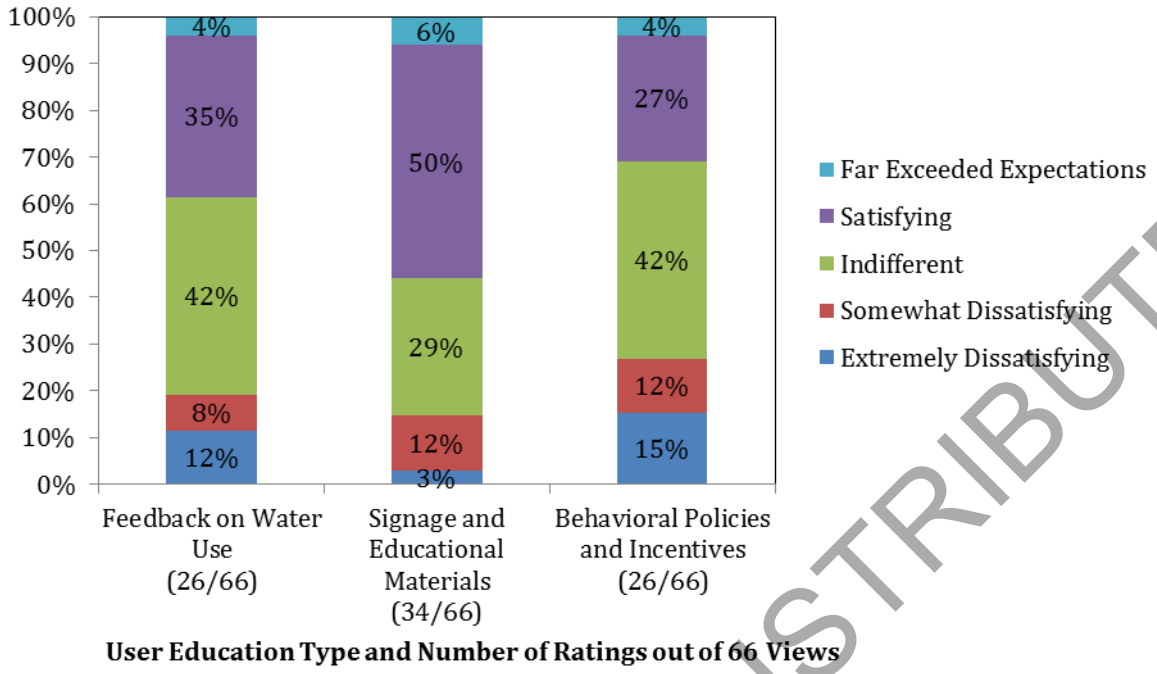

Figure 8.9 Response breakdown for User Education category

Feedback on water use was successful in creating water and power savings, and respondents suggested that in their experience, tracking was very effective when an average or benchmark was provided (Table 8.14). Negative experiences involved lack of engagement with leadership and facilities managers. Some respondents were also upset when feedback was only provided for negative behaviors. Respondents reported positive experiences with signage and educational materials related to easy implementation and scalability, as well as positive influences on user perceptions. Negative experiences involved the lack of useable data, and cases when users ignored signage, continuing in their old habits. Behavioral policies and incentives were reported as very effective where rebates were concerned, but were ignored in the experience of other respondents.

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Table 8.14
Experiences described for user education type

Type & Alt Text	Positive Experiences	Negative Experiences
Feedback on Water Use User/occupant feedback on water use	• Water and power savings • Tracking especially effective with points of comparison	• Lack of engagement with leadership • Only supplied for negative problems
Signage and Educational Materials Signage and educational materials explaining how and why to conserve water	• Easily implemented • Scalable • Promotes positive views in users	• No useable data • Ignored in favor of habit
Behavioral Policies and Incentives Incentives for users to conserve water	• Rebates very effective	• Ignored by users

8.5 SUMMARY AND CONCLUSIONS

Though the survey was distributed to thousands of individuals, only 95 reported problems. There are many possible explanations for this being so low. One is that a majority of the target population is very satisfied with their systems, or is not aware of problems, so felt no need to participate.

The known problems most reported were noted by about a third of respondents. These included leaks and clogging of pipes, user complaints about insufficient hot water, early system failure, and water taste, odor, or color. These are all symptomatic issues, but do give indicators for managers to focus monitoring efforts on, and to use for other studies.

For all categories of innovations, negative satisfaction ratings were reported by a minority of respondents, indicating that these technologies are perceived to be working effectively in the majority of cases. These experiences are likely to support further diffusion of these technologies given what we know about experiences of early adopters. Some innovation types, such as landscaping measures, had little or no negative experiences reported. Toilets and Urinals, especially the non-water varieties, had the most negative response. The largest proportions of severe negative experiences also seem to have occurred in these non-water toilet innovations, followed by blackwater and then greywater reuse. It may be that these sewage related innovations inspire the strongest negative feelings because of humanity's evolved aversion to bodily waste. However, blackwater and greywater systems also have amongst the highest percentage of extremely positive responses.

Negative experiences were described for most of the innovations considered, and positive experiences were described for all but one. These experiences involve design, process, and human behavior, and suggest many topics for improvement and future research. Positive experiences

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tended towards systems working as intended, few surprises were reported. Respondents were pleased with cost and water savings for many innovations. The negative experience descriptions had several common themes. Water conserving fixtures and fittings failed to clear waste or to carry it through wastewater pipes, due to insufficient flow. Maintenance difficulties were also reported for many innovations, either through difficulty with the innovation itself, or through failures to communicate with maintenance staff. Negative perceptions about high costs were also reported for innovations in several categories.

In addition to offering green building professionals some information about what to look out for, these results suggest several areas of future research. Quantifying the impacts of these experiences on adoption rates would be very relevant to designers and vendors. The prevalence of both unmet and exceeded payback expectations suggests future research into understanding and improving the accuracy of financial expectations for these innovations. Furthermore, research could be done to develop more robust innovations that leverage the positive responses identified in this study, as well as address negative responses.

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CHAPTER 9: INTERVIEWS WITH GREEN BUILDING PROFESSIONALS ABOUT THEIR EXPERIENCES WITH WATER CONSERVATION MEASURES

9.1 ABSTRACT

Phone interviews were conducted with a sample of green building professionals from multiple disciplines including, but not limited to, facility managers; architects; and engineers; about their experiences with water conservation measures in green buildings. Subjects were asked about their successes with water conservation measures, as well as difficult experiences. They were also asked to give advice based on their experiences for other professionals attempting their own conservation measures. Interview transcripts were analyzed using thematic analysis to identify successes and difficulties and evaluate frequency of occurrence, which were sorted by type of water conservation measure. Some themes emerged, including non-water urinal clogging and odors, line clogs where insufficient pipe slope was given for high-efficiency toilets, and difficulty educating maintenance personnel about procedures. Multiple subjects also shared the sentiment that water is underpriced and undervalued, and prices should and will go up in the future.

