Water quality challenges in buildings during prolonged low or no occupancy: a cause for concern during COVID-19 lockdowns and related building closures

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ABSTRACT

Introduction: In compliance with the COVID-19 lockdown restrictions, many non-essential workplaces and public spaces were closed or left sub-operational with no or low occupancy for several months. The abrupt and unprecedented long periods of building closures have raised concerns about the proliferation of opportunistic premise plumbing pathogens that may be a biohazard for returning occupants.

Objective: In this review paper, we discuss microbiological water quality concerns during periods of no or low occupancy, as experienced during the COVID-19 lockdowns.

Methods: PubMed and Google Scholar databases were searched for peer-reviewed articles using specific keywords. The literature search was extended to grey literature. The paper focuses on *Legionella*, as a pathogen of concern, in building water systems that are not well managed and the potential risks to workers and other occupants.

Results: Most articles suggest a positive relationship between stagnation or reduced water usage and compromised microbiological quality of building water systems, but the effects are site-specific and are associated with biofilm formation and disinfectant decline. Considerations for building water risk assessment are discussed as a decision-making framework for selecting appropriate responses to anticipated changes in water quality.

Conclusion: The unprecedented building closures due to COVID-19 lockdowns present a hazardous event likely to impact building water quality. Building owners and facility managers, especially in high-risk settings, should consider conducting risk assessments of water systems during low-occupancy periods to identify potential risks and apply appropriate corrective measures, where necessary.

INTRODUCTION

Building water systems play an important role in the distribution of water through complex pipe networks. If not well maintained, microbial growth, persistence, and transmission of opportunistic pathogens, particularly *Legionella*, can cause acute and sometimes fatal illnesses in susceptible individuals. The unprecedented coronavirus disease (COVID-19) pandemic impacted economies worldwide.[1] Disaster management strategies, including lockdown measures and remote work to minimise transmission in various workplace settings, resulted in reduced water usage in many non-essential buildings. There is a growing concern that reduced building water usage created favourable conditions for microbial proliferation, with potential exposure to opportunistic premise plumbing pathogens (OPPPs) such as *Legionella*, and adverse health effects for returning occupants.[2-4] At the beginning of the Pandemic, health ministries were forced to convert facilities, including sports stadiums, hotels, conference centres, and even cruise ships into field hospitals and quarantine centres to cope with the extraordinary demand for hospital beds.[5] Poor oversight of potential risks after periods of low or no occupancy in these facilities could lead to unintended health consequences for patients and healthcare workers.[6]

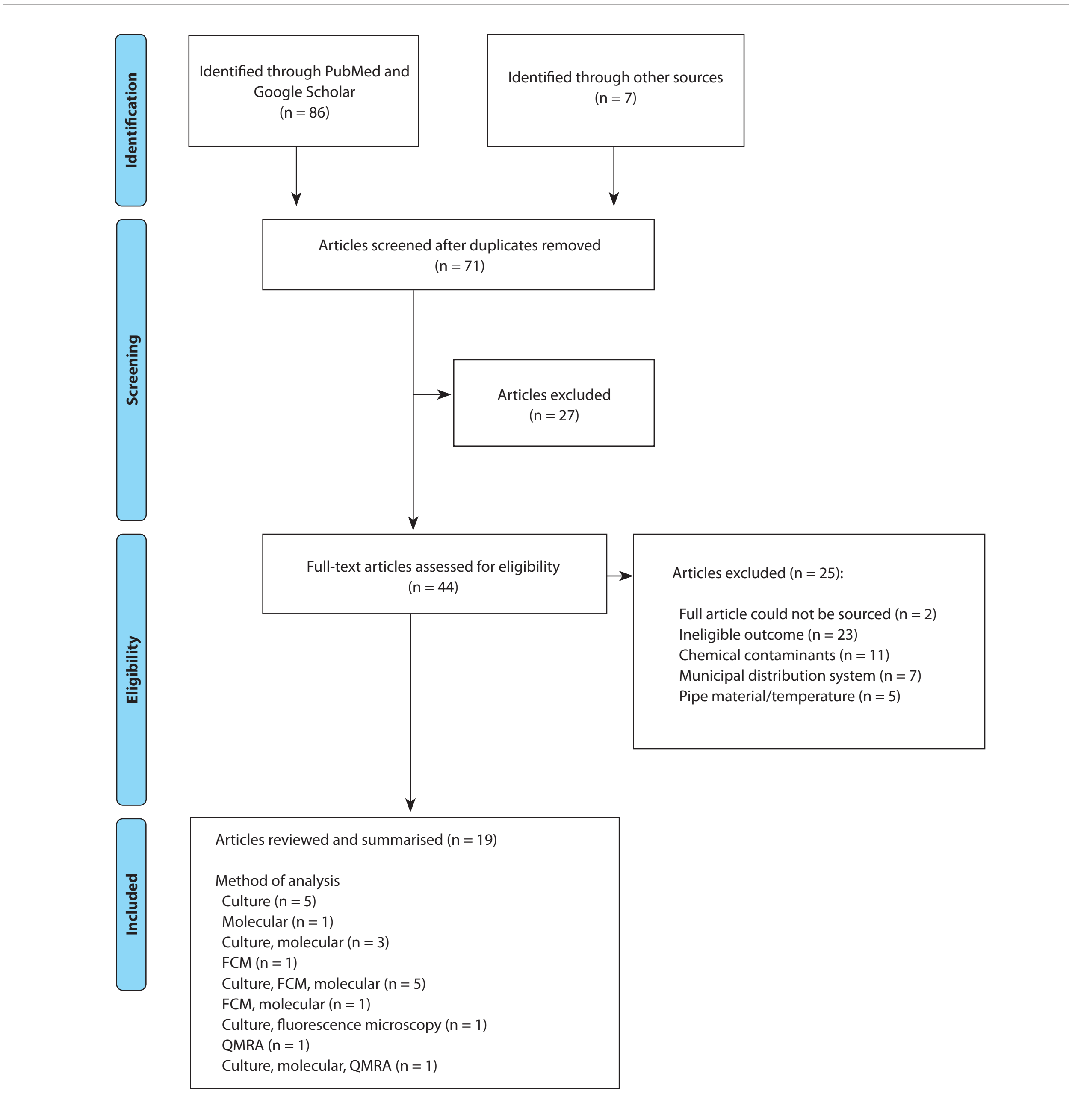
The projected intermittent COVID-19 waves due to microbial resurgence, the emergence of new variants of SARS-CoV-2,[7, 8] and the digitisation of many workplaces compelled some organisations to adopt telecommuting strategies, perpetuating water quality issues if the building water systems were not maintained. There is a paucity of information about water contamination risks, particularly during prolonged building closures. The two most recently published reviews on the topic provide critical accounts of the assumptions surrounding the definition and impact of stagnation in premise plumbing systems (PPSs) and *Legionella* growth,[9] and discuss issues to consider when developing and implementing guidelines for restoring building water systems to baseline conditions, after extended periods of no or limited water use.[3]

