Water Age and Plumbing Pathogens

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Contributor: Faisal Hai

One of the most important characteristics that can affect the growth and proliferation of opportunistic pathogens in premise plumbing systems is water age. Water age is a term that represents the average time taken for water to reach its point-of-use from its point-of-entry within a distribution system. It is more precisely defined as a summation of residence time from the treatment facility to the water meter of a building (i.e., mains distribution) and residence time from the water meter to the point of use (i.e., premise plumbing distribution). Water age can be described primarily as a function of water demand, system design, and system operation. As demand increases, the time that water is resident in a system decreases.

Keywords: opportunistic premise plumbing pathogens ; legionella ; water age ; chlorine residual

1. Factors Contributing to Increased Water Age

Increased retention time or stagnation is a common occurrence in drinking water distribution systems due to demand fluctuation and long intermissions [1]. Particularly with main distribution, capital planning often dictates that systems be designed to maintain pressures and quantities for future demand, which can cause increased water age if present-day demand is significantly less than that which is forecast [2].

Dead ends are essentially underutilised or redundant sections of piping where water tends to stagnate and sediment readily builds up. These can occur in water main and premise plumbing distribution systems yet can be avoided through proper design and operation [3]. Notwithstanding this, water age is likely to increase in main and premise plumbing distribution systems as water conservation practices are adopted at the community level [4][5].

Water age is also expected to be higher in green building systems when all other variables are held constant [5]. Preliminary data indicate that water age in modern green homes averages 250% higher than in conventional residences. Table 1 illustrates a number of standard practices in green buildings that reduce demand and/or increase total system volume to yield higher water ages. Table 2 indicates the extent to which such measures can decrease demand within individual buildings.

Table 1. Examples of water and energy conservation strategies that reduce flow and increase volume in premise plumbing systems (information source [3]

Type of Green Building	Observation
Net-zero rainwater office building	On-site storage of up to 11,350 L. Demand was estimated to be 1700 L per month during the spring and up to 5500 L month during the summer. This resulted in a variable water age between 2 and 6.7 months.
Leadership in Energy and Environmental Design (LEED) certified healthcare suite	Water demand was 60 times less water than equivalent conventional commercial buildings. A water age of 8 days was attributed to very low use at each tap in patient exam rooms, coupled with large diameter pipes stipulated by plumbing code.
Net-zero energy house	Used 4 times less water than an equivalent house studied. At this site, water age was observed before and after installation of a solar water heater. Hot water storage and age was increased by up to 1.7 days.

Table 2. Example of reduction of water usage (i.e., increased water age) from conservation efforts in green buildings (data source [3][5]).

Type of Facility	Water/Energy Conservation Strategies That Can Increase Water Age
Commercial buildings	A high number of fixtures increases system stagnation

Type of Facility	Water/Energy Conservation Strategies That Can Increase Water Age
	Rainwater harvesting requires adequate storage to ensure adequate supply during droughts
	Decreased water use through behavioral changes results in high water age
	Efficient fixtures reduce flow up to three times increasing water age proportionally
Residential buildings	Solar water heaters can double hot water storage volume
	Rainwater harvesting reduces tap water used for non-potable purposes
	Distribution system water age is higher because water utilities sell less water than 10 years ago
	Efficient fixtures reduce flow up to three times, increasing water age proportionally

Using rainwater or reclaimed water concurrently decreases demand and increases the overall system volume. Since large storage volumes are necessary to endure drought, tanks are often sized to satisfy weeks or even months of demand. Furthermore, the quality and safety of rainwater used for potable water uses remains relatively less studied [6][7]. Many hot water system configurations require large tank sizes in open-loop systems that provide increased system volumes and water ages. Water-efficient fixtures also significantly reduce flow and therefore demand [8]. For example, an inefficient showerhead can use between 15 and 25 L of water per minute, while an efficient showerhead can use between 6 and 8 L of water per minute. As showers tend to run for more than 3 min, there may be enough time to replenish the old water in the supply pipes leading to that shower. The situation is more critical for basins that are regulated between 4 and 6 L per minute but have a usage run time that is often less than 10 s. This pulls 'slugs' of heated water into a premise system without it ever actually reaching the end of line, providing new nutrients to enhance biofilm.