9.2 INTRODUCTION

Water conservation measures are frequently employed in buildings, in efforts to save money, promote sustainability, and improve public image. These measures are present in a large number of certified green buildings, as certification programs promote or require their inclusion. There are many different types of measures employed in these buildings, ranging from user interface products like high-efficiency water closets and faucet aerators to building-scale wastewater treatment plants. What these measures have in common is that they are meant to reduce the use of externally treated potable water, and they are innovative in the sense that they are unfamiliar to the adopter (Rogers, 2003).

Because the outcomes of the implementation of these innovative practices can have major consequences on the future adoption of similar innovations by others (Ash et al., 2007; Rogers, 2003), it is in the interest of those impacted by their success to understand what happens when they are installed. A fair amount of anecdotal evidence exists already, such as negative experiences with non-water urinals (Guevarra, 2010; Shapiro, 2010). There have also been several scientific studies, particularly related to opportunistic pathogen growth in water heating systems (Bagh et al., 2004; Brazeau and Edwards, 2012; Codony et al., 2002; Mathys et al., 2008). The most comprehensive formal study to date examined the results of an internet survey given to green building professionals, and identified multiple areas of potential future study.

This paper reports the next step of that exploratory study, where a series of in-depth phone interviews was conducted with a multi-discipline sample of green building professionals about their experiences with water conservation measures.

Participants were initially drawn from a pool of internet survey respondents that opted in to this portion of the study. After this pool was exhausted, the researchers expanded the pool by purposively sampling institutional owners and facility managers regionally with multiple green buildings in their portfolios, to maximize exposure to possible outcomes of interest.

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The survey was designed to take about 30 minutes, and consisted of a series of questions about the respondents and their organizations, their experiences with water conservation measures both good and bad, and their thoughts on the future, including advice for others who might be interested in implementing similar measures.

9.3 RESEARCH METHODS

This was an exploratory study into professional experiences with water conservation measures in green buildings. An interview process was designed to elicit experiential data from participants' professional practice.

9.3.1 Subject Sources

The initial sample consisted of respondents to the internet survey from a previous phase of this study who had opted in to this phase. Of the 27 who expressed interest on the survey, 13 ultimately completed the interview. In order to expand the number of participants and buildings represented, the researchers sought institutional facility managers with multiple facilities in their portfolios. Virginia universities and city and county governments with LEED (Leadership in Energy and Environmental Design) certified buildings in their portfolios as included in the LEED directory (US Green Building Council, 2014) were contacted. This effort brought the number of respondents who completed interviews up to 25.

Because of the sensitive nature of some of the stories shared, any information that could be used to identify participants has been removed.

9.3.2 Interview Process

Interviews were conducted over the phone, and recorded by researchers. The process was designed to take approximately 30 minutes. Interviews began with an informed consent script (Appendix A) and a brief statement re-iterating the purpose of the interview. A series of open ended questions, broken down into four different parts, were then asked (Appendix B). The first section determined job functions and building portfolios. The second section determined organizational goals and behaviors regarding water conservation. The third section dealt with professional experiences, asking specifically about difficulties and major successes with water conservation. The fourth section inquired about perspectives on the future of water conservation in green buildings, in general and within their organization. The interviews ended with a question requesting advice for others trying to implement water conservation measures in their own buildings.

9.4 RESULTS

This was an exploratory study, seeking experiential data such as practitioner perspectives and outcomes of innovation adoption and implementation as the basis for future studies. Given the nature of the sample and the interview process, the aim of the study was not to undertake statistical analysis for the purpose of generalization. Instead, results are presented as a series of statements, first of successes, then of difficulties, and finally of advice given. They have been paraphrased

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and re-ordered by the types of systems involved, in order to protect the identity of interviewees. Categories are the same as those used in the previous study, consisting of 9 categories of 33 innovations (Table 9.1) (Chambers, 2014). Because the interview design measured self-reported experiences, not all of these innovation types were represented in the results. Additionally, counts have been included for experiences mentioned by multiple interviewees to give an indication of the frequency of occurrence across the sample.

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Table 9.1
Categories and types of innovations (Chambers 2014)

Category	Innovation
Toilets and Urinals	Water Conserving Toilets Water Conserving Urinals Non-Water Toilets Non-Water Urinals Alternative Flushometer Valves
Shower and Faucet Fixtures	Low Flow Fixtures Alternative Controls Self-Powering
Plumbing	Alternative Piping Manifold Distribution Cured-in-Place Pipe Lining High Performance Epoxies
Water Heating	Recirculation On-Demand Solar Heat Recovery
Appliances	Water-Efficient Dishwashers Water-Efficient Clothes Washers Water-Efficient Icemakers
Alternative Water Sources	Rainwater Harvesting Greywater Reuse Blackwater Reuse Process Water Recycling/Reuse Condensate Recovery Municipal Nonpotable
Landscaping	High Efficiency Irrigation Water Conserving Plant Selection Green Stormwater Retention and Infiltration Grey Stormwater Retention and Infiltration
Performance Monitoring	Water Audits Sub-Metering
User Education	Feedback on Water Use Signage and Educational Materials Behavioral Policies and Incentives

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9.4.1 Participation

A total of 25 interviews were conducted. The interview subjects represented multiple professional roles. While the largest percentage were facility managers, individuals with other roles such as plumbers, engineers, utility managers, architects, vendors, scientists, executives, and financial professionals were represented by one or more participants. All of these individuals had in common that their professional roles involved water conservation measures in green buildings. The subjects also represented multiple different types of organizations, including local government, armed services, private industry, non-profit, and higher education.

9.4.2 Successes

Interviewees were asked to talk about their greatest successes with water conservation measures. Responses were sorted by relevant water conservation measure categories and innovation types. They were then paraphrased for clarity and identity protection, and similar responses were combined and summarized in a table (Appendix C). Each type of success was given a reference number for ease in using the Appendices. The count of interviewees stating similar successes was also recorded. Results were ordered by category and innovation, then by amount of repetition.

Interviewees described 34 distinct successes. These successes largely involved systems working as well as or better than intended. Several others described successful programs and policies that reduced waste and user difficulties through recycling (S32), free products (S16), or creating accountability (S29).

9.4.3 Difficulties

Interviewees were asked to describe difficulties and challenges they had faced with water conservation measures. Responses were sorted by categories and types of relevant water efficiency measures. They were then paraphrased for clarity and identity protection, and similar responses were combined and summarized in a table (Appendix D). Each type of difficulty was given a reference number for ease in using the table. The count of interviewees stating similar difficulties was also recorded. Results were ordered by category and innovation type, then by amount of repetition.

Interviewees described 51 distinct difficulties. These difficulties varied widely. Recurrent themes included a lack of knowledge amongst users and owners (D4, D10, D14, D36, D50), and inaccurate manufacturer claims (D5, D9, D33).

9.4.4 Advice Given

Interviewees were given the opportunity to provide any advice they might have for others in their position seeking to implement water conservation efforts. Responses were paraphrased for clarity and identity protection, and similar responses were combined and summarized in a table (Appendix E). Each distinct piece of advice was given a reference number for ease in using the table. The count of interviewees giving similar advice was also recorded. Results were ordered

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by amount of repetition. This table was not organized by type of water efficiency measure because many of the pieces of advice are general or cover multiple types.

Interviewees described 29 distinct pieces of advice, covering many different things. Most commonly, they made statements about how water was undervalued and underpriced (A1) and that efforts for conservation needed to expand beyond bathrooms into recycling and recovery (A2). Education (A3) and policy involvement (A4) were also repeatedly encouraged.

