








Article

# Managing Water Quality in Premise Plumbing: Subject Matter Experts' Perspectives and a Systematic Review of Guidance Documents

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Received: 13 December 2019; Accepted: 17 January 2020; Published: 26 January 2020



**Abstract:** Although many guidance documents have been developed to inform the design and operation of building water systems to ensure safe water quality, there is a lack of consensus on some topics. This study interviewed 22 subject matter experts (SMEs) to identify topics of concern for managing water quality in buildings and compared SME views with information available on these topics in 15 systematically screened important guidance documents. The study found 18 design and 11 operational topics as critical for managing water quality in buildings. No one guidance document addressed all these topics, suggesting that a compendium of available guidance is needed. SMEs most frequently recommended temperature and residual disinfectant measurements as good parameters for monitoring overall building water quality. Both SME and guidance document recommendations for temperature for controlling opportunistic pathogen growth were reasonably consistent with water heater setpoint >60 °C. However, hot water temperature recommendations varied between 50 and 55 °C for other locations (i.e., the water temperature at the tap or end of the return loop). On the contrary, recommendations for disinfectant residual levels (0.2–2.0 mg/L), flushing frequency (1–14 days), and allowable time for hot water to reach the tap (10–60 s) were not consistent. While this study was able to reconcile diverging views on some of the water quality topics, such as identifying common guidance for water heater set point to at least 60 °C, it also highlights lack of definitive guidance on other critical topics, such as residual level, flushing frequency, hot water time to tap, and the use of thermostatic mixing valves, indicating that these are significant knowledge gaps that need further investigation. The study concludes that there is a need for developing evidence-based guidance, particularly on the topics where expert opinions diverged.

**Keywords:** *Legionella*; opportunistic premise plumbing pathogens; water quality in buildings; guidance documents; water heater setpoint temperature; disinfectant residual; mycobacteria

## 1. Introduction

Water quality in the water supplier's distribution system is subject to monitoring and regulation, but once water enters a building plumbing system, the responsibility for maintaining water quality shifts to the building owner, occupants, and/or facility manager. In many cases, these stakeholders are not water quality specialists but nevertheless must address an array of water quality concerns. These concerns are driven by the potential for water quality to deteriorate in building plumbing systems due to chemical and biological reactions in the bulk water and interactions with pipe surfaces [1]. One manner in which water quality may deteriorate in buildings is through the growth of opportunistic premise plumbing pathogens (OPPPs) (i.e., *Legionella pneumophila* [2,3], non-tuberculous mycobacteria, *Pseudomonas aeruginosa*, etc.), which can be enabled by the loss of residual disinfectant over extended residence times. Extended residence times in building plumbing can also allow for corrosion (which may release copper and lead) and the continued formation of disinfection byproducts (DBPs) (TTHMs, HAAs).

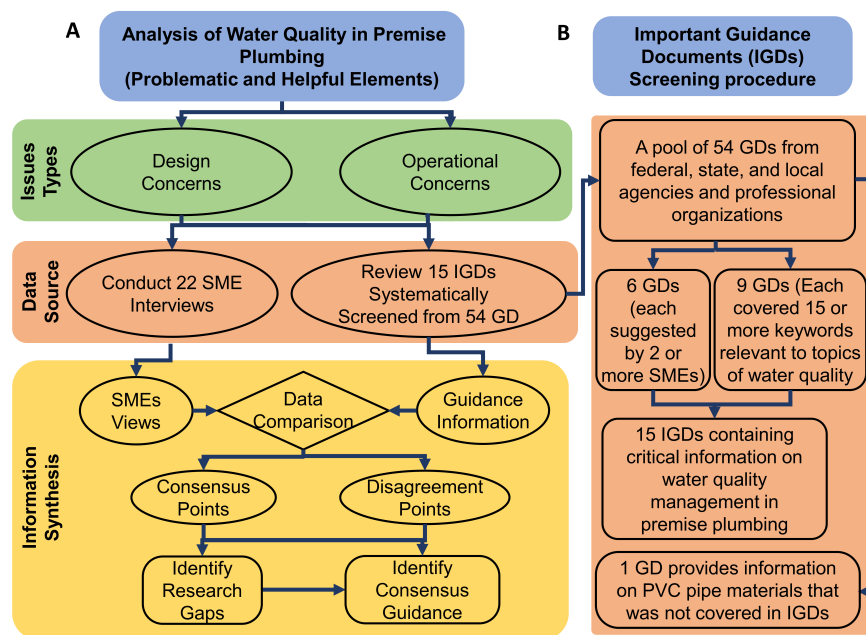
Operators and researchers have been working on identifying conditions that are favorable or unfavorable to water quality in buildings and thus seeking to identify management steps for ensuring water quality in building plumbing systems [4–6]. Management guidance has focused primarily on preventing Legionnaires' disease, as this is a US Centers for Disease Control and Prevention reportable illness (the only one caused by opportunistic pathogens known to be found in building plumbing) [7] has been associated with high litigation costs [8,9], and has driven public concerns [10]. To address these risks, numerous federal, state, and local agencies and organizations worldwide have developed guidance for managing water quality in buildings, many of which focus on *Legionella* control [11–13]. Academic research has also focused on *Legionella*; Bédard et al. [4] have provided a temperature diagnostic to identify high-risk areas and optimize *Legionella pneumophila* surveillance in hot water distribution systems. Similarly, Rhoads et al. [5] studied how water heater temperature setpoint and water use patterns influence the occurrence of *Legionella pneumophila* and associated microorganisms at the point of use.

Despite the existence of guidance documents, this guidance is not always consistent across sources [13–15]. Guidance documents do not always explain the underlying causal model and full evidence basis for their recommendations, which makes it difficult to understand why recommendations may differ or where the evidence base is lacking. In addition, guidance documents are, by their nature, consensus documents and may have gaps where consensus cannot be reached. In contrast, subject matter experts (SMEs) can provide perspectives on causal models and the strength of available evidence that may be missing or implicit in guidance documents and can provide views on areas for which consensus has not yet been reached.