This paper provides an in-depth review of studies on factors affecting building water quality after periods of reduced water usage, to better understand microbial contamination and growth during reduced water demand, also referred to as stagnation, in PPSs. We highlight the importance of performing site-specific building water risk assessments (RAs) as a decision-making framework when selecting appropriate control measures and responses to anticipated changes in water quality. The review also provides guidance on points to consider when verifying the effectiveness of corrective actions, including what to test for, where and what to sample, sampling frequency, test methods, and interpretation of results. Emphasis is placed on *Legionella* as one of the most notoriously difficult OPPPs to manage, with case numbers reported to be increasing, globally.[10, 11]

We anticipate that this information will assist building owners, facility managers, environmental health practitioners, infection control personnel, health and safety officers, occupational hygienists, and other stakeholders to proactively manage the risk of opportunistic pathogen-related illnesses in the built environment.

METHODS

We searched PubMed and Google Scholar for peer-reviewed articles published in English from 2000 to 2021, using keywords related to water quality in large buildings, i.e. stagnation, disinfectant residuals, biofilms, *Legionella* growth, risks and control, and *Legionella* risks during COVID-19 lockdown. Reference lists of selected articles were manually searched to identify additional papers (Figure 1). We included both field and experimental primary research studies on PPSs. Grey literature was included, specifically guidance documents on managing *Legionella* risks during COVID-19 building closures, from internationally recognised institutions or government agencies such as the Centers for Disease Control and Prevention, United States of America (CDC USA), American Water Works Association (AWWA), and the European Study Group for *Legionella* Infections (ESGLI). Publications focusing on temperature, plumbing materials, chemical contaminants, municipal distribution systems, and cooling towers were excluded as they were considered beyond the scope of this paper. Studies were characterised using the following variables: origin, type of building, water usage pattern, parameters assessed (population) and detection methods, main findings (outcomes), and recommendations.



FCM: flow cytometry, QMRA: quantitative microbial risk assessment

Figure 1. PRISMA-like flowchart summarising the article selection

Table 1. Summary of reviewed articles relating to water quality issues as a result of no or low building occupancy

Study type, country	Type of building	Water use pattern	Method(s) of analysis and microbial parameters assessed	Main findings (outcomes)	Recommendations
Field study, Italy[2]	Cold water taps and showers in three wards (62-beds) of a university hospital	Wards had been closed for three months due to the COVID-19 pandemic	Culture Coliforms, *E. coli*, *Enterococci*, *P. aeruginosa*, *Legionella*	• Generally, risk of waterborne diseases increased due to water stagnation in unused buildings during lockdown • *Legionella* contamination higher after lockdown than pre-lockdown in some wards	• Implement a water safety plan, including staff training and more rigorous environmental microbiological surveillance in all hospitals • Survey building water network previously closed for > 1 week before starting normal services so that waterborne disease risks, including Legionnaires' disease, are minimised
Field study, USA[4]	Cold and hot water showers in university buildings using chloraminated water	Wholly or largely unused for > 2 months due to the COVID-19 pandemic	Culture, molecular (qPCR) simulation (QMRA) Total bacteria (16S rRNA genes), *Legionella* spp., *L. pneumophila*, *L. pneumophila* serogroup 1, NTM, MAC	• Culturable *Legionella*, *L. pneumophila*, and *L. pneumophila* sg1 genes not detected • Most (12/14) pre-flush samples positive for *Legionella* spp. • Most (9/10) pre-flush samples positive for NTM and MAC • Flushing rapidly restored disinfectant residual and decreased bacterial gene targets to building inlet concentrations within 30 minutes, but opportunistic pathogens regrew • Low health risks from opportunistic pathogen exposure during showering	For buildings with history of *Legionella* or NTM contamination: • Routine flushing and cleaning to increase water turnover and maintain disinfectant residual in storage tanks • Flushing periodically during shutdown, or at least flushing within 2–3 days of building re-occupancy
Field study, China[15]	Cold water taps in university buildings and a community residential building	Little or no water usage in buildings for nearly four months, except for the community residential building	Culture, FCM, molecular (qPCR,16S rRNA Illumina sequencing) HPCs, *L. pneumophila*, *P. aeruginosa*, *E. coli*, *Enterococcus faecalis*, *Shigella* sp., *Salmonella* sp., endotoxin	• Long-term water stagnation resulted in deteriorated water quality, which increased microbiological risks • Disinfectant residual decreased significantly while HPCs increased significantly with stagnation • *L. pneumophila* occurred in 91% of stagnant water samples with high turbidity (> 1 nephelometric turbidity unit) • Took 1–2 months for bacterial levels to return to normal levels	• Health risks from pathogenic bacteria in stagnant water require attention, and countermeasures are needed before buildings are re-opened • Routine flushing coupled with cleaning of water tanks (pathogens regrow with routine flushing alone), taking into account plumbing design, complexity of components, and stored volume of water relative to water use. Flushed water can be used for non-potable purposes, e.g. landscape irrigation and floor washing • Maintain a disinfectant residual, e.g. by installing automatic disinfectant device • Monitor water quality of buildings frequently • Residual chlorine can be used as early warning indicator for microbiological safety of tap water with long stagnation
Field study, China/USA[16]	Cold tap water in multi-story university dormitory buildings	Two-month dormitory shutdown with no water usage	Culture, molecular (16S rRNA Illumina sequencing) HPCs, sequencing for *Legionella*	• Stagnation significantly elevated HPCs and *Legionella* relative abundance • Elevated *Legionella* infection risks in buildings with prolonged closure	Urgent need to mitigate *Legionella* infection risks during re-opening of buildings previously closed due to COVID-19
Field study, Canada[17]	Cold and hot water systems in a 10-story, 450-bed children's hospital	Induced variable controlled stagnation time periods (1, 24, 48, 72, 120 and 240 hours)	Culture, fluorescence microscopy HPCs, total viable and total bacterial cell counts	• Short stagnation periods (1 hour) had lower culturable bacteria than longer periods (≥ 24 hrs), probably due to biofilm detachment; bacterial load not significantly higher with increasing stagnation time • Flushing large volumes of water was required to reduce viable and total cell counts after stagnation in cold water system	• For buildings with extended non-occupancy, daily flush may not be more beneficial than weekly flush • For low-use taps or after longer stagnation (≥ 24 hrs), flush only stagnant water specific to tap and connecting pipes • For HCFs, small sampling volume on first flush is preferred to evaluate distal contamination and increase chances of bacteria recovery • Standardised sampling protocols, taking into account sample volume and prior stagnation, for better RA and interpretation of results against targeted thresholds for infection prevention