9.4.5 Summary of Response Categories

Counts of successes and difficulties were tabulated for the categories of water conservation measures reported on in the interviews (Table 9.2).

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Table 9.2
Summary of response types for categories reported on

Category	Successes	Difficulties
Alternative Water Sources	9	12
Blackwater Reuse	2	3
Condensate Recovery	3	
Greywater Reuse		4
Rainwater Harvesting	4	5
Landscaping	2	6
Green Stormwater Retention and Infiltration	1	1
High Efficiency Irrigation		3
Water Conserving Plant Selection	1	1
Other		1
Shower and Faucet Fixtures	3	10
Alternative Controls	1	3
Low Flow Fixtures	2	7
Toilets and Urinals	7	18
Alternative Flushometer Valves	3	5
Low Flow Urinals		
Non-Water Urinals	1	3
Water Conserving Toilets	1	9
Non-Water Toilets		1
Performance Monitoring	2	0
Sub-Metering	1	
Other	1	
User Education	8	0
Signage and Educational Materials	6	
Other	2	
Other	3	5
Total	34	51

9.5 DISCUSSION AND CONCLUSIONS

The successes reported by interviewees in many cases involved systems or features working as intended or expected. These results may help provide encouragement for future adopters or current proponents. The less commonly utilized successes discussed, such as recycling toilets (S32), offering products to commercial entities (S16), or requiring sign-offs on product manuals (S29) suggest future studies or changes in policy that could improve the success of water efficiency efforts.

While the nature of this investigation makes drawing statistical conclusions difficult, there were some things that were experienced by many of the interviewees. These, especially, may

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deserve future attention. Some, like issues with non-water urinals (D34), are highly visible and have gained notoriety within the industry. Plumbing issues from high efficiency water closets related to line slope and length that cause clogs (D37) are less visible to people who are not plumbers or facility managers, and need to be addressed in the design phase. That this was the most repeated difficulty suggests a need for further investigation to determine whether it is indeed common, and if solutions other than slope adjustment exist.

A repeated theme in the difficulties reported was lack of knowledge by owners or maintenance persons (D4, D10, D14, D36, D50). Some interviewees had attempted to mitigate these issues with policy changes requiring sign-offs (S29), reducing conflicts, but not significantly reducing failures. This suggests a need for investigation into how to improve education about maintenance procedures for these water efficiency products, as some of the advice given also attests (A6).

The advice given by interviewees also showed some common themes. Over a third of respondents commented that water is undervalued and underpriced (A1), that prices need to go up, and that they will. Multiple interviewees also suggested that water efficiency focus should shift from bathrooms where a point of diminishing returns is being reached towards water recycling and recovery, where large gains still remain to be made (A2).

One repeated piece of advice was to do thorough investigation into water efficiency measures before adopting them (A3). This echoes a theme from the difficulties that manufacturer claims may not always be accurate (D5, D9, D33) or that designers may lack expertise (D6). Programs such as MaP Testing (MaP, 2014) already exist to assist to identify products that do not work, so finding ways to improve the visibility of these programs might be the most fruitful research pursuit.

That the interview sample was geographically concentrated in Virginia suggests the possibility of biases related to this location. Future research into this subject might include studies in other geographical regions.

9.6 SUMMARY

This chapter presented the results of a series of interviews with green building professionals about their experiences with water conservation related measures. They were asked about their successes and difficulties, and then to provide advice for others. These stories and bits of advice may help other adopters avoid problems or attain greater success. Some areas of possible future research were also identified, particularly into issues related to line carry with water-conserving toilets and insufficient slope, and into educating maintenance personnel on proper care of unfamiliar fixtures and features.

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CHAPTER 10: LESSONS LEARNED

10.1 INTRODUCTION

Each of the water quality issues described in this report is linked in some way to the water age within the plumbing system. Water age is increased by installing low flow devices and implementing potable water-saving technologies and seeking to use alternative water source for potable and non-potable uses such as rainwater collection, water reuse, and reduced use campaigns, among other strategies. While plumbing codes developed for green buildings identify the best strategies to reduce water use in buildings, and standards to protect buildings against the regrowth of harmful waterborne pathogens, there are not specific warnings, suggested strategies to maintain low water use, or frameworks for selecting desirable controls while ensuring there are not problems with rapid disinfectant residual decay, pathogen growth, and corrosion of premise plumbing. Decreasing pipe diameters seems like a promising choice to help decrease water age, but restrictions on in-pipe velocity, minimum pipe diameter requirements for fire demand, and minimum pipe diameter requirements based on the number of fixtures may limit the ability for designers to decrease the overall volume of the system to levels that are capable of maintaining adequate water age. For now, the most effective solution for buildings that implement green water strategies that are supplied by a public water utility may be to simply implement flushing at the farthest point from the entry point to introduce "new" water to the building plumbing system regularly. The amount and frequency of water to be flushed will like vary depending on various factors; however, the goal is to achieve and maintain a disinfectant residual in the plumbing system. For new buildings, it is recommended to minimize plumbing system volume and complexity. Unfortunately, there are not specific recommendations for buildings seeking off-the-grid status. Even with flushing, the source water quality may not change appreciably. Solutions for off-the-grid buildings are problematic because each building is unique and there is not currently sound science to aid in understanding all problems

10.2 RAPID LOSS OF DISINFECTANT

Abiotic and biotic reactions increase the rate at which residuals disappear. Water residence times, temperature, and nitrification seem to have the largest impact on decay, which may also have secondary impacts including causing pH fluctuations, microbial (re)growth, increased corrosion, and taste and odors problems. While several strategies exist for maintaining disinfectant residuals, none are effective for all systems all of the time (Table 10.1). It should be noted that many of these strategies have disadvantages and limitations. For example, varying the chloride to sulfate ratio in chloraminated systems is complex and cannot easily be done. Relative effectiveness should be taken into consideration for each strategy. For premise plumbing, the easiest and most straightforward solution to maintaining a residual is decreasing water age by implementing flushing (<1% of total daily flow has been effective in one building) if water is supplied by a utility that meets all U.S. EPA drinking water regulations at the building point of entry.

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Table 10.1
Stakeholder responsibilities for maintaining adequate disinfectant residuals

Strategy	Stakeholder(s)
Limit the use of material with high chlorine demand	Designer Material manufacturer to some degree
Increase the chlorine: ammonia ratio in chloraminated systems	Utility, Building disinfection system manager
Increasing overall concentration of residuals applied	Utility, Building disinfection system manager
Raising pH	Utility, Building disinfection system manager
Controlling microbial growth	Combination of efforts
Flushing the system	Utility if problem is widespread, Building owner/operator if it is localized, Consumer

10.3 IN-BUILDING DISINFECTION SYSTEMS

Many building operators do not have the staff or expertise to properly maintain and operate all in-building disinfection systems. To the extent possible, it is better to rely on the expertise and experience of the utility plant operators. The site-dependent efficacies of many commercially available in-building treatment systems are not well understood. Most data is produced in field studies that have different overall goals, different methods for water quality analysis, sampling protocols, vigor of study, and parameters measured; therefore, it is difficult to make comparisons and draw over-arching conclusions. In some instances, how the system will react with the existing premise pluming is not well defined. For example, the pH dependent metal ion speciation of copper in copper-silver ionization systems could render the ions ineffective at eradicating microorganisms. However, as green buildings seek to become more independent (i.e. “net-zero”), they will like have to turn to in-building disinfection systems to ensure their water quality.