In this study, our goal is to elicit SME views of important factors influencing water quality in premise plumbing systems and compare this information with what is found in existing guidance documents. This goal is achieved through the following four steps: to (1) identification of subject matter expert concerns regarding water quality in buildings; (2) assessment of information available in guidance documents on these concerns; (3) identification of indicator parameters and appropriate ranges for these indicator parameters that may be used to manage these concerns from guidance documents and SMEs; and (4) identification of gaps in understanding that are either acknowledged by SMEs or suggested by discrepancies among SMEs and guidance document views.

## 2. Data Sources and Methodologies

This study identified critical issues for maintaining water quality in building plumbing systems through semi-structured interviews of SMEs and contrasted this information with that obtained from a review of existing guidance documents on water quality in building plumbing systems (Figure 1A). A comparison was then made between the data obtained from these two sources, and recommendations for integrating guidance across documents were developed.



**Figure 1.** (A) Schematic showing the process of data collection and analysis for water quality management in premise plumbing. (B) Flow chart showing screening the important guidance documents (IGDs) from a pool of guidance documents. (SME—subject matter expert; GD—guidance document; IGDs—important guidance document.)

### 2.1. Subject Matter Experts Consultations

Approval for recruiting human research subjects was provided by the Drexel Institutional Review Board (IRB ID# 1705005417). SMEs were not personally identified in this work in accordance with the approved protocol. However, SMEs were given an opportunity to review this manuscript and to request statements in this work be attributed to them as acknowledgment of their contributions. No SME contacted requested personal attribution.

A snowball sampling approach [16] was used for recruiting subject matter experts (SMEs) with interdisciplinary backgrounds from across the United States to include a diversity of viewpoints. The primary SME interviews were conducted between April and November 2017, and subsequent follow-ups were made during the coding process, if required. Among 36 SMEs contacted, 22 agreed to participate in the study, including experts from academic research (41%), government (27%), the plumbing or facilities management industry (18%), and drinking water utilities (14%). SMEs participated in a roughly 1 h semi-structured phone interview to discuss a series of questions related to water quality in building plumbing. The interview protocol consisted of nine general questions (detailed in Supplementary Information 1) about building plumbing system operational and design parameters that have most significant impact on water quality, appropriate indicators of water quality in this context, existing sources of information and guidance, tools required for water quality monitoring and management, significant knowledge gaps, and other experts in the area.

Two interviewers generated their interview notes during the interviews. Based on the interview notes, the interviewers flagged common themes and generated a scheme for coding the interviews. The coding process consisted of recording the presence of favorable and unfavorable mentions of each topic coverage (i.e., “favorable” mentions indicated that the factor is protective of, or beneficial to water quality, and “unfavorable” mentions indicated that the factor contributes to the degradation of water quality) by each SME in a standard template along with notes on the specific reasoning behind these overall assessments. If a single SME made one or more favorable (or unfavorable) points on a topic, then that SME was coded as having favorable (or unfavorable) views present for that topic coverage. A single SME could be coded as making both favorable and unfavorable mentions for each topic coverage;

we did not attempt to quantify the “degree” of discordance and as such, we did not tally the number of favorable or unfavorable points mentioned by an individual SME on a given topic. To assess the consistency of the coding protocol, both interviewers coded five interview responses individually, and agreement between the reviewers’ coding was evaluated based on the percentage of matching codes for each item on the template. An agreement score of greater than 80% was achieved on all five coded expert interviews, and the coding protocol was then applied to the remaining interviews.

## 2.2. Existing Guidance and Selection of Important Guidance Documents (IGDs)

Guidance documents were defined as any policy, ordinance, regulation, or recommendation put forth by a government or professional society. A pool of guidance documents was compiled through a literature search that was guided by the topics and priorities identified in the SME interviews, which tended to emphasize opportunistic pathogens, particularly *Legionella* spp. The literature search included an internet search conducted using phrases such as ‘building water quality’ and ‘*Legionella*’ in databases such as ‘Web of Science’ and ‘Google Scholar.’ However, the search was not restricted to documents addressing *Legionella*. Guidance documents were also collected from the references of relevant building water quality review papers such as Parr et al. [13]. A pool of 54 such building water quality guidance documents from various federal, state, and local agencies and professional organizations from the United States and worldwide was identified, and a list of these documents is shown in Table S1 of the SI. The scope of the study did not permit all of these sources to be reviewed in detail. For this reason, the guidance documents were first separated into two tiers. The first tier, referred to as important guidance documents (IGDs), consisted of 15 documents that were searched for all topics identified by the SME interviews. The remaining 39 documents were consulted only when a topic identified by the SME interviews was not addressed in the IGDs.

The process of identifying IGDs from the pool of 54 guidance documents is shown in Figure 1B. Guidance documents were selected as IGDs for either of two reasons: (1) the document was specifically identified by multiple SMEs as important and (2) a keyword search indicated that the document covered a high percentage of topics identified as relevant by SMEs. For the first selection approach, 6 documents were cited as important by two or more SMEs and were included as IGDs. The remaining 16 guidance documents, each recommended by only one of the SMEs and the 32 guidance documents not mentioned by SMEs were reviewed for relevance. A list of 50 keywords relevant to the topics of water quality concerns in premise plumbing systems was identified from the SME interviews in this study (see Table S2 of SI for the full list). This list included water quality indicators (i.e., conductivity, pH, etc.), design specifications (thermostatic mixing valves, pipe size, etc.), and operational actions and parameters (water age, disinfectant residual, flushing, etc.) mentioned by SMEs during interviews; a complete list of these keywords is included in the supplementary information (Table S2). Each of the guidance documents was then searched for these 50 keywords. A cutoff score of 15 or more mentions of different keywords was set, which resulted in 9 additional documents being identified as IGDs for a total of 15 IGDs as shown in Table 1. These guidance documents predominantly address *Legionella* but include general guidance (reports 3 [17], 5 [18], and 6 [19] in Table 1) and one that addresses *Pseudomonas aeruginosa* (report 14 [20] in Table 1).

**Table 1.** List of important guidelines documents (IGDs) identified using subject matter expert (SME) recommendations and topic coverage (TC; see text for a description of how counts were developed).