Table 1 continued opposite

Table 1 continued

Study type, country	Type of building	Water use pattern	Method(s) of analysis and microbial parameters assessed	Main findings (outcomes)	Recommendations
Field study, USA[18]	Green buildings with water and energy conservation features and a conventional house; cold and hot water taps	Elevated water age depending on building (days to months of water retention)	Molecular Total bacteria (16S rRNA gene) *Legionella* spp., *L. pneumophila*, *Vermamoeba vermiformis*, *Mycobacterium avium*	• Pathogenic gene copies and total bacterial genetic markers detected at higher concentrations in all green buildings compared to conventional building and flushed water samples • Rapid disinfectant loss in all green buildings	• Temporary solution for green buildings connected to drinking water mains is routine flushing to maintain disinfectant residuals and temperature, and control corrosion • Green building designs with water conservation features should minimise water retention in buildings • Avoid conditions conducive to OPPPs in green buildings, e.g. disinfectant decay and poor temperature control • Avoid unnecessary water storage in green buildings
Field study, Germany[19]	Cold water (taps and showers) from residential and nursing home, hotel, and sports facilities with *Legionella* contamination history	Standard operating conditions	Culture *Legionella* spp., *L. pneumophila*, HPCs	*Legionella* spp. occurrences significantly correlated with stagnation, temperature, and pipe length	• Culture methods cannot always reliably reveal contamination and infection risks • Longitudinal rather than cross-sectional sampling approach provides a better risk estimate for outlets within a building water system • Parameters that lead to colonisation are unique to the individual system and should be dealt with as unique problems • Estimation of *Legionella* risks in building water outlets should consider combinations of temperature, stagnation, pipe length, etc.
Simulation, USA[20]	Simulated residential premise plumbing supplied with freshly treated drinking water	Simulated stagnation periods of up to 48 hrs and induced biofilms	QMRA *L. pneumophila*	• Stagnation of up to 48 hrs in the presence of biofilms significantly increased *Legionella* annual infection risk compared to clean pipes • Decay of residual chlorine due to biofilms during 48-hour stagnation increased *Legionella* annual infection risk compared to when biofilm was absent	Reduce stagnation, maintain residual chlorine, and suppress biofilm growth, especially in dead-ends, to better manage *L. pneumophila* infection risk in building water systems
Field study, Switzerland[21]	Cold water from taps in households served with treated water from the same network	Standard operating conditions with overnight stagnation	Culture, FCM, molecular (DGGE) HPCs, TCCs, ATP levels, microbial communities	• TCCs, ATP levels, and HPCs increased after stagnation • Microbial composition shifts observed after stagnation • Cell concentrations returned to normal after five-minute flushing	• Short flushing of taps prior to use to reduce microbial cell concentrations following stagnation periods • Development of validation methods and guidelines on microbiological quality of in-house water installations are needed
Field study, Finland[22]	Cold and hot water systems in office building with 250 employees working regular office hours	Standard operating conditions with overnight and weekend stagnation	Culture, molecular HPCs, ATP levels, total microbial counts, and 16s rRNA gene copy numbers	• Viable microbial biomass increased due to stagnation in cold water • Microbial biomass (HPC, ATP levels and total 16s rRNA gene copy counts) higher in biofilms of cold water system than hot water system. Cold water system was mostly stagnant with irregular consumption during sampling • HPC and total microbial counts were higher in cold than in hot water system	Water should be flushed before use after stagnation to ensure acceptable microbiological and chemical quality
Field study, USA[23]	Three four-storey university housing buildings with stable free chlorine for the duration of study	Controlled access for 5–6 days to create stagnation periods	FCM, molecular (16S rRNA Illumina sequencing) Cell counts, microbiome	• Bacterial community composition changes from city supply following ~ 6-day stagnation along with increase in TCCs and depleted disinfectant residual • Small-diameter distal end pipes had highest cell counts and deviated most from the city-water supply microbiome	• Hospitals and extended care facilities should upgrade PoUs of disinfection to counteract disinfectant decay and within-pipe cell growth • Precise flushing of smaller-diameter pipes, rather than whole building, is preferred to prevent stagnation while minimising water waste
Field study, UK[24]	12 private houses and medium-sized research building receiving chlorinated water	Variable, depending on location in building; all experienced weekend and Christmas holiday stagnation	FCM TCCs, ICCs	• Water from infrequently used taps had the highest TCCs and ICCs following weekend and Christmas stagnation periods • Flushing reduced microbial load in less frequently used cold water taps only	• Microbiological water quality depends on building-specific parameters • Tap water profiling is recommended to assess plumbing system hygiene and maintenance