Regulating in-building disinfection will pose a new challenge. ASHRAE Standard 188, a new standard still in public review at the time of writing, is a step forward because it assigns responsibility to a specific stakeholder (the building owner/manager) in cases of *Legionella*-related outbreaks. However, various parts of how the standard will be implemented, and the legal and water quality repercussions that might result, are not well defined. There are three specific areas that need improvement:

- A protocol for measuring influent chlorine residuals should be a specified protocol in the standard and should be designed to maximize the likelihood of identifying systems with low chlorine residuals throughout the plumbing system.

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- A framework for identifying potential long-term detrimental effects of thermal disinfection with regards to efficacy of the treatment and physical integrity of the plumbing system should be provided.
- A framework for selection between different disinfectant system types should be provided. The current *Legionella* control guidelines and standards do not provide this. When selecting a system, the engineer must consider the integrity of existing plumbing, safety of consumers, and ability to properly maintain and monitor the system over long periods of time in the face of considerable knowledge gaps and uncertainties.

An initial iteration of such frameworks is presented in Chapter 3. Other standards are needed for the control of other opportunistic pathogens because controls that work for *Legionella* may not be effective for other pathogens.

10.4 CORROSION

10.4.1 Blue Water

The occurrence of blue water (Type III pitting) is more common at the end of distribution systems and is often characterized by low chlorine residuals, less overall water use (high water age), and dead ends. Waters where soluble copper is the dominant form of copper in blue water are typically lower in pH, and problems usually dissipate over time. If they do not, pH can be raised above 7.6 or orthophosphate corrosion inhibitor can be dosed. Problems with blue water where particulate copper is the dominant form of copper usually develop after an initiation time and usually do not dissipate over time. Increased levels of chlorine can also be effective in inhibiting particulate copper release in high pH, low alkalinity waters. In these cases, water age and maintenance of chlorine residual can be key to solving problems.

10.4.2 Pinhole leaks

For waters that are known to form pin hole leaks, very low overall use and low chlorine residuals can exacerbate problems, especially when the leaks are microbiologically driven. Sulfate reducing bacteria play an important role in some cases of pitting. They produce a micro-anaerobic environment beneath tubercles. While flushing and increased disinfectant residual might help, replacement of the plumbing is sometimes necessary when SRB are involved. There are no proven remediation techniques that are effective for all systems.

10.4.3 Lead leaching

While the relative corrosivity of utility water is probably most important factor for causing lead leaching, even mildly corrosive waters that routinely pass Lead and Copper Rule sampling can have problems when water age is high. The highly corrosive nature of rainwater is of particular concern when it is used in potable water systems with lead bearing plumbing components. For very corrosive waters, some level of treatment is required. The new definition of lead-free brass per ANSI/NSF standards (60, section 8 and 9) will help reduce issues with lead in water, but until all buildings are rid of lead-laden brass devices, lead remains an on-going concern.

10.5 TASTES AND ODORS

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Consumers are good indicators of water quality problems occurring in the distribution and building plumbing system. High water age and low disinfectant residuals are key causes factors for taste and odors; however, consumers also voice complaints about chlorine odor as well, which is necessary to identify and resolve many water quality and microbial problems. Some practitioners have reported consistent problems with sulfate reducing bacteria (rotten egg odor) in hot water systems, even if the water heater set point is above 60 °C where extensive flushing and disinfection have been implemented. New materials being developed and used in green buildings are ANSI/NSF rated for health. These tests do not address aesthetics and some synthetic materials being implemented could eventually contribute to taste and odor issues. To the extent taste and odor problems are isolated in a particular building, possible solutions (in order of likely increasing complexity) include flushing, designing and reducing water residences times, minimizing dead ends, using point of use filtration, booster chlorination, or other disinfectant.

10.6 RAINWATER HARVESTING

The corrosive nature of rainwater makes leaching of metals a concern. Rainwater quality and quantity varies greatly between regions. Rainwater can absorb contaminants from the air and roofing materials – including volatile organic compounds, heavy metals, and nutrients for biological growth. In some areas rainwater quality may not be adequate to drink (e.g. areas with high industrial activity) without additional treatment. Proper materials selection in rainwater systems is paramount, especially when used for potable water. Standards such as NSF 14, 60, and 61 as well as international green plumbing codes should be followed for material selection and installation practices. Research into rainwater quality in potable rainwater systems is needed to fully assess the safety and aesthetic implications of using this alternative water source.

10.7 MICROBIOLOGICAL CONTAMINANTS

10.7.1 Microbiological regrowth

Low water residence times and maintaining chlorine residual play key roles in preventing microbial growth. Although other strategies such as limiting nutrients entering the distribution system (e.g. assimilable organic carbon) also play a key role, many nutrients can be produced in the distribution system, decreasing the likelihood this strategy will be successful in controlling re-growth. Premise plumbing, in general, provides conditions such as intermittent flow, moderate temperatures, lower disinfectant residuals, and higher surface area to volume ratios that are ideal microbial growth. Maintaining temperature and disinfectant targets, and low water age, are viable strategies to avoid regrowth.

10.7.2 Metered Faucets

Increased incidence of *Legionella* and other opportunistic pathogens in metered faucets have raised concerns with installing these water-saving devices in plumbing systems. Although the cause for higher pathogen occurrence in these faucets is not fully understood, hypotheses for the cause(s) include water age, overall flow rate, materials used in the manufacturing process, testing

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and shipping of the faucets, and poor installation practices. The issues observed with these green devices bring into question other untested green building water conservation strategies.

10.8 GREEN BUILDING PLUMBING CODES

Standards, codes, and guidelines provide information about how to achieve reduced water demand in buildings, but infrequently provide information on potential changes to water quality that result from their use. A more integrated approach to reducing water demand would be beneficial to make the designers and building owners/operators more aware of the ways in which these green technologies and strategies can change the water quality within a building.

10.9 CASE STUDIES

The three case studies illustrated a range of water (and energy) conservation techniques that are being implemented to achieve a reduction in water demand. The solutions ranged from simply using low flow devices to using alternative water sources. In many cases, the effectiveness of treatment strategies applied to green building water systems are largely untested. For example, Field Site #3 with the use of GAC filtration and UV irradiation for treatment of rainwater, resulted in high concentrations of *Legionella* spp. and opportunistic pathogen host organisms. As a result, there appears to be a shift in responsibility for the safety of drinking water in green buildings, intentionally or unintentionally, away from utilities to individual home and building owners/operators. A better understanding of the chemistry and microbial ecology of green building plumbing systems is needed, along with efficacy studies of disinfectant approaches.