Sl. No.	Title	Reference	Reason SELECTED	SME Mentions	Relevant TC
1	Legionellosis: Risk Management for Building Water Systems	ASHRAE, 2018 [11]	SMEs, TC	12	20
2	<i>Legionella</i> and the prevention of legionellosis	WHO, 2007 [21]	SMEs, TC	3	31
3	Water safety in buildings	WHO, 2011 [22]	SMEs, TC	1	30
4	Developing a water management program to reduce <i>Legionella</i> growth & spread in buildings	CDC, 2017 [12]	SMEs, TC	10	21
5	Guidelines for Environmental Infection Control in Health-Care Facilities: Recommendations of CDC and the Healthcare Infection Control Practices Advisory Committee (HICPAC)	CDC, 2003 [18]	SMEs, TC	1	30
6	2016 Annex to the model aquatic health code: scientific rationale	CDC, 2016 [19]	TC	-	29
7	European technical guidelines for the prevention, control, and investigation, of infections caused by <i>Legionella</i> species	European Guidelines Working Group, 2017 [23]	SMEs, TC	1	30
8	Code of practice: Prevention and Control of Legionnaires' disease 2010	Government of Western Australia, 2010 [24]	TC	-	17
9	Legionnaires' Disease: Section II: What water systems in workplaces are potential sources of Legionnaires' bacteria (LDB)?	OSHA, (1996) [25]	TC	-	22
10	Requirement to Reduce <i>Legionella</i> Risk in Healthcare Facility Water Systems to Prevent Cases and Outbreaks of Legionnaires' Disease (LD)	CMS, 2017 [26]	SMEs, TC	3	9
11	Drinking Water Criteria Document for <i>Legionella</i> (Final Draft)	U.S. EPA, 1985 [27]	SMEs, TC	4	21
12	VHA Directive 1061: Prevention of healthcare-associated <i>Legionella</i> disease and scald injury from potable water distribution systems	Department of Veterans Affairs, 2014 [28]	SMEs, TC	1	17
13	VHA Directive 2008–2010: Prevention of <i>Legionella</i> disease	Department of Veterans Affairs, 2008 [29]	SMEs, TC	2	11
14	Health Technical Memorandum 04-01: Safe water in healthcare premises. Part C: <i>Pseudomonas aeruginosa</i>	UK Department of Health-Part C, 2017 [20]	SMEs, TC	1	18
15	Management of <i>Legionella</i> in Water Systems	NASEM 2019 [30]	TC	-	40

The shortlisted 15 IGDs were carefully reviewed and favorable and unfavorable information on each topic of water quality concern was coded and detailed notes were made on the specific reasoning behind these overall assessments. For three design topics and one operational topic guidance on the topics were either not found in the IGDs or found in only a single IGD; in those cases, a search of the remaining 39 non-important guidance documents was conducted. In only 1 case was relevant guidance found in one of the non-IGD documents, resulting in an additional guidance document being consulted. Thus, the guidance identified and compiled in Tables 2 and 3 contains information from a total of 15 IGDs [11,12,18–30] and 1 non-IGD [31].

**Table 2.** Summary of the favorable and unfavorable views of SMEs and guidance documents on various premise plumbing design factors. F—favorable and UF—unfavorable references.

Design Factors	SME F-Mentions	SME UF-Mentions	Guidance F-Mentions	Guidance UF-Mentions	Reference
Distant taps/devices	0	3	0	2	UF-WHO, 2007 [21]; NASEM, 2019 [30]
Low flow fixtures	0	7	0	2	UF-Department of Veterans Affairs, 2014 [28]; NASEM, 2019 [30]
Oversized pipe diameters	0	5	0	2	UF-CDC, 2003 [18]; NASEM, 2019 [30]
Building size	0	6	0	3	UF-WHO, 2007 [21]; WHO, 2011 [22]; CDC, 2016 [19]
Building layout (are water fixtures close to each other)	0	3	0	2	UF-WHO, 2007 [21]; CDC, 2003 [18]
Hydraulics of system: poorly balanced flow, short circuiting, dead ends, long travel times	0	12	4*	4*	F and UF-WHO, 2007 [21]; CDC, 2003 [18]; WHO, 2011 [22]; NASEM, 2019 [30]
Green buildings	0	6	1	1	F and UF-NASEM, 2019 [30]
Flexible shower hoses	0	3	0	2	UF-WHO, 2007 [21]; NASEM, 2019 [30]
Pipes exposed to temperature extremes	0	5	0	2	UF-OSHA, (1996) [25]; NASEM, 2019 [30]
Electronic faucets	0	7	0	2	UF-ANSI/ASRAE, 2018 [11]; NASEM, 2019 [30]
Hot and cold water mixing, including thermostatic mixing valves (TMVs)	2	5	4	2	F-OSHA, (1996) [25]; WHO, 2007 [21]; CDC, 2003 [18] F and UF-NASEM, 2019 [30] UF-WHO, 2011 [22]
In-building treatment (e.g., carbon filter, chlorination, etc.)	8	3	2	2	F and UF-CDC, 2003 [18]; NASEM, 2019 [30]
Point of use treatment	1	2	3	2	F-WHO, 2011 [22] F and UF-CDC, 2003 [18]; NASEM, 2019 [30]
Hot water recirculation	3	4	1	2	F and UF-NASEM, 2019 [30] UF-CDC, 2003 [18]
Pipe material-copper	4	7	2	3	F and UF-WHO, 2007 [21]; NASEM, 2019 [30] UF-WHO, 2011 [22]
Pipe material PVC	2	2	1	3	F and UF-NASEM, 2019 [30] UF-WHO, 2007 [21]; WHO, 2011 [22]
Pipe material PEX	2	1	2	2	F and UF-UK Department of Health, 2017-Part A [31]; NASEM, 2019 [30]
Electric water heaters	0	3	0	1	UF-NASEM, 2019 [30]

\* In addition to direct guidance for plumbing hydraulics these counts include guidance for pipe size, distant taps, etc., as they also contribute to the building plumbing hydraulics.

**Table 3.** Summary of the favorable and unfavorable views of SMEs and guidance documents on various premise plumbing operational factors. F—favorable and UF—unfavorable reference.