Table 1 continued on the next page

Table 1 continued

Study type, country	Type of building	Water use pattern	Method(s) of analysis and microbial parameters assessed	Main findings (outcomes)	Recommendations
Field study, USA[12]	Cold and hot water systems in 437-bed hospital complex with three cases of hospital-acquired Legionnaires' disease over 18-month period	Variable water usage pattern with large secondary distribution and water storage tanks	Culture *Legionella*	Dead-leg removal reduced but did not eradicate *Legionella* colonisation in system	Disinfection sites, e.g. storage tanks should be situated closer to distal outlets to minimise disinfectant decay during distribution
Field study, USA[13]	Controlled model plumbing system with clear PVC pipes	95% water recirculation and 5% continuous flow with turbulent, laminar, and stagnant flow regimes	Culture *Legionella*	• Turbulent flow had highest *Legionella* counts and biofilm accumulation, followed by laminar flow and stagnant flow • Unable to demonstrate increased *Legionella* colonisation due to stagnation	Controlled studies in large buildings needed to validate removal of areas of stagnation, including dead-legs
Field study, China[25]	SSDWP connected to a DWDS in a university campus	Controlled stagnation times with operating temperature of 22–26 °C during July–August 2019 summer holidays	Culture, FCM, molecular (Illumina 16S rRNA sequencing) HPC, TCCs, ICCs, microbiomes	• ICCs and HPCs increased with stagnation time more rapidly in SSDWP than in DWDS • Microbial diversity increased with stagnation time in SSDWP • Pathogenic bacteria communities increased with water stagnation • Disinfection residual not detected in purifier • AOC increased with stagnation time	• Backwashing, terminal disinfection, and filter replacement should be conducted regularly in water purifiers • If measures are impractical, automatic backwashing or disinfection can be integrated with household purifiers to improve anti-bacterial performance • Residual disinfectants should be compulsory in terminal water storage tanks
Field study, USA[26]	Newly renovated low-energy and low-water use residential green building with PEX pipes	Standard operating conditions with 72 hrs maximum stagnation time	Culture, molecular (qPCR) HPCs, bacteria gene copy numbers	Infrequently used hot water basement fixtures determined as hot spots for degraded water quality (lowest disinfectant residual and high bacteria concentration-HPC and gene copies)	Sampling protocol should consider fixture usage and distance from service line to account for differences in water age, disinfectant residual, and microbiological characteristics
Field study, USA[27]	New (5–11 months) university campus buildings with taste and odour complaints; copper plumbing	Water conservation features	Culture *L. pneumophila*, *P. aeruginosa*, HPCs, HABs, APB	Rapid chloramine decay and microbial regrowth observed in buildings using advanced water conservation features	• Design of water systems in buildings should consider impacts of low water usage on microbial regrowth • Consider reducing pipe diameter or ensure minimal flushing to maintain palatable water
Field and controlled studies, 11 countries in Europe, USA, and Africa[14]	Office and residential buildings	Standard operating conditions with overnight stagnation	Culture, FCM, molecular (qPCR) TCCs, microbiome composition, *L. pneumophila*, *M. avium*, *Acanthamoeba* spp., *V. vermiformis*	• *Legionella* sequencing data positively correlated with biofilm cell concentration • Biofilm TCCs correlated positively with frequency of hose use	• Shower hoses should be considered in building drinking water risk management strategies • Effective management of building water plumbing should be supported by effective monitoring
Field study, USA[28]	Cold and hot water systems in a highly water-efficient, single-family residential building	Reduced water usage due to low-flow water saving fixtures	Culture, FCM, molecular (qPCR) *Legionella* spp., *L. pneumophila*, *Mycobacterium* spp., HPCs, TCCs, gene copy numbers	• Reduced water usage led to increased stagnation, which was positively correlated with elevated *Legionella* and *Mycobacterium* spp. gene copies, TCCs, and low chlorine levels • Reduced water usage and increased stagnation can have unintended consequences in water quality	• Flushing of taps or onsite disinfection to control microbial growth and opportunistic pathogens, especially in buildings with low-flow plumbing and high occupancy of the elderly and the immunocompromised • In event of suspected waterborne disease, water samples should be collected throughout the building, not only at the entry point where water quality is more likely to comply with drinking water standards

AOC: assimilable organic carbon, APB: acid-producing bacteria, ATP: adenosine triphosphate, dead-end: closed pipework through which no water passes, DGGE: denaturation gradient gel electrophoresis, DWDS: drinking water distribution system, FCM: flow cytometry, HAB: heterotrophic aerobic bacteria, HCF: healthcare facility, HPC: heterotrophic plate count, ICC: intact cell count, MAC: *Mycobacterium avium* complex, NTM: nontuberculous mycobacteria, OPPP: opportunistic premise plumbing pathogen, qPCR: quantitative polymerase chain reaction, PEX: cross-linked polyethylene, PoU: point of use, PVC: polyvinyl chloride, QMRA: quantitative microbial risk assessment, RA: risk assessment, rRNA: ribosomal ribonucleic acid, SSDWP: small-scale distributed water purifier, TCC: total cell count

RESULTS

A total of 93 potential articles were identified; 22 duplicates were removed, leaving 71 articles for screening (Figure 1). Subsequently, 27 articles were excluded as the topics were not related to the review, leaving 44 articles that were assessed for eligibility. A further 25 articles were excluded as they were not eligible for various reasons. Nineteen articles met the inclusion criteria and are summarised in Table 1. Most (n =18) were field-based and one was a simulation study. We collated some of the major drivers of the microbiological quality of building water systems, including stagnation, disinfectant residuals, and biofilms. We provide insights into how these factors impact microbial changes and, ultimately, water quality in buildings with reduced water demand due to low or no occupancy.

Most studies reviewed demonstrated a positive correlation between stagnation (measured qualitatively as low withdrawal or reduced water usage), from hours to several months, and inferior water quality. It was evident that the effects of stagnation are complex and difficult to separate from factors such as biofilm development and disinfectant loss.

Water samples in most of the articles reviewed, including biofilm studies, were collected at the point of entry (PoE) and point of use (PoU) (taps, showers, showerheads, and other fixtures)(Table 2). Many articles on *Legionella* occurance, such as that by Sidari et al. (2004),[12] which evaluated the effect of removing and repairing dead-legs (length of pipework leading to a fitting through which water passes infrequently when there is a draw-off from a fitting; and intermittently used fixtures and equipment), did not mention where the water samples were collected. The only paper describing a study where water samples were collected at points other than the PoU was that by Liu et al. (2006).[13] The authors simulated the effect of flow regimes on *Legionella* occurrence in biofilms and samples (bulk water and biofilms) were collected from the pipes after disconnection.