10.10 USGBC INSIGHT REPORT

Trends in pathways for achieving Leadership in Environmental Engineering Design (LEED) certification for water efficiency credits were examined. Projects pursing WEc1: Water Efficient Landscaping, projects most often pursue the use no permanent landscape irrigation as means to decrease their overall potable water use. Rainwater was the most common non-potable water source used to replace potable water used for landscaping. In order to reduce the amount of wastewater effluent for buildings in WEc2, high efficiency toilets and non-water urinals were more common than on-site treatment and reuse of the effluent. Overall, identifying the most common ways building designers are achieving these water conservation goals will help direct future research and efforts to further reduce water use.

10.11 CLIMATE FACTORS

Differences in pathways to achieving LEED water efficiency credits between climate regions defined by EERE and NOAA climate systems were examined. Irrigation selections showed differences between most regions under both climate systems. The choice of no permanent irrigation was least used in the Hot-Dry EERE region and three western NOAA regions. Water closet choices showed some differences, with dual flush toilets being selected significantly more in the EERE Marine and NOAA Northwest region. High efficiency urinals showed differences in only one climate classification system, being selected significantly more in the EERE Marine region than in the Hot-Dry and Mixed-Humid regions.

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Results may be related to societal expectations and cultural norms. For instance, landscaping that requires more water than is naturally available in a particular region is common if there is cultural emphasis given to ornate lawns and gardens. The inclusion of climate specific guidelines within the newer green building rating systems could make climate specificity more prevalent in green building water efficiency strategies. Specifically, use of potable water resources for irrigation could be specifically discouraged in some regions of the U.S.

Further study of why the decisions that were made were made could also influence future certification guidelines. For instance, some possible influences on decisions that need further investigation are the input of various stakeholders in the design process, local and regional water efficiency legislation, and local water sensitivity related to non-climate factors such as demand. In addition, understanding if, or when and how, water feature decisions are made because of specific climatic region and water source sensitivity would useful to help influence future buildings design process to be more sustainable to the entire region, and not just the energy and water efficiency of that particular building. The main concern is that while some water conservation practices are overall more "efficient" they might not be ideal in every climate region.

10.12 GREEN BUILDING SURVEY

An internet survey was developed to synthesize experiences of green building professionals with water conservation related innovations. Participants rated their experiences with 33 types of water efficiency innovations, and indicated problems they had experienced. The most common problems were due to pipe leaks and clogs, insufficient hot water, premature system failure, and complaints about taste, odor, or coloration. The majority of respondent ratings of technologies were positive or neutral. Green landscaping innovations were overwhelmingly positive in all categories. Non-water urinals and toilets had the most negative response distributions, followed by blackwater and greywater recovery systems. Attempts to change consumer behavior related to how water is used had mixed results. In general, the lack of negative responses related to specific devices suggests people are overall satisfied with the perceived performance of these innovations. Areas for improvement for this area include lack of engagement with leadership, lack of useable data, or people ignoring behavioral policies that were outside regular norms.

10.13 INTERVIEWS

Phone interviews were conducted with green building professionals from multiple disciplines about experiences with water conservation measures in green buildings. Subjects were asked about their successful and challenging experiences. They were also asked to give advice based on their experiences for other professionals attempting their own conservation measures. Several themes appeared, including clogging and odors associated with non-water urinals, line clogs where insufficient pipe slope was given for high-efficiency toilets, and system problems and failures resulting from difficulties educating maintenance personnel about procedures. Multiple subjects also shared the sentiment that water is underpriced and undervalued, and prices should and will go up in the future.

In the future, achieving effective water conservation in buildings will not be limited to optimizing specific devices, but instead will likely incorporate design of whole water systems. This not only includes potable water supply systems, but consideration of wastewater systems as

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part of a larger green building design strategy as well. However, a way to mitigate concerns with adverse effects caused by these systems on potable water quality will be needed. For example, in high-efficiency system designs where flushing is necessary to reduce water age, the flushed water could be recovered for non-potable uses. Considering the design of the building water system as a whole, both upstream and downstream of the point of use, will be essential to ensure high water quality while achieving conservation goals in the green buildings of the future.

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APPENDIX A – INFORMED CONSENT SCRIPT

Green Building Design: Water Quality and Utility Management Considerations
Interviews
Consent Script

As this study will be done over the phone, verbal consent will be obtained. The script follows:

Thank you for participating in Green Building Design: Water Quality and Utility Management Considerations. Before we continue, I need to read you a consent script to ensure you are fully aware of what you are participating. At the end, I will ask you to give verbal consent before we continue.

This study is being performed by Virginia Tech in conjunction with the Water Research Foundation. Researchers include Dr. Marc Edwards, Dr. Annie Pearce, both professors at Virginia Tech, and Ben Chambers and William Rhoads, graduate students at Virginia Tech.

The study is designed to identify and understand unanticipated consequences of green water technologies and practices on water use in buildings. It is a multi-phase research study with internet surveys, phone interviews, and site visits. Subjects are green building professionals in the United States, and there are expected to be about 50 participants in this phone interview phase.

This portion of the study will take approximately 30 minutes of your time, all over the phone. I will ask you a series of open-ended questions about your experiences, and allow you to respond to your satisfaction. We will be recording and transcribing your responses, but all identifying information will be removed and replaced with an ID code to protect your privacy, and the only individuals with access to this information will be the four research workers. It is possible that the Institutional Review Board (IRB) may view this study's collected data for auditing purposes. The IRB is responsible for the oversight of the protection of human subjects involved in research. We will not quote you or use identifying information without express written consent from you. Data will be destroyed three years after publication of results.

There are no expected risks to this study. Benefits are the knowledge of common problems with green water systems that they might be studied and fixed, which could improve your professional life.

There is no compensation for this interview. You are free to withdraw at any time without penalty. You are free to not answer any questions if you choose without penalty.

Do you have any questions?

If you have any further questions, the contact information for the investigators and IRB have already been provided by email.

Have you heard and understood the consent language for this study? Have you had all of your questions answered? Do you give your voluntary consent?

Thank you. We can now begin.

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APPENDIX B – INTERVIEW QUESTIONS

Green Building Design: Water Quality and Utility Management Considerations
Interviews
Data Collection Instruments

Interview Question Worksheet

Demographics - Understanding the Interviewee and their Organization (5 min)

1. What is your Job Title? What did you do before this?	
2. Tell us about your building portfolio or buildings with which you are involved. a. Types of buildings, number b. Special functions, if any, with respect to water	
3. What are your job tasks and responsibilities? What role do you play with respect to <organization's> buildings?	

Organizational Choices about Water Technologies (10 minutes)

4. What are your organization's goals with regard to building water conservation and use? a. General impression - important? Ambitious? b. Links to any explicit written goals or policies c. Verification of any policies we learned about on the web	

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5. How have these goals influenced the types of water technologies used in your projects?	
6. What else (e.g., external policies, incentives, programs) has affected the technologies and systems used?	
7. What have been your major successes with innovative water-related technologies over the past 5-10 years? a. What has been tried? b. What has been routinized?	

Unanticipated Consequences of Innovations (10 min)

8. What innovations have resulted in unexpected or undesirable outcomes? a. Project details b. Technologies used c. Causes of problems d. Resolution <Provide prompt from survey if completed>	
9. What types of building water problems have you heard about but not experienced personally?	
10. Have these experiences changed how you approach future projects? In what way?	