Operational Factor	SME F-Mentions	SME UF-Mentions	Guidance F-Mentions	Guidance UF-Mentions	References
Low demand due to conservation or under-occupancy	0	12	0	4	UF-WHO, 2007 [21]; WHO, 2011 [22]; CDC, 2017 [12]; NASEM, 2019 [30]
Infrequently used fixtures	0	4	0	4	UF-CDC, 2016 [19]; European Guidelines Working Group, 2017 [23]; Department of Veterans Affairs, 2014 [28]; NASEM, 2019 [30]
High water age	0	18	0	10	UF-WHO, 2007 [21]; WHO, 2011 [22]; CDC, 2017 [12]; CDC, 2003 [18]; European Guidelines Working Group, 2017 [23]; OSHA, (1996) [25]; U.S.EPA, 1985 [27]; Department of Veterans Affairs, 2014 [28]; UK Department of Health, 2017 [20]; NASEM, 2019 [30]
High carbon/nutrient water	0	6	0	3	UF-WHO, 2007 [21]; European Guidelines Working Group, 2017 [23]; NASEM, 2019 [30]
Residual is good or loss of residual is bad	12	0	12	0	F-WHO, 2007 [21]; WHO, 2011 [22]; CDC, 2017 [12]; CDC, 2003 [18]; CDC, 2016 [19]; European Guidelines Working Group, 2017 [23]; Government of Western Australia, 2010 [24]; OSHA, (1996) [25]; U.S. EPA, 1985 [27]; Department of Veterans Affairs, 2014 [28]; Department of Veterans Affairs, 2008 [29]; NASEM, 2019 [30]
Low residual from utility supply	0	3	0	0	
Other aspects of water quality from utility	0	3	0	4	UF-WHO, 2011 [22]; CDC, 2003 [18]; CDC, 2017 [12]; NASEM, 2019 [30]
Chloramine rather than chlorine	10	0	4	0	F-Department of Veterans Affairs, 2008 [29]; European Guidelines Working Group, 2017 [23]; CDC, 2003 [18]; NASEM, 2019 [30]
Keep hot water hot and cold water cold	6	0	12	0	F-ASHRAE, 2018 [11]; WHO, 2007 [21]; WHO, 2011 [22]; CDC, 2003 [18]; CDC, 2016 [19]; European Guidelines Working Group, 2017 [23]; Government of Western Australia, 2010 [24]; OSHA, (1996) [25]; U.S. EPA, 1985 [27]; Department of Veterans Affairs, 2014 [28]; Department of Veterans Affairs, 2008 [29]; NASEM, 2019 [30]
Temperature control of water heater	14	0	7	0	F-WHO, 2007 [21]; CDC, 2017 [12]; CDC, 2003 [18]; CDC, 2016 [19]; European Guidelines Working Group, 2017 [23]; OSHA, (1996) [25]; NASEM, 2019 [30]
Flushing	12	3	11	0	F-ASHRAE, 2018 [11]; WHO, 2007 [21]; WHO, 2011 [22]; CDC, 2017 [12]; CDC, 2003 [18]; European Guidelines Working Group, 2017 [23]; Government of Western Australia, 2010 [24]; OSHA, (1996) [25]; Department of Veterans Affairs, 2014 [28]; UK Department of Health, 2017, Part C [20]; NASEM, 2019 [30]

### 2.3. Indicators and Significant Knowledge Gaps in Water Quality in Buildings

As indicated in the SME interview questions (see Supplementary Information for the questions), SME views on two other topics, indicator measurements for water quality monitoring and significant knowledge gaps in premise plumbing water quality management, were also compiled. SMEs were asked to rate the importance of different water quality parameters as 'Good,' 'Fair/Limited,' and 'Poor' in terms of their ability to indicate overall water quality in buildings. Ranges of water quality indicator parameters were identified from the selected IGDs. In addition, for two of the parameters, an additional source was consulted as being an established source of guidance. Specifically, for the allowable temperature range, the International Plumbing Code [32] was consulted, and for time to a temperature at the tap, the American Society for Plumbing Engineers was consulted [33]. Knowledge gaps in water quality management were identified by two different approaches: (1) disagreement among SMEs on a particular topic was taken as evidence that a knowledge gap existed for that topic. This type of knowledge gap could occur when some SMEs are unaware of or misinterpret available information, or when available knowledge is not definitive, leading to different interpretations (2) the consensus among SMEs that a knowledge gap existed on a particular issue. This type of knowledge gap could occur when the available information is not known, or available only in an obscure source not known to many of the SMEs. Guidance documents were also reviewed for the information on these SME identified knowledge gap issues, and available information was summarized.

## 3. Results and Discussion

### 3.1. Identification of Critical Factors for Water Quality Management in Buildings

The 18 design issues identified during the SME interviews are shown in Table 2, along with a count of the number of favorable and unfavorable mentions in both the SME interviews and the guidance documents. Six of these factors related broadly to increased water age (residence time), and were viewed negatively by both SMEs and guidance documents: distant taps, low flow fixtures, oversized pipe diameters, building size, building layout, hydraulics of system (hydraulics in this context generally referring to the absence of dead zones and speed and directness of flow through the system). Green buildings may be included as a 7th factor in this category as they typically contain low use fixtures (which were perceived as contributing to high water age) and potentially other design features, which may lead to long water ages, such as rainwater collection and greywater reuse. There is good agreement among the SMEs and guidance documents on these factors in that they are mentioned frequently and generally in a negative light. The only favorable mentions among these seven factors are the favorable mentions of hydraulics by 4 guidance documents, which relate to the benefits achieved by good hydraulics, whereas the other mentions by SMEs and guidance documents referred to negative aspects of poor hydraulics. Thus, this does not indicate an actual divergence of opinion.

Three other design factors were viewed unfavorably by both SMEs and guidance documents. Flexible shower hoses (which may leach organic carbon), pipes exposed to temperature extremes (passing through boiler rooms or uninsulated areas), and electronic (automatic) faucets were viewed as providing conditions conducive to the growth of opportunistic pathogens.