Our literature search identified only one study in Africa (Proctor et al., 2018),[14] highlighting a gap in this crucial research on the continent. This may be attributed to a general lack of awareness and full appreciation of water quality concerns in PPSs, despite deteriorating water quality due to inadequate investment in infrastructure and the effects of climate change. We highlight considerations for site-specific risk assessments for building water systems.

Legionella risks in premise plumbing systems

Legionellae are gram-negative bacteria that are ubiquitous in natural aquatic environments, albeit at concentrations too low to cause infections.[37] However, the bacteria can colonise PPSs, proliferating to harmful levels with substantial risk for infection in susceptible individuals.[38] Potential reservoirs include showerheads, decorative water features, hospital plumbing (dental water lines and respiratory equipment), heating, ventilation, and air conditioning systems, among others.[10, 39] The most common transmission route is inhalation of contaminated water aerosols,[10] although aspiration has also been documented.[11] *Legionella* infections, collectively known as legionellosis, comprise Legionnaires' disease (LD), an acute pneumonia-like infection often requiring hospitalisation, and Pontiac fever, a milder flu-like illness.[40] High-risk groups include the aged (older than 50 years) and those with underlying health conditions.[10, 36] More than 50 species and 70 serogroups have been described to date, with *Legionella pneumophila* accounting for over 90% of all notified LD cases, globally.[41]

Although legionellosis is a notifiable disease in many countries, including South Africa, a lack of awareness, coupled with severe under-reporting and misdiagnosis, presents challenges to accessing prevalence data. Nevertheless, legionellosis case numbers are reported to be increasing, globally,[10, 39, 41] with drug-resistant isolates from healthcare water systems being of particular concern.[42] In South Africa, 93 laboratory-confirmed legionellosis cases were notified from 1 January 2018 to 30 September 2020, with the majority of cases (n = 72; 77.4%) reported in the Western Cape province;[39] the case fatality ratio was 20.8%. The condition was most common in individuals with comorbidities (n = 64; 81.3%), those aged 40 to 69 years (n = 65; 69.9%) and males (n = 61; 65.6%). Whilst difficult to ascertain the source of infection due to poorly completed case investigation forms, ongoing surveillance and improved investigation of LD are important for cluster identification, particularly during the COVID-19 pandemic when lockdown measures resulted in restricted use of buildings, potentially increasing the risk for *Legionella* growth in PPSs.[39, 43]

Reported outbreaks are most often associated with deficiencies in building water quality management, including operating conditions and maintenance.[41, 43] Premise plumbing systems inherently offer ideal conditions for microbial growth due to their complexity and extensive pipe networks.[18, 44, 45] In summary, periodical stagnation, inadequate disinfectant residual, and biofilm formation, among other risk factors, individually or in combination, may result in deterioration of water quality in closed buildings, as discussed below.

DISCUSSION

Stagnation concerns in premise plumbing

In PPSs, stagnation occurs when water within pipes remains idle until an outlet is used at any point in a building water system;[19] it can be intermittent or permanent.[44] Stagnation is associated with a drop in disinfectant residuals to ineffective levels, biofilm development, ambient temperatures, and increased bio-available nutrients.[46, 21] These conditions provide an ideal environment for plumbing microflora, such as *Legionella*, to flourish. As such, stagnation is commonly considered a proxy for inferior microbial water quality.[19, 45]

Many studies have reported a positive association between stagnation and microbial occurrence and growth, including that of *Legionella*. For example, bacterial cell concentrations and activity increased by several orders of magnitude, following overnight stagnation, as reported in 2010.[21] Similar findings were reported for weekend,[22] week-long,[23] two weeks,[24] and 1-4 weeks[22] stagnation. A six-month study involving nine buildings with histories of *Legionella* contamination also reported a significant correlation between *Legionella* occurrence and stagnation, temperature, and pipe length, suggesting interactions between these factors.[19] Several green building water quality studies support these findings.[18, 26, 28] Unsurprisingly, the researchers involved in these studies recommend flushing of taps post stagnation, although this might not be appropriate in water-scarce countries. A limitation of some of the studies is the lack of information on microbial baseline data before sampling, which is critical for meaningful comparisons and decisions about what constitutes unacceptable duration and frequency of stagnation.[9]

Conversely, using culture methods, two studies showed no association between stagnation and *Legionella* growth.[12, 13] However, conventional culture methods can raise important biases given the ability of *Legionella* to enter a viable but non-culturable (VBNC) state in response to stress conditions,[47, 48] and its association with free-living protozoa like amoeba,[44] which can affect recovery and quantification, thus underestimating *Legionella* concentration levels in water systems. Using molecular techniques, Bédard et al. (2018)[17] reported similar results for a hot water system in a large hospital in Canada following a controlled 10-day stagnation. It should be noted that only two taps of the system were studied, which is not representative of the extent and nature of the entire system. Moreover, the large volume of samples collected (1 L) may draw water from further within the system as opposed to a small volume of stagnant water in the distal ends.[17] The intrinsic characteristics of systems, including cold versus hot water systems and plumbing material, can also contribute to variations in results. It has been postulated that higher copper levels, present after prolonged stagnation, can impact culturability.[17]

Limited studies have evaluated the impact of COVID-19 lockdowns on the microbiological quality of building water. De Giglio et al. (2020) reported significant post-lockdown *L. pneumophila* contamination compared to pre-lockdown levels in three hospital wards in Apulia, southern Italy, that had been temporarily closed for three months following repurposing for COVID-19 patients.[2] The authors attributed this to lockdown building inactivity. In another study (Hozalski et al., 2020), *Legionella* spp. gene markers were frequently detected in unoccupied (partially or fully, for approximately two months) university buildings in Minnesota, USA.[4] Contrary to the findings reported by De Giglio et al. (2020),[2] *L. pneumophila* was not detected in any samples tested by Hozalski et al. (2020).[4] Nevertheless, more than 20 *Legionella* spp. are pathogenic, and their presence in PPSs indicates inadequate control to prevent bacterial regrowth, which should be addressed to prevent recurrence and potential proliferation to harmful levels.