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11. What is the most challenging innovation (water or not) you have undertaken on a project? a. Why was it challenging? b. What was the outcome?	

Perspectives on the Future of Water-related Innovations (5 min)

12. What do you see as the future of <organization's> buildings with respect to water? a. How do you see things changing in the next five years? b. Ten or more?	
13. What will be driving those changes? a. Internal factors b. External factors	
14. How successful is the field of 'green' water technologies now? How does it need to change in the future?	
15. What advice would you have for others trying to innovate in their building water systems?	

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APPENDIX C – INTERVIEWEES' GREATEST SUCCESSES WITH BUILDING WATER CONSERVATION MEASURES

Reference	Category	Innovation	Count	Description
S1	Alternative Water Sources	Blackwater Reuse	1	Users expressed pleasure upon realizing that the plant beds they had been admiring were part of the treatment system.
S2	Alternative Water Sources	Blackwater Reuse	1	Pleased with the functioning of blackwater treatment systems.
S3	Alternative Water Sources	Condensate Recovery	2	Recovering condensate and stormwater resulted in significant savings on water use.
S4	Alternative Water Sources	Condensate Recovery	2	Because sewerage rates were based on water draw, using non-utility sources such as condensate recovery for non-sewer applications such as evaporative coolers and landscaping removed the problem of paying for sewerage that was not being used.
S5	Alternative Water Sources	Condensate Recovery	1	Cooling tower water management was a significant source of savings at low investment cost.
S6	Alternative Water Sources	Rainwater Harvesting	2	Using rainwater for landscaping irrigation resulted in cost savings.
S7	Alternative Water Sources	Rainwater Harvesting	2	Pleased with the functioning of rainwater harvesting systems.
S8	Alternative Water Sources	Rainwater Harvesting	1	Pleased with functioning of vortex upright filters.
S9	Alternative Water Sources	Rainwater Harvesting	1	Using rainwater as a source for ultra-pure industrial or lab water significantly reduced the costs for treatment, as it is more pure than tap water.

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Reference	Category	Innovation	Count	Description
S10	Landscaping	Green Stormwater Retention and Infiltration	2	Pleased with the functioning of green stormwater retention and infiltration systems.
S11	Landscaping	Water Conserving Plant Selection	3	Pleased with reduced irrigation cycling allowed by drought resistant plant selection.
S12	Performance Monitoring	Other	2	Leak surveys have been successful in dramatically reducing fault-related water waste.
S13	Performance Monitoring	Sub-Metering	1	Individual building bills for a large facility created internal competition and awareness that led to many users and personnel searching for ways to reduce water use.
S14	Shower and Faucet Fixtures	Alternative Controls	3	Automatic cutoff sinks have worked well, and have prevented multi-day discharge from people leaving sinks on in little used bathrooms over weekends.
S15	Shower and Faucet Fixtures	Low Flow Fixtures	2	Low-flow sinks and showers have consistently proven cost effective, particularly because of hot water energy savings.
S16	Shower and Faucet Fixtures	Low Flow Fixtures	1	By going to restaurants and offering to install a water saving version of a dishwashing nozzle product for free, a utility reduced stress on their water supply while giving significant annual savings to the restaurants.
S17	Toilets and Urinals	Alternative Flushometer Valves	3	Dual-flush toilets have been well received and worked well.
S18	Toilets and Urinals	Alternative Flushometer Valves	1	Pressure assisted flush toilets have worked well.
S19	Toilets and Urinals	Alternative Flushometer Valves	1	Customers appreciate touch free sensors on toilets and sinks, and are asking for them on other features, like towel dispensers.

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Reference	Category	Innovation	Count	Description
S20	Toilets and Urinals	Water Conserving Urinals	2	Pint flush urinals have been well received and worked well.
S21	Toilets and Urinals	Water Conserving Urinals	1	Half-gallon flush urinals have been well received and worked well.
S22	Toilets and Urinals	Water Conserving Toilets	2	High efficiency toilets have worked well.
S23	Toilets and Urinals	Non-Water Urinals	1	High visibility of non-water urinals has made many users notice them and get excited.
S24	User Education	Other	1	Pleased with the success of LEED criteria at promoting water efficiency and making it mainstream, accepted practice.
S25	User Education	Other	1	Pleased with the success of WaterSense at promoting water efficiency and making it mainstream, accepted practice.
S26	User Education	Signage and Educational Materials	2	User education has helped to reduce water usage.
S27	User Education	Signage and Educational Materials	1	By setting up demonstration gardens, involving gardening clubs, and making educational materials accessible at points of sale, xeriscaping was successfully promoted in the community by the utility.
S28	User Education	Signage and Educational Materials	1	WaterSense was successfully promoted for new homes in an area, easing strain on the water utility.
S29	User Education	Signage and Educational Materials	1	Providing new owners and maintenance staff manuals and maintenance logs and requiring them to sign papers off on having received and read them has reduced conflict and litigation, though it has not significantly reduced failure incidence.
S30	User Education	Signage and Educational Materials	1	Teaching plumbers about MaP testing and other certifications has stopped wholesale rejection of efficient toilets after bad experiences.

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Reference	Category	Innovation	Count	Description
S31	User Education	Signage and Educational Materials	1	MaP testing and other certifications have helped to reduce the spread of greenwashing and ineffective products.
S32	Other	Other	1	All the toilets being replaced were recycled for building materials, utilizing a waste stream and saving landfill space.
S33	Other	Other	1	Centralized treatment systems for lab or process water significantly reduced waste and maintenance costs.
S34	Other	Other	1	Successful codification of water softening saved water heater efficiency and plumbing fixtures from scaling.

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APPENDIX D – INTERVIEWEES' DIFFICULT EXPERIENCES WITH BUILDING WATER CONSERVATION MEASURES

Reference	Category	Innovation	Count	Description
D1	Alternative Water Sources	Blackwater Reuse	1	Blackwater system was very susceptible to whole system failure due to minor malfunctions such as blown fuses or loose contacts.
D2	Alternative Water Sources	Blackwater Reuse	1	Facility did not budget for major maintenances of blackwater system, and a plumbing failure could not be repaired. The system has been sitting unused for years.
D3	Alternative Water Sources	Blackwater Reuse	1	Lack of incentives in some rating systems for blackwater treatment directed focus away from it in spite of the significant water savings possible.
D4	Alternative Water Sources	Greywater Reuse	3	Lack of proper maintenance by uninformed or unwilling maintenance staff caused greywater systems to go septic. Reducing maintenance load with measures such as adding backwashing filters has reduced problems.
D5	Alternative Water Sources	Greywater Reuse	1	Greywater systems have not performed to manufacturer claims.
D6	Alternative Water Sources	Greywater Reuse	1	Greywater systems have failed because they were designed by people without the proper expertise.
D7	Alternative Water Sources	Greywater Reuse	1	Greywater systems were blamed for all bad odors in buildings, regardless of actual fault.
D8	Alternative Water Sources	Rainwater Harvesting	2	Poor installation jobs for rainwater harvesting systems by novices caused failures including tank contamination, pump bun-out, plumbing cross-contamination, discolored water, and systems going septic.
D9	Alternative Water Sources	Rainwater Harvesting	1	Rainwater harvesting systems or components did not perform consistently with manufacturer claims.