Other factors showed a mix of favorable and unfavorable mentions. In some cases, this mixture was due to actual disagreements. Thermostatic mixing valves were sometimes viewed favorably as enabling high water temperatures (which protect against opportunistic pathogen growth) to be used in the majority of the hot water system while protecting the user against scalding. Others viewed them negatively and even advocated for their removal when possible due to their creation of a favorable temperature for opportunistic pathogen growth somewhere across the thermal gradient present at the valve, which might include most or all locations downstream of the valve, and their potential to fail and allow hot and cold water to mix. Additionally, biofilms present on the valve itself could contribute to pathogen growth.



In other cases, the mix of favorable and unfavorable mentions does not reflect conflicting points of view but rather commonly held nuanced views that acknowledge favorable and unfavorable aspects of different features. For example, in-building treatment and point of use treatment were generally acknowledged as being capable of improving water quality but were also viewed as a challenge to implement correctly, involving a range of unintended effects (nitrification due to chloramination, precipitate from copper-silver ionization, corrosion and disinfection byproduct formation from disinfectants, maintenance, increased costs, and administrative burdens). Hot water recirculation was generally viewed as needed in some applications, but when implemented with inadequately high temperatures (see Table 4 below and accompanying discussion below regarding what constitutes a sufficiently high temperature), it has the potential to create conditions favorable for pathogen growth by providing high residence times at pathogen-favorable temperatures (return lines are particularly challenging to maintain at an adequate temperature).

Pipe material considerations elicited a range of views. Several mentioned the anti-microbial properties of copper and the potential for PVC and PEX pipe to leach organic carbon, which could enhance the growth of opportunistic pathogens. Nevertheless, none of the SMEs strongly advocated for one type of pipe material over another. The issue of organic carbon leaching from plastic pipes was indicated by SMEs as a quality control issue, requiring proper testing and certification, rather than an unavoidable drawback of all plastic pipes. The antimicrobial properties of copper were seen as influencing the microbial ecology of the plumbing system but not necessarily in favorable ways, given that more problematic organisms, such as *Legionella* spp., and other opportunistic pathogens capable of living inside amoebae, may be able to develop resistance under certain selective pressures, such as the presence of copper, and outcompete other microorganisms. As only one of the IGDs, the National Academies report [30], mentioned PEX pipe, the 39 non-IGD documents were searched for information and an additional source was found to provide guidance on PEX pipe. The UK Department Health [25] identified British Standard 6920 as being applicable, while the National Academies report [30] indicated a need for US standards that address the potential for microbial growth. Both guidance documents identified standardized testing methods as being vital to addressing concerns with PEX pipe, and hence closely matched the SME views on this topic.

Of the 18 topics related to design factors, three factors—electric water heaters, PEX pipe materials, and green buildings—were addressed by only one of the 15 IGDs. In all three cases, the IGD which addressed the topic was the National Academies report [30]. The 39 other (non-IGD) documents were searched for these topics, and additional information was found for one topic in one report; specifically The UK Department Health report [25] included information on PEX pipe, as described above. None of the 39 non-IGD reports provided guidance on the remaining two topics, electric water heaters and green buildings. Electric water heaters were mentioned mostly unfavorably by SMEs and by the National Academies report [30] as creating a thermally stratified reservoir with lower temperature water (favorable for opportunistic pathogen growth) able to pool at the bottom. Green buildings were viewed unfavorably by six of the SMEs with no favorable mentions by SMEs. The National Academy report [30] emphasized the negative aspects while also mentioning favorable features such as energy and water conservation, and suggested incorporating water quality into certification processes for green buildings, such as the LEED standards.

While all of the design topics were covered in at least one guidance document, no one guidance document covers all the factors identified by the SMEs. When a topic is addressed by a guidance document in some cases both favorable and unfavorable aspects are covered but in other cases, multiple documents would need to be consulted to appreciate the range of views on a topic (e.g., the WHO 2011 [22] mention only negative aspects of copper pipe while the WHO 2007 [21] and the National Academies report [30] provide both favorable and unfavorable aspects of copper pipe). This indicates a need for a more comprehensive synthesis of available guidance so that designers and facility managers can access information on all these topics from a single source or a compendium enabling the user to access information from multiple sources.

**Table 4.** Water quality parameters and ranges.

Parameter	Ranges	References	SME Views
Temperature	Hot water: >50 °C Cold water: <20 °C Water Heater: Not less than 60 °C Return: Not less than 50 °C	WHO, 2007 [21]	Range from 49–60 °C for water heater setpoint median = 54.5 °C (6 SMEs) Mixing valve temperature for handwashing and eyewashes should be set lower, 24 °C (1 SME)
	Water Heater: >60 °C Water temperature: ≥50 °C	OSHA, (1996) [25]	
	Hot water: >50 °C Cold water: <20 °C	WHO, 2011 [22]	
	Water heater: >60 °C Cold water: <20 °C Hot water: ≥51 °C	CDC, 2003 [18]	
	Hot water: ≥55 °C	U.S. EPA, 1985 [27]	
	Water Heater: >60 °C Hot-water temperature: >55 °C Cold water: <25 °C	NASEM, 2019 [30]	
	Cold water: ≤19.4 °C Hot water: ≥51.1 °C	Department of Veterans Affairs, 2014 [28]	
	Heater outgoing: at least 60 °C; Return: at least 50 °C POU: 50–55 °C Cold water: ≤25 °C	European Guidelines Working Group, 2017 [23]	
Residual in Plumbing System	Hot water < 43 °C	International Plumbing Code, 2015 [32]	
	Chlorine residual: 0.2–1 mg/L (at the point of delivery)	European Guidelines Working Group, 2017 [23]	Chloramine residual: >0.3 (1 SME) 0.5 mg/L (1 SMEs) Chlorine residual: 0.2 mg/L (1 SME)
	Free chlorine residual: 1–2 mg/L	CDC, 2003 [18], U.S. EPA, 1985 [27]	
Free chlorine residual: 0.2–0.5 mg/L	WHO, 2007 [21]		
Residual in Spas Pools	Chlorine/Bromine: 3–5 mg/L	European Guidelines Working Group, 2017 [23]	
	Free Chlorine: 3–5 mg/L Free Bromine: 4–6 mg/L	Government of Western Australia, 2010 [24]	
Flushing	Low flow fixtures: at least daily in the morning for 1 min	UK Department of Health, 2017-Part C [20]	Building water systems: Once in a week (2 SMEs); Unoccupied building: Every 2–3 days (1 SME)
	Once in a week	European Guidelines Working Group, 2017 [23]	
	Low flow fixtures: Twice per week	Department of Veterans Affairs, 2014 [28]	
Parameter	Ranges	References	SME Views
Heat Shock	At least 60 °C and flush for 5–10 min	WHO, 2007 [21]	70 °C for 30 min, 65–70 °C is ineffective as it selects heat resistant microorganism (1 SME)
	Temperature: >60 °C (preferable >70 °C) and flush	WHO, 2011 [22]	
	Temperature: 71–77 °C and flush for at least 5 min	CDC, 2003 [18]	
	At least 70 °C and flush for 5–20 min	OSHA, 1996 [25]	
	70–80 °C for 72 h and flush for 5 min	European Guidelines Working Group, 2017 [23]	
	71 °C for 72 h and flush for 15 min	U.S. EPA, 1985 [27]	
Shock Chlorination	Temperature: 71–77 °C and flush for at least 30 min	Department of Veterans Affairs, 2014 [28]; Department of Veterans Affairs, 2008 [29]	
	Free chlorine level: at least 2 mg/L for at least 2 h and flush Water Heater: 20–50 mg/L of free chlorine residual and flush	Department of Veterans Affairs, 2014 [28]	
Time to Tap	Hyper chlorinate the system by flushing for at least 5 min with water containing at least 2 mg/L free residual Chlorine Water Heater: 20–50 mg/L free chlorine residual	CDC, 2003 [18]	
	50–55 °C within 1 min at POU	European Guidelines Working Group, 2017 [23]	Up to 1 min acceptable (1 SME)
	Minimum 55 °C within 1 min at distal points	NASEM, 2019 [30]	
10–30 s	ASPE, 2003 [33]		