Increased microbiological risks, indicated by reduced residual chlorine, elevated HPCs, and turbidity were reported in university buildings with reduced or no water usage for almost four months in Fujian province, south-eastern China.[15] It took 4-54 days to restore building water quality to normal levels. The presence of *L. pneumophila* gene markers in 91% of the water samples, despite the absence of the culturable cells – possibly due to VBNC status – further confirmed increased microbiological risks in these buildings. Reports on *Legionella* detection in buildings, following COVID-19 lockdown, have also appeared on media platforms.[49] However, these should be treated with caution. Scientific studies are needed to ascertain these claims, using appropriate building water system characterisation and the collection of baseline data.

It is plausible that low building occupancy, resulting from COVID-19 precautionary measures and other similar situations, could lead to stagnation in PPSs. The World Health Organization's (WHO's) 2011 report on water safety in buildings lists poor flow and stagnation due to intermittent use or extended periods of no use (e.g. floors/wings of hotels with seasonal occupancy, hospital wards, schools) as hazardous

Table 2. Overview of building water system components associated with microbial concerns

Component	Definition	Water quality concern	References
PPSs	Piping connecting buildings from PoE to PoU and all associated equipment, treatment devices, fixtures, and appliances related to providing water in the building. Also known as building water systems	• High plumbing surface-to-volume ratio is ideal for biofilm formation • Unique pipe materials that react with disinfectants or leach nutrients into water • Variable occupancy patterns affect flow conditions and water age • Difficult to maintain temperature and residual disinfectant targets that discourage microbial growth	Hozalski et al., 2020[4] Salehi et al., 2018[26] WHO, 2007[29]
PoU fixture or fitting	Any plumbing receptacle, device or appliance that can be temporarily or permanently fixed in place to provide, store or dispose water, e.g. shower heads, taps (faucets), sinks, bathtubs, eyewash stations, water-using medical equipment, toilets	• High surface-to-volume ratio suitable for biofilm formation • Generate aerosols that can contaminate surfaces or be inhaled (0.3–10 µm) • Prone to disinfectant decay with increased distance from service lines	Johnson et al., 2013[30] Allegra et al., 2020[31]
Dead-leg and dead-end	Dead-leg: length of pipework leading to fitting through which water passes infrequently when there is a draw-off from a fitting. Intermittently used fixtures and equipment can become dead-legs depending on how long they remain unused Dead-end: redundant length of pipework that does not lead to anything, is completely closed at one end, and through which no water passes, e.g. outlet, equipment or valve that is no longer being used, or capped-piping installed for future plumbing expansion	• Contribute to stagnation in PPSs due to low or no water circulation • Out of reach of disinfectants due to low or no water circulation • Offer favourable conditions for biofilm formation and bacteria proliferation, including *Legionella*	National Academies of Sciences, Engineering, and Medicine, 2020[32]
Decorative fountains/ water features, e.g. spa pool, misting device	A spa pool (also known as heated spa, portable spa, hot tub, whirlpool, whirlpool spa, bubble bath or jacuzzi) is a self-contained body of warm (usually > 32 °C), agitated water designed for sitting in (rather than swimming). May or may not be drained, cleaned or refilled after each use Misting devices include those used for cooling. Typically installed in outdoor areas to produce and release water aerosols that flash evaporate in the surrounding air, resulting in reduction of ambient temperature	• Can create favourable conditions for pathogen growth if not adequately maintained and routinely cleaned • Pipework, pumps and filters used for air and water circulation; provide large surface areas for bacterial growth • Generate aerosols during operation • Prone to thermal gain, especially if located in the sun • Submerged heat-generating lighting, UV units, and pumps contribute to warm water temperatures • Prone to stagnation due to closed system and if turned off for extended periods • Wet or damp surfaces promote biofilm formation unless appropriately managed	Palmore et al., 2009[33] Haupt et al., 2012[34] Smith et al., 2015[35] Masaka et al., 2021[36]

PoE: point of entry, PoU: point of use, PPS: premise plumbing system, UV: ultraviolet events.[43] Additional research to establish the impact of long-term stagnant water periods with extensive system characterisation and systematic sampling to build statistical confidence, would be valuable for informing risk prediction and mitigation.[9]

Disinfectant residual concerns

Potable water is disinfected to meet prescribed national standards before entering buildings for the intended use. Nevertheless, disinfectant decay to below detectable levels is common with reduced water usage.[50] Extended stagnation periods, as experienced in some buildings during COVID-19 lockdowns, may exacerbate the degradation of disinfectant residuals in PPSs.[3] The lack of pre-COVID-19 data presents challenges when identifying lockdown effects on disinfectant decay and the subsequent impact on the microbiological quality of PPSs.

Chlorine residuals were completely depleted in six-day stagnant water samples and were negatively correlated with microbial cell counts in a study in three four-storey buildings in Champaign, USA published by Ling et al. (2018).[23] Similarly, infrequently used basement fixtures with longer stagnation periods in a residential green building in West Lafayette, Indiana, USA were considered as hot spots for degraded water quality due to depleted disinfectant residual and increased microbial concentration.[26] Reports of rapid disinfectant decay and elevated microbial levels in green building water systems, most likely due to older water inherent in these buildings and high disinfectant demand of the copper piping, corroborate these findings.[18,27] Baseline residual chlorine concentrations (0.48 mg/L) declined significantly to below the recommended level (0.05 mg/L) in most university buildings with reduced or no water usage due to COVID-19 shutdowns in Fujian province, south-eastern China.[15] This decline was significantly correlated with HPC levels for completely stagnant laboratory water samples. Interestingly, the HPC values dropped below detection levels when residual chlorine concentration reached the national standard (0.05 mg/L) a week after resumption of water usage.