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Reference	Category	Innovation	Count	Description
D10	Alternative Water Sources	Rainwater Harvesting	1	Lack of proper maintenance of rainwater harvesting systems by owners, particularly regarding pre-filters, has caused systems to go septic.
D11	Alternative Water Sources	Rainwater Harvesting	1	Water discoloration from green roof substrates discouraged the use of toilets containing the water.
D12	Alternative Water Sources	Rainwater Harvesting	1	Rainwater corroded copper pipes.
D13	Landscaping	Green Stormwater Retention and Infiltration	1	Bio-retention system took more maintenance than was budgeted, and undesired species took over.
D14	Landscaping	High Efficiency Irrigation	2	Users superseded high efficiency irrigation system technology intent or did improper maintenance due to lack of understanding of the systems.
D15	Landscaping	High Efficiency Irrigation	1	High efficiency irrigation systems were not life cycle cost effective individually. Grouping buildings for economies of scale fixed this.
D16	Landscaping	High Efficiency Irrigation	1	In green roof systems, drip irrigation did not work with highly porous substrate as water just fell through, leaving many areas dry. Porosity also made moisture sensors ineffective. With spray systems, significant amounts of water were lost to evaporation and the breeze.
D17	Landscaping	Other	1	Architects did not understand the implications of their landscape decisions on stormwater discharge to the neighborhood, causing flooding of some areas.
D18	Landscaping	Water Conserving Plant Selection	1	Xeriscaping saved on water and O&M, but proved not to be cost effective due to the low cost of water.
D19	Shower and Faucet Fixtures	Alternative Controls	1	Automatic faucets regularly failed, and replacement parts were difficult or expensive to obtain.

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Reference	Category	Innovation	Count	Description
D20	Shower and Faucet Fixtures	Alternative Controls	1	Users complained about automatic faucets making tooth brushing and other non-hand washing actions difficult.
D21	Shower and Faucet Fixtures	Alternative Controls	1	Automatic faucets made it difficult or impossible to get hot water out of sinks.
D22	Shower and Faucet Fixtures	Low Flow Fixtures	2	Low flow faucets made it difficult to get hot water out of sinks.
D23	Shower and Faucet Fixtures	Low Flow Fixtures	2	Faucet aerators were found to grow bacteria. They were replaced with antimicrobial models.
D24	Shower and Faucet Fixtures	Low Flow Fixtures	1	Users removed faucet and shower aerators to increase flow.
D25	Shower and Faucet Fixtures	Low Flow Fixtures	1	Users removed faucet aerators for use in construction of drug paraphernalia (bongs or water pipes). Aerators were replaced with locking models.
D26	Shower and Faucet Fixtures	Low Flow Fixtures	1	Users complained about low flow faucets increasing the time necessary to fill containers.
D27	Shower and Faucet Fixtures	Low Flow Fixtures	1	Faucet aerators were found to have significant scale buildup and required undesirable extra maintenance.
D28	Shower and Faucet Fixtures	Low Flow Fixtures	1	Low flow showerheads in old buildings provided inconsistent pressures and flow rates.
D29	Toilets and Urinals	Alternative Flushometer Valves	2	Automatic flush toilets had significant numbers of false flushes.
D30	Toilets and Urinals	Alternative Flushometer Valves	1	Automatic flush toilets regularly failed, and replacement parts were difficult or expensive to obtain.
D31	Toilets and Urinals	Alternative Flushometer Valves	1	Remote operated flushometer controls have been promoted by salespersons as an easy way to get LEED certification and easily increase toilet flow afterwards.
D32	Toilets and Urinals	Alternative Flushometer Valves	1	Dual flush toilets were unnecessarily placed in bathrooms with urinals.

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Reference	Category	Innovation	Count	Description
D33	Toilets and Urinals	Alternative Flushometer Valves	1	Dual flush toilet valves were not accurate.
D34	Toilets and Urinals	Non-Water Urinals	7	Non-water urinals caused drain clogging and foul odors.
D35	Toilets and Urinals	Non-Water Urinals	1	Non-water urinal cartridges were repeatedly destroyed by chewing tobacco expectoration from users.
D36	Toilets and Urinals	Non-Water Urinals	1	Non-water urinal cartridges were destroyed by janitorial staff emptying mop buckets containing cleaning products into them.
D37	Toilets and Urinals	Water Conserving Toilets	10	High efficiency toilets created plumbing problems due to the water content and pipe slope, possibly compounded by line length.
D38	Toilets and Urinals	Water Conserving Toilets	2	High efficiency toilets created problems with sewer lines due to the water content, requiring extra flushing.
D39	Toilets and Urinals	Water Conserving Toilets	2	Users complained about odors in high efficiency urinals.
D40	Toilets and Urinals	Water Conserving Toilets	1	Pipe roughness created problems with high efficiency toilets in older buildings.
D41	Toilets and Urinals	Water Conserving Toilets	1	After encountering problems with high efficiency toilets, plumbers have refused to consider them ever again.
D42	Toilets and Urinals	Water Conserving Toilets	1	Water conserving toilets and urinals were not life cycle cost effective when implemented only in low usage buildings. Combining them with high usage buildings for large design or retrofit projects made them financially justifiable.
D43	Toilets and Urinals	Water Conserving Toilets	1	Water conserving toilets over strengthened wastewater stream to sewage treatment facility, necessitating major upgrades.
D44	Toilets and Urinals	Water Conserving Toilets	1	Users tampered with high efficiency toilet valves to increase flow, causing damage.

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Reference	Category	Innovation	Count	Description
D45	Toilets and Urinals	Water Conserving Toilets	1	Construction or project managers insisted upon the installation of standard flow fixtures despite specifications.
D46	Toilets and Urinals	Non-Water Toilets	1	Mistakes during construction caused vent clogging on a composting toilet system that caused foul odors for a long time before being caught and repaired.
D47	Other	Other	2	Lower water use in some areas has increased water age and decreased chlorine residuals, creating water quality issues. Fire codes mandated fire sprinklers in new homes, requiring larger supply lines and meters, further compounding this problem.
D48	Other	Other	1	Experience with problems with early water efficiency technologies made during the 1990s has caused people to refuse to try or even consider new versions.
D49	Other	Other	1	Self-priming traps did not fill due to the combination of low-use and low-volume fixtures, allowing sewer odors to escape. Regular flushing of drains was required.
D50	Other	Other	1	Owners and operators lacked good information about the maintenance and use of their water conservation features. They did not seek information due to the undervaluing of water.
D51	Other	Other	1	Contractors who are used to operating in a particular way and already have established supplier relationships have been difficult to convince to make water conservation changes.