While no single guidance document covers all the topics, the National Academies report [30] covers more of the topics, 16 out of 18, than any other document. The second and third highest number of topics were covered by the WHO (2007) [14] and the CDC (2003), with eight and seven topics addressed, respectively. It is also notable that the National Academies report [30] covers favorable

and unfavorable aspects of eight topics, while for the remaining eight topics (flexible shower hoses, distant taps, low flow fixtures, electronic faucets, electric water heaters, oversized pipes, pipes exposed to temperature extremes, and hydraulics/poorly balanced flow), the National Academies of Science, Engineering, and Medicine (NASEM) report [30] and all SME views are negative. Thus, when the National Academy report [30] includes only negative aspects of these topics, one might reasonably conclude that there are few or no highly salient favorable aspects of these topics, rather than concluding that the report missed important favorable aspects of the topics.

The 11 important operational factors identified during the SME interviews are summarized in Table 3. Similar to the design factors, issues leading to higher water age were cited frequently and consistently viewed as unfavorable (low demand, infrequently used fixtures, high water age) by both SMEs and guidance documents. High carbon and nutrient water were also viewed unfavorably due to their potential to support microbial growth.

Another set of issues pertains to the maintenance of a disinfectant residual in the plumbing system (these are related to water age as residual decays with time). These include maintaining a disinfectant residual (consistently viewed as favorable by SMEs and guidance documents) and low residual being provided by the water supply (negatively viewed by three SMEs but not explicitly addressed by any guidance documents). The surface water treatment rule requires surface water suppliers to maintain detectable residual levels for surface water systems [34]. While neither the surface water treatment rule nor the guidance documents considered here provide specific guidance for building water quality managers, monitoring for residual at the influent could serve as a check on this issue. Three SMEs and four guidance documents mentioned other aspects of water quality (i.e., other than residual levels) from the utility, and generally included distribution system issues such as main breaks, loss of pressure, cutoff of supply, and sloughing of materials from distribution system pipes (see National Research Council 2006 report [34] and Propato and Uber 2004 [35], for a consideration of water quality in the utility distribution system piping).

The use of chloramine rather than chlorine was noted as favorable by 10 SMEs and four guidance documents. None of the responses reviewed identified chloramine as an unfavorable factor, but there was a great deal of nuance and uncertainty expressed on the issue. Chloramine is viewed as more persistent and better able to penetrate biofilms but has the drawback that it allows for the possibility of nitrification if the residual is not maintained. There was some degree of consensus that chloramine is more effective for limiting *Legionella* spp. growth, but much less clarity was apparent regarding its impacts on mycobacteria. Mycobacteria were consistently viewed as more resistant to disinfection. Some view the use of chloramines as having the ability to open up ecological niches for mycobacterial growth by preferentially removing competitive bacteria. Others saw chloramine as useful for limiting the growth of mycobacteria even though it could not eliminate them.

Temperature control was frequently mentioned as an important operational factor. The qualitative adage of “keeping the hot water hot and the cold water cold” was endorsed by 6 SMEs and 12 guidance documents. Control of the temperature setpoint on the water heater was mentioned favorably by 14 SMEs and seven guidance documents with 0 unfavorable mentions. Flushing received 12 favorable and three unfavorable mentions by SMEs and 10 favorable and 0 unfavorable mentions by guidance documents. Favorable views saw flushing as bringing in fresh residual disinfectant and controlling microbial growth. A long duration between uses was seen as a possible factor in stressing the biofilm and leading to detachment and mobilization of opportunistic pathogens into bulk water. There was a contrary view that noted that flushing brings more nutrients and carbon to the pipe biofilm, which can enhance growth. Overall, the impacts of flushing likely depend on a complex interplay of residual levels, carbon and nutrient levels, and frequency of flushing.

The operational factors tend to fall at least generally into somewhat clearer favorable vs. unfavorable categories, which is in contrast to the design factors, many of which were noted as having both favorable and unfavorable aspects. Flushing is the only factor that has both favorable and unfavorable mentions. However, views on chloramines were nuanced and included some mentions of

potential tradeoffs as noted above, although these were not identified as clearly unfavorable aspects of chloramines.