More recently, disinfectant residuals were acknowledged as an

Table 3. Considerations for building water quality risk assessment for potential microbial growth during reduced or low occupancy

Activity	Consideration	Comment
Hazard and hazardous event identification • Major microbial hazard of concern in PPSs is *Legionella*, specifically, *L. pneumophila*, given the global increase in notified cases. • Building closures present a hazardous event that can impact building water quality due to prolonged stagnation.	• Duration when building or parts thereof were closed. • History of the facility with regard to water quality issues, e.g. presence of *Legionella*. • Walkthrough assessment to inspect system for potential sources of contamination (low-use / high-risk outlets), e.g. aerosol-generating devices, storage tanks, dead-legs/dead-ends, water heaters/coolers, etc. • Alterations or modifications of the water system that may introduce areas of stagnation or low-flow. • Water source, e.g. municipal, roof harvested rain water, or recycled/grey water.	• All water supply systems are potential reservoirs of microorganisms, including *Legionella*, even if water is treated. • There are no set standards to define unacceptable levels of building occupancy or period of stagnation. Rule of thumb: reduced occupancy can result in water stagnation, which can compromise water quality. • Schematic characterisation of plumbing system will help identify high-risk areas but requires someone who understands the layout. • Use of checklists to document observations and inventory of plumbing components is encouraged.
Exposure assessment to decide who might be harmed Depends on the purpose of the building, services provided, and who has access, including workers, visitors (e.g. patients), and contactors.	Presence of the pathogen does not automatically imply a health problem; other factors must be considered, including: • Vulnerability of people with access (age, illness, or compromised immunity). • Potential exposure events or work activities while at the facility. For *Legionella*, this is use of, or close proximity to, aerosol-generating devices. • Frequency and duration of stays/visits, use of aerosol-generating devices or outlets, e.g. showers.	There are no occupational exposure limits for pathogens such as *Legionella* and other OPPPs.
Control measures in place Building closures can present challenges to monitoring and routine maintenance of control measures, e.g. temperature monitoring, periodic flushing of less used outlets, and water quality testing.	• Determine if there was operational monitoring and recording of control measures during building closure. • Consider action level specifications of routine controls. • Non-routine/operational controls should be addressed at design phase	• Monitoring records should be up-to-date and accessible, so that the system can be assessed. To be useful, operational monitoring should provide real-time or near real-time results. • A risk management approach integrates several methods, including elimination of stagnation or dead ends, reduction of aerosol formation, maintenance of adequate temperatures, and use of materials unfavourable to biofilm development.
Rate the remaining risk Rate the remaining risk under the existing control measures. If no control measures exist, then the level of risk may be high.	A risk scoring matrix, whereby the likelihood of a hazard occurring is combined with the severity of consequences, can be used to assess and rank the risks.	Aim is to prioritise hazardous events that are likely and may have moderate to catastrophic consequences, requiring immediate corrective action.[44]
Implement corrective action Corrective actions should be informed by the RA and depend on available resources; can include one or a combination of interventions such as flushing, thermal shock, and shock disinfection.	• If microbial growth in the water system is suspected due to the ineffectiveness of existing control measures, and the risk of exposure is unacceptably high, consider implementing corrective action(s) before returning the water systems to action. • Engage competent personnel or professional assistance to prevent mistakes, or injury of or exposure to workers, visitors or contractors to microbial contaminants.	If high risks are identified, a plan of action should be developed, detailing corrective actions to be undertaken to return water quality to normal conditions. Include timeframes and delegate responsibilities for implementing corrective action timeously to prevent potential exposures.

PPS: premise plumbing system, OPPP: opportunistic premise plumbing pathogen important parameter for monitoring building water quality by subject matter experts, and were mentioned in several guidance documents, as shown in a survey by Singh et al. (2020).[50] However, monitoring of disinfectant residuals is generally not a requirement for most drinking water standards.[50, 51] Further research is therefore needed to determine the appropriateness of disinfectant residual as an indicator of water quality, particularly regarding *Legionella* amplification.[50]

Biofilm concerns during stagnation

Water stagnation, especially in the presence of low disinfectant levels, can encourage the proliferation and persistence of premise plumbing biofilms,[44] contributing to microbial loading in potable water.[51, 52] Biofilms are problematic because they are difficult to remove once established,[53] they provide bacteria with nutrients, provide protection from disinfectants, and induce VBNC and chlorine decay.[47,48] Biofilms also offer an ecological niche to free-living amoeba where *Legionella* can survive,[54, 55] further reducing the efficacy of disinfectants.

The constructional complexity of PPSs presents a limitation for biofilm studies, allowing sample collection only at PoU, which is not representative of the entire water system and does not adequately reflect systemic issues. Biofilms in the last few metres of the water system before the PoU present a potential health risk, particularly in healthcare facilities (HCFs), where both health workers and patients can be exposed to OPPPs when showering and bathing.[56] In a study published by Huang et al. (2020), the annual infection risk of *Legionella* was significantly higher when water stagnated for up to 48 hours in pipes with biofilms compared to those without biofilms.[20] Proctor et al. (2018) reported that *L. pneumophila* was detected in biofilms of showerheads, faucets, and humidifiers in high-occupancy buildings such as HCFs and hotels, with *Legionella* sequencing data correlating positively with biofilm TCC.[14] They also reported that frequently used hoses had the highest biofilm concentrations after weekend stagnation, and that biofilm TCC was significantly higher in shower hoses of premises that did not use a disinfectant. Shower hoses are characterised by long stagnation periods, mild-to-warm temperatures (22–43 °C), and high biodegradable carbon leaching – conditions that support bacterial proliferation and biofilm development.[53] Hence, interventions targeting biofilm growth suppression may reduce the risk of *Legionella* proliferation.[14, 57] Currently, control strategies directly targeting biofilms in PPSs are limited, and maintenance practices such as chemical and thermal disinfection are more effective against planktonic microorganisms compared to sessile microorganisms in biofilms.[32] This calls for science-based evidence of the efficacy of maintenance procedures on biofilms, to guide mitigation strategies.