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APPENDIX E – ADVICE GIVEN BY INTERVIEWEES TO OTHERS IN THEIR FIELDS SEEKING TO IMPLEMENT WATER CONSERVATION EFFORTS

Reference	Count	Advice
A1	9	Water is currently undervalued and underpriced. Prices should or will increase, making these measures more cost effective and popular.
A2	6	Water efficiency in bathrooms is nearly at its peak. It is time to shift focus to recycling and recovery in areas such as condensate, HVAC, and process water.
A3	5	Make sure that fixture options are well researched before making selections. Talk to people who have used them. Do not rely on price, manufacturer specs, or aesthetics alone, and be aware of possible parts supply issues.
A4	5	Get involved in the policy decision making process for codes and standards, and make sure that government makes features like green architecture and rainwater and greywater recovery legal and easy to accomplish in all jurisdictions. Meeting criteria like WaterSense could become required.
A5	3	When installing toilets with low volume flushes, avoid long line carry and make sure there is sufficient grade.
A6	3	Always lead with a strong education program. Following instructions and manuals is extremely important. Make sure that your maintenance people read them. If you are passing a project off, make sure the new owners or managers sign a statement that they have received and read the instructions. Including log books may also help.
A7	2	When designing or implementing water conservation efforts, be sure to take a holistic look at the facility. This will help to find the areas where the biggest difference can be made.
A8	2	Do thorough cost-benefit analyses to ensure that plans make sense. Be aware of energy efficiencies, materials, plumbing schemes, and possible future add-ons. The minute energy savings from things like self-powering auto-flush or faucet systems alone are not sufficient reason to install them.
A9	2	Sustainability decisions should be made in the first part of the design process for maximum impact and minimum cost. Structural differences are likely to help more than the details of what is selected inside, and won't cost any extra if made early in the design phase.
A10	1	If drawing water from a well, be aware that grit from the well may impact the function of plumbing fixtures.
A11	1	If you are an early adopter of an innovation, start with a small scale test.

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Reference	Count	Advice
A12	1	Investigate the cleaning capabilities of sinks with reduced flow before implementing them in highly sensitive buildings such as hospitals.
A13	1	Completely waterless technologies meet resistance because of human perceptions of the necessity of water for cleaning things. When up against this, get the lowest flow possible with suitable performance.
A14	1	Long term studies (10 years or more) need to be done on the effects of water efficient fixtures on pipes.
A15	1	The industry would benefit greatly from regional benchmarks for water conservation. Standards, codes, and the like could be dramatically improved with this information.
A16	1	Try to install wastewater treatment systems that have some built-in redundancy and partial function if minor parts fail.
A17	1	Don't think of greywater systems as add-ons. When designing buildings, imagine that they will be installed eventually, and plan accordingly.
A18	1	Don't forget to look for leaks and check plumbing fixtures for proper function.
A19	1	Make sure to do water and stormwater calculations in the context of the neighborhood as well as the building, especially in flood-prone areas.
A20	1	Rainwater, greywater, and blackwater treatment systems would benefit greatly from true turnkey systems.
A21	1	Don't forget that low water use plants need extra attention the first year or two to get established, or you'll lose a lot of them.
A22	1	Stagger Y joints in sewage plumbing at least a few feet, to avoid 'perfect storms' of paper out of low-flow toilets catching and clogging.
A23	1	Look for other sources of water for evaporators to save on sewage bills if you pay sewage based on draw. Wells are one source.
A24	1	Don't tell occupants about minor changes, especially in flow rates on sinks and toilets. They tend not to notice on their own, and then they don't complain about having to make changes to their routine.
A25	1	Trying to turn a desert into an oasis doesn't work. Use climate appropriate landscaping. Try to get past the east coast idea that green is good and brown is bad.
A26	1	We should all be using water that is 'fit for purpose', but most people have a hard time accepting or understanding that. There needs to be a matchup between end uses and water source and treatment. You don't need drinkable water to flush a toilet.
A27	1	Larger water recycling projects tend to be more economically viable. Think big.
A28	1	When dealing with wastewater treatment systems, don't let your manufacturer only provide the equipment. Make sure they work with you to develop a whole working system. These systems take a lot of collaboration.

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Reference	Count	Advice
A29	1	Try not to work with too many subcontractors, as doing so increases the chances of confusion, miscommunication, and mistakes.

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ABBREVIATIONS LIST

Ag – Silver (ions, metal, could refer to particulate and/or soluble).
ANSI – American National Standards Institute.
AOC – assimilable organic carbon.
ASHRAE – American Society for Heating, Refrigeration, and Air-conditioning Engineers.
ATP – Adenosine triphosphate.
AWT – Association of Water Technologies.
BART – Biological activity reactivity test.
BCV – Blacksburg-Christiansburg-VPI Water Authority.
CCPP – Calcium Carbonate Precipitation Potential.
CDC – Center for Disease Control.
CFU – colony forming unit.
CPVC – Chlorinated polyvinyl chloride (premise plumbing pipe material).
Cu – Copper (ions, metal, could refer to particulate and/or soluble).
DBPR –Department of Business and Professional Regulation.
DGGE – Denaturing gradient gel electrophoresis.
DN – Denitrifying bacteria.
DNA – deoxyribonucleic acid.
DO – Dissolved oxygen.
DOH – Department of Health.
DWS – Maui Department of Water Supply.
EDC-IS – Epidemiology Disease Control, and Immunization Services.
EERE – US Department of Energy's Office of Energy Efficiency and Renewable Energy.
EF – electronic faucet.
G6PD - Glucose-6-phosphate dehydrogenase.
GAC – Granular activated carbon (filter).
HAB – heterotrophic aerobic bacteria.
HACCP – Hazardous Analysis Critical Control Point.
HDPE – High density polyethylene.
HPC – heterotrophic plate count.
IES – Illuminating Engineering Society.
IgCC – International Green Construction Code.
LCR – Lead and Copper Rule.
LD – Legionnaires' disease.
LEED – Leadership in Environmental Engineering Design.
LSI – Langelier Saturation Index.
MAC – Mycobacterium avium complex.
MC – monochloramine.
MCCP – Measured Calcium Carbonate Precipitation.
MDCHD – Miami-Dade County Health Department.
MDPE – Medium density polyethylene.
MPW – Marshall pitting water.

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MRDL – Maximum Residual Disinfectant Level.
NAHB – National Association of Home Builders.
NB – Nitrifying bacteria.
NI – Nucleation Index.
NOAA – National Oceanic and Atmospheric Administration.
NOM – Natural organic matter.
NRC – National Research Council.
NSF – National Science Foundation.
NTM – Non-tuberculosis Mycobacteria.
OPPP – Opportunistic pathogen in premise plumbing.
OR – odds ratio.
OSHA – Occupational Safety and Health Administration.
PAH – Polycyclic aromatic hydrocarbons.
Pb – Lead (ions, metal, could refer to particulate and/or soluble).
PCR – polymerase chain reaction.
PCU – Pinellas County Utility.
PEX – Cross-linked polyethylene (premise plumbing pipe material).
PVC – Polyvinyl chloride (premise plumbing pipe material).
QA/QC – Quality Assurance/Quality Control.
qPCR – Quantitative polymerase change reaction.
rRNA – ribosomal ribonucleic acid.
SRB – Sulfate reducing bacteria.
TOC – total organic carbon.
t-RFLP – terminal restriction fragment length polymorphism.
U.S. – United States.
U.S. EPA – United States Environmental Protection Agency.
UNC – University of North Carolina.
USGBC – United States Green Build Council.
UV – ultraviolet (light, disinfection).
VOC – Volatile organic carbon.
WHO – World Health Organization.
WQRC – Water Quality Research Council.

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