The only operational issue identified as important by the SMEs but not addressed in any of the guidance documents was low residual from the utility. Some of the topics were addressed by most of the guidance documents (10 addressed water age, 12 indicated that hot water should be kept hot and cold water kept cold, 12 noted the importance of residual, and 11 addressed flushing). This topic coverage is markedly better than the situation for the design factors, where none of the factors were addressed by more than five of the guidance documents. Of the 10 topics addressed by the guidance documents, the NASEM report [30] is the only guidance document that covered all 10. The second highest percentage of topic coverage is eight by the European Guidelines Working Group, 2017 [23], and the third highest is seven by both the WHO, 2007 [14] and the CDC [15]. As noted above, the NASEM report [30] also had the best topic coverage of the design topics.

### 3.2. Indicators of Water Quality in Buildings

The SMEs identified eight different general indicators of water quality that can be measured in buildings (Table 5). Residual disinfectant and temperature were the most commonly mentioned indicators with nine and seven mentions, respectively. Both were generally seen as good indicators (seven of nine mentions for residual and seven of seven mentions for temperature). Adenosine triphosphate (ATP) was mentioned favorably by two of three SMEs, while heterotrophic plate count was mentioned favorably by two of five. Both indicators are gross measures of microbial activity that do not offer specific information on opportunistic premise plumbing pathogens, which may be why they were not endorsed as widely as temperature and residual disinfectant. However, measures of specific opportunistic pathogens were not widely endorsed either, with only one SME characterizing this as a good indicator out of four who mentioned it. This is generally due to the expense and difficulty of measuring opportunistic pathogens. Total organic carbon (one good out of one SME mention) and assimilable organic carbon (one good out of three SME mentions) were both noted but not widely endorsed. Just two SMEs mentioned the time required for the temperature at the hot water tap to stabilize, but both saw it as a good indicator, providing information about flow that supplements a simple temperature measurement. One SME was explicit that lower temperature measurements were acceptable provided a system's flow was well balanced and that time to reach final temperature at the tap was a good indicator of whether a systems flow was well balanced (i.e., without zones of poor flow that lead to pockets of lower temperature and high water age).

**Table 5.** SME identified indicators of water quality management in buildings.

Water Quality Indicator Parameters	SME Characterization of Value of Indicator		
	Good	Fair/Limited	Poor
Residual disinfectant	7	1	1
Temperature in plumbing system pipes/heater	7	0	0
Adenosine triphosphate (ATP)	2	0	1
Heterotrophic plate count	2	2	1
Opportunistic pathogen concentrations	1	3	0
Total organic carbon	1	0	0
Assimilable organic carbon	1	2	0
Time for hot water temperature to stabilize at tap	2	0	0

### 3.3. SME-Recommended Indicator Parameters for Managing Water Quality in Buildings

For seven parameters identified by SMEs as important in managing water quality in buildings, quantitative recommendations from the guidance documents were compiled and are shown in Table 4. In most cases, SMEs did not give quantitative ranges for acceptable values of these parameters. Where one or more SMEs did provide a quantitative value, the values are noted in the last column of the table.

### 3.4. Significant Knowledge Gaps in Buildings Water Quality Management

Table 6 summarizes 11 knowledge gaps that were identified as significant based on the two selection approaches adopted: (1) disagreement among SMEs and (2) consensus among SMEs that a gap exists on a particular issue. The majority of these issues (#1–9) are directly related to one of the design or operational factors discussed in Table 2 or Table 3 above. The remaining two issues (#10–11) are more related to fundamental research, but such fundamental research may be expected to generate an evidence base that informs a variety of design and operational factors in premise plumbing. Among the 11 issues identified, five were based on disagreements among SMEs and/or guidance documents while the remaining six were based on consensus among the SMEs that the knowledge gaps exist. Of the five items for which there was disagreement, disagreements on flushing frequency (#1) and residual levels (#2) appeared to represent discrepancies in the particular values selected in the absence of definitive evidence. Attitudes toward thermostatic mixing valves (#3) appeared to diverge due to differing levels of awareness as to their potential to foster OPPP's growth, differing views on the risk–risk tradeoff between OPPPs and scalding, and differing views on the potential for regular maintenance of the valves to mitigate the OPPPs risk. Differences on the tradeoff between chloramine and chlorine (#4) appeared to result from the differing interpretation of an evidence base, which is not definitive. Views on appropriate temperature control (#5) were consistent in viewing temperatures below about 49 °C as favorable to *Legionella* spp. growth but diverged with respect to how far above, the temperature was appropriate. Recommendations for water heater setpoint were consistent across the five water quality guidance documents that made specific recommendations for heater setpoint as all recommend a setpoint of at least 60 °C. However, guidance on the temperature in the plumbing distribution system was not completely consistent with recommendations from water quality guidance documents falling in the range between 50 and 55 °C, while the International Plumbing Code requires <43 °C. While there was consensus that both temperatures and hydraulics matter, some saw high temperature as critical for OPPPs control, while others indicated that OPPPs could be controlled at somewhat lower temperatures with appropriate hydraulics (short flow paths, a balanced flow that avoids stagnation, etc.). These differences may reflect differences in views on the risk–risk tradeoff (with one SME suggesting that scalding represents a trivial risk compared to a much higher risk of Legionnaires' Disease) between OPPPs and scalding, different views on the performance and impact of thermostatic mixing valves, and differing interpretation of evidence from field studies.

One SME noted “sizing and layout” as an overarching knowledge gap. While many SMEs mentioned this as an important issue, it was not generally mentioned in the context of a knowledge gap and hence is not included in Table 6. However, holistic issues such as this may not be discrete gaps but may require dedicated efforts to synthesize knowledge into guidance. Thus, the gaps in this case might be to synthesize what is known about water quality in buildings into design guidance to better inform sizing and layout decisions.