Following unprecedented stagnation periods over several months during the COVID-19 pandemic, re-occupation of once-deserted buildings and sudden resumption of water use can result in rapid changes in the water flow rate. This can disrupt portions of biofilms into the bulk water column,[58] with the potential to reach PoU at doses sufficient to cause infections in susceptible populations.[59] The first flush upon building re-opening is a possible point of concern for human exposure through the inhalation of contaminated aerosols.[4, 6]

Table 4. Considerations for verification of the effectiveness of control measures or remedial actions

What to test for?
- Many drinking water quality standards/guidelines have adopted bacterial pathogen indicators (total coliforms, faecal coliforms and *Escherichia coli*) for microbiological quality monitoring, even though their presence does not always correlate with other pathogenic microorganisms. Hence, tests should include *Legionella* detection and enumeration.
- Other parameters, such as disinfectant residuals (chlorine/chloramine) and temperature (hot and cold water), should be measured onsite during sampling, and benchmarked with the city's main water supply. Disinfectant residual monitoring provides a good indicator that building water turnover is being adequately managed.
- Temperature monitoring may provide a good indicator that a flushing programme is moving sufficient water through the system.

Where to sample?
- Critical sampling points, representative of the entire system (different buildings, floors, wings, etc.) can be mapped, depending on the size of the facility.
- Sampling points should include high-risk areas such as faucets, emergency showers, eyewash stations, high-pressure jet areas, areas with low disinfectant concentrations (e.g. storage tanks), intensive-care units, surgery suites and problematic outlets with recurring positive results, etc.
- Generally, any water source that may generate aerosols should be considered a potential source for *Legionella* transmission.

What type(s) of samples to collect?
- Different sample types provide different information, e.g. biofilm swabs versus bulk water, stagnating first-draw versus 'after flushing' samples, and hot versus cold water samples.
- Sample type information must be reported to ensure that results are interpreted correctly and that appropriate recommendations are made. It is generally recommended to flush at least 2–3 minutes prior to drawing the first sample, for representation of the actual conditions in the plumbing system.
- Use personnel with competency in sampling procedures and sample handling as this may affect laboratory results and response action.

Sampling frequency
- Sampling frequency should be informed by a site-specific RA and should reflect a balance of the benefits and the costs of obtaining more information.
- To determine effectiveness of corrective action, sampling and testing should be repeated to ensure that the water is safe for use.

Choice of test method in testing laboratory if outsourcing
- Several culture and molecular water quality tests have been developed over the years; some are qualitative, determining only presence/absence, while others are quantitative, providing estimates of concentration levels of the target organism.
- The priority may be confirmation or quantification, determining viability, or distinguishing serogroups or sequence type.
- Culture methods are more ideal for RA than molecular methods, which cannot differentiate infectious from non-infectious genetic material, making it difficult to assess the risk.
- Consider proximity of facility to testing laboratory to ensure sample integrity is maintained during transport. Long-distance shipping will require cold chain maintenance, which may increase costs.

Interpretation of results
- National or international guidelines and standards relevant to the building type (e.g. hospital with high-risk occupants, fitness centre) should be consulted to interpret test results.
- Competent personnel should be assigned this role so that results are interpreted correctly and appropriate actions are taken to prevent risk of exposure.

RA: risk assessment

Although OPPPs, particularly *P. aeruginosa*, share common characteristics regarding disinfectant resistance and growth in biofilms in PPSs,[56] we did not consider them in our review for various reasons. For example, the source of *P. aeruginosa* in PPSs appears to be more external – as retrograde contamination via patients and workers or from the sink environment – than systemic.[56] In fact, *P. aeruginosa* is rarely detected in bulk water samples within plumbing systems.[56] Consequently, most prevalence studies on *P. aeruginosa* in high-risk buildings such as hospitals focus on faucet and drain contamination as possible sources of *P. aeruginosa* infections.[56] Furthermore, *P. aeruginosa* is not regulated in drinking water in most countries[60] and infections are not notifiable,[54] making it difficult to assess the burden of disease. Nevertheless, *P. aeruginosa* and other OPPPs are of growing concern and should not be ignored as they are difficult to eradicate once established. More research is needed to understand how these OPPPs respond in premises that have intermittent water demands and stagnation, as several factors may promote their growth and persistence in plumbing systems.

Premise plumbing risk assessment for decision making

The COVID-19 pandemic underscored the importance of a proactive approach to managing building water quality. Risk assessments (RAs) are an essential component for managing building water quality and infection control, particularly in high-risk buildings.[43] According to the South African Department of Employment and Labour,[61] RAs, guided by competent person(s), should be carried out on water systems that have been idle for extended periods and are likely to present risks upon building re-opening. In conducting an RA of a building's water system, several critical issues must be considered, as presented in Table 3. Microbiological water-quality testing to verify the effectiveness of control measures and 'fitness-for-use' of the water is highly recommended.

Table 4 summarises important points to consider when verifying the effectiveness of control measures or remedial actions following periods of reduced water demand in PPSs. This information is generic and should be informed by site-specific RAs. Although this information is critical, some guidance documents on potential *Legionella* risks due to COVID-19 lockdown that were reviewed, did not provide detailed information on the sampling strategy, choice of test methods, and interpretation of results.

CONCLUSION

There is a potential for microbial growth in some PPSs, following COVID-19 lockdowns, and warnings to be mindful of the associated health hazards, such as legionellosis, are understandable. Building owners and facility managers should review the RAs of their PPSs to identify hazards, prioritise risks, and apply appropriate corrective measures. More importantly, site-specific premise plumbing RAs should be considered as an integral component of the 'one-health' approach to managing building water quality and infection prevention and control. More research on the risk factors for *Legionella* colonisation in buildings' water systems, including prolonged building closures, is needed to support these efforts.

KEY MESSAGES

1. Reduced water usage due to building closures, as experienced during COVID-19 lockdowns, can result in water quality deterioration in buildings.
2. Every building is unique and the microbial quality of the water is dependent on several factors, which should be considered when assessing building water contamination risks.
3. Control measures to reduce contamination risks should be guided by site-specific risk assessments.

DECLARATION

The authors declare that this is their own work; all the sources used in this paper have been duly acknowledged and there are no conflicts of interest.

AUTHOR CONTRIBUTIONS

Conception and design of the study: AG, TS
Data acquisition: AG, LS
Data analysis: AG
Interpretation of the data: AG, TS, LS
Drafting of the paper: AG, TS, LS
Critical revision of the paper: AG, TS, LS

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