**Table 6.** Summary of the key knowledge gap issues in premise plumbing based on SME views.

Concern Areas	Significant Knowledge Gap Issues	Basis for Knowledge Gap Identification
Flushing (Operational)	1. Determine optimum flushing frequency considering the tradeoff between residual replenishment and OPPPs nutrient feeding.	Disagreement among SMEs and GDs
Residual levels (Operational)	2. Determine optimum numerical values for residual concentrations under different conditions with consideration of OPPPs control and tradeoffs with DBP formation.	Disagreement among SMEs and GDs
Thermostatic mixing valves (Design)	3. Investigate TMVs as problematic elements for OPPPs growth and if just alternative designs or proper maintenance can resolve issues.	Disagreement among SMEs
Chloramine vs. chlorine (Operational)	4. Investigate tradeoffs between disinfectants and if chloramines are effective for mycobacteria control.	Disagreement among SMEs and GDs
Temperature control strategy (Design and operational)	5. Despite a consensus understanding of temperate effects on <i>Legionella</i> , there is a lack of consensus on the emphasis on temperature, hydraulics, and the role of mixing valves for OPPPs control. Very roughly one might describe the approaches as: (1) use high temperature (60 °C heater setpoint) and (2) use more moderate temperature (49–55 °C heater setpoint) but require short flow times and limited temperature drops in pipes.	Disagreement among SMEs
Water heater type (Design)	6. Compare water quality of on-demand tankless heaters with tanked heaters.	Consensus that gap exists among SMEs
Pipe materials (Design)	7. Investigate suitable pipe materials or anti-microbial coating for OPPPs growth. 8. Investigate impacts of copper as pipe material with respect to <i>Legionella</i> and other OPPPs, leaching properties, and compatibility with hot water.	Consensus that gap exists among SMEs
Control strategy (Operational)	9. Does temperature control work for mycobacteria and other OPPPs too? How do microbial communities adapt/shift in composition in response to temperature changes?	Consensus that gap exists among SMEs
OPPPs Characterization	10. <i>Legionella</i> (and other OPPPs) growth characterization with respect to temperature, time, residuals, nutrients, and other conditions. 11. Standardize OPPPs characterization techniques (staining, etc.) and identify factors associated with OPPPs (concentration, etc.) and health risk	Consensus that gap exists among SMEs

#### 4. Conclusions

This study used SME interviews to identify 18 critical design topics and 11 critical operational topics for ensuring water quality in building plumbing systems. All of the 18 design topics were covered across nine IGDs and 10 of the 11 operational topics were covered across 14 IGDs, with each topic covered in at least one IGDs. While no one IGD covers all 29 topics identified by the SMEs, the 2019 National Academies report [30] was the most significant document, covering 26 topics (16 design and 10 operational), followed by the WHO (2007) [14] and the CDC (2003) [15], with 15 (eight design and seven operational) and 14 (seven design and seven operational) topics covered, respectively. In general, the operational topics were covered among many IGDs (up to 12 documents addressed some of

the topics) while none of the design topics were addressed by more than five IGDs. Clearly, “coverage” of the topics can vary widely among the guidance documents, with some providing more detailed advice than others which may only mention the issue. The degree of coverage is not addressed here.

The favorable and unfavorable views of SMEs and existing guidance information generally tend to agree on most of the design and operational topics of concern. In some cases, the diverging views were more nuanced, acknowledging favorable and unfavorable aspects of different features rather than actual disagreement. For example, in-building treatment, hot water recirculation, and the effectiveness of chloramine for mycobacteria were topics that prompted a productive discussion. Among the least addressed topics, low residual from utilities was the only topic not covered by any of the guidance documents. Pipe material prompted the elicitation of a range of views. Consistent with SME views, a blanket recommendation for preferred pipe materials is probably not possible, but guidance could be updated based on more evidence base from existing technical literature and more scientific research to specifically highlight the nuanced aspects of the limitations on the anti-microbial properties of copper and the potential for PVC and PEX pipe to leach organic carbon which could enhance the growth of opportunistic pathogens. Guidance is not currently available regarding what specific design, water chemistry, hydraulic, etc., conditions are most appropriate for determining the selection of each pipe material in a way that can be easily interpreted by stakeholders, and how water quality might vary of the life cycle of a building differentially as a function of those characteristics depending on the material selection. Temperature (accounting for this as a general factor, with some diversion on where this parameter should be measured in the system) and residual disinfectant controls were generally considered as good indicator parameters for monitoring building water quality by SMEs.

This study provides a compendium of the divergent views and lack of guidance through a systematic study design and analysis. While this study was able to identify relatively convergent views on some of the water quality topics, such as temperature control, it also highlights the lack of definitive guidance on some other critical topics, such as residual level, flushing frequency, hot water time to tap, and the use of thermostatic mixing valves. Based on the SMEs and guidance recommendations presented in this study, there is a need for developing guidance that is evidence based, particularly on the topics that lack guidance or present split opinions. Such guidance needs to clearly identify the nuanced views on these topics and refer the reader to specific standards where applicable. This study provides a reference point for researchers and regulators to focus on future actions to reduce health risks from exposure to water in building plumbing systems.

**Supplementary Materials:** The following are available online at <http://www.mdpi.com/2073-4441/12/2/347/s1>, Subject Matter Experts (SMEs) Interview Protocol. Table S1: List of all 54 guidance documents examined for building water quality management guidelines. Table S2: List of 50 keywords relevant to the topics of water quality concerns in premise plumbing systems used for searching guidance documents to screen important guidance documents (IGDs) of high topic coverage of water quality concerns.

**Author Contributions:** Conceptualization—K.A.H., P.L.G., A.F., and S.V.M.; SME interviews—K.A.H. and P.L.G.; guidance document review—M.R., Z.Y., R.S., S.K., and A.F.; analysis of results from guidance documents and interviews—K.A.H., P.L.G., M.R., Z.Y., R.S., S.K., and A.F.; preparation of tables and figure—K.A.H., R.S., M.R., and Z.Y.; writing—original draft preparation—R.S.; writing—review and editing—all authors. All authors have read and agreed to the published version of the manuscript.

**Funding:** This manuscript was developed under Assistance Agreement No. R836880 awarded by the U.S. Environmental Protection Agency. It has not been formally reviewed by the EPA. The views expressed in this document are solely those of the authors and do not necessarily reflect those of the Agency. The EPA does not endorse any products or commercial services mentioned in this publication.

**Acknowledgments:** We gratefully acknowledge the insights provided by the subject matter experts. Charles Haas, Drexel University, reviewed and provided valuable comments on a draft of the manuscript. The authors would also like to thank three anonymous reviewers for their insightful comments that have helped improve this manuscript significantly.

**Conflicts of Interest:** The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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