2. Expected Changes in Water Quality Resulting from Elevated Water Age

Water age is a major factor in water quality deterioration within distribution systems, which occurs via reactions within the bulk water and/or interactions between plumbing materials and the water [2]. As water is conveyed through the system, it is subject to various chemical, physical, and aesthetic transformations, which will proceed to a greater or lesser extent according to factors such as water flow rate, finished water quality, plumbing materials, and deposited materials.

Evidence strongly indicates the potential for high water age to negatively impact the quality of drinking water in main and premise plumbing distribution systems. It is associated with problems including disinfectant stability, corrosion of plumbing components, scaling, development of tastes and odours, and microbial (re)growth [9][10][5][11][12]. Symptoms of high water age are often diagnosed via consumer complaints. Monitoring of various chemical and biological water quality parameters might also reveal high water age, for example, lower than expected disinfectant residuals, elevated levels of disinfectant by-products, and elevated bacterial counts [2].

Water quality concerns that can be caused or worsened by increased detention time in distribution systems, with implications on public health, are summarised in Table 3 below.

Table 3. Chemical, biological, and physical water quality issues worsened by high water age.

Chemical Issues	Biological Issues	Physical Issues
Disinfection decay and by-product formation	Microbial proliferation	Temperature fluctuations; taste and odour
Corrosion of fixtures and leaching of metals from fixtures		

3. Loss of Disinfectant Residual and Microbial Ramifications

Disinfectant decay is more likely to occur in premise plumbing systems than in main distribution due to higher pipe surface area-to-water volume ratios, more frequent stagnation points, longer detention times, higher temperatures, and lower disinfectant residuals [13][14][15].

Traditionally, the control of pathogens by water utilities has been achieved by coagulation, filtration, and disinfection at the point of treatment prior to distribution [3]. Free chlorine and monochloramine are the two main disinfectants preferred by utilities [16]. Mounting evidence suggests that this is no longer a sufficient approach, especially for systems challenged by high water ages, including green building designs.

The purpose of a secondary disinfectant residual in water supplied by utilities is to protect the consumer against pathogens and bacterial regrowth [4][3]. The selected disinfectant must ultimately inactivate microorganisms in bulk water, control or remove biofilm, and inactivate microorganisms associated with that biofilm [17]. Unlike free chlorine and monochloramine, ozone and ultraviolet light are not effective as residual and, therefore, they are effective only at the point of use [4][18][2][19][20][21][22].

Rhoads and Edwards [3] discuss how residuals can disappear as a result of abiotic and biotic reactions within the bulk water and/or between plumbing surfaces and the water. Factors that affect the persistence of disinfectant residuals include water quality, plumbing materials (including adhering biofilms), and system operation. In their survey of green building water systems, Rhoads et al. [5] found that chlorine and chloramine residuals were often completely absent in the green building systems, decaying up to 144 times faster in premise plumbing with high water age when compared to distribution system water.

Water quality decreases with increasing distance from the point of treatment as disinfectants decay and residual concentrations fall below adequate levels. This inevitably results in a shift towards rapid bacterial growth [4][14][23]. The efficacy of various disinfection methods applied for the control of opportunistic premise plumbing pathogens is detailed in Section 4, which includes a discussion of the role of in building disinfection systems.

4. Formation of Disinfectant By-Products

Organic and inorganic disinfection by-products (DBPs) form as disinfectants react with naturally occurring materials in potable water distribution systems [2]. DBP formation potential varies within and between systems and is a function of chemical and physical characteristics including pH, temperature, type and level of organic matter, type and level of disinfectant residual, and contact time. Increased potential for DBP formation has been linked to increased water ages or contact times. Resulting changes in water quality could cause DBP reactions to proceed faster and go further. The challenge is to interrupt the cycle induced by the requirement for higher disinfectant dosages as decay occurs, thereby increasing DBP formation potential.

More than 600 DBPs have been identified in chlorinated tap water, including haloacetic acids (HAAs) and trihalomethanes (THMs) [24]. The USEPA describes how people who drink water containing HAAs and THMs in excess of maximum contaminant levels (MCLs) for a prolonged number of years have an increased risk of getting cancer, or experience problems with their liver, kidneys, or central nervous system [2]. However, the WHO recommends that “efficient disinfection must never be compromised” and “microbiological quality must always take precedence” when a choice must be made between meeting either microbiological guidelines or guidelines for disinfectants and disinfectant by-products [25]. Thus, it might be concluded that waterborne pathogens pose a more serious and immediate threat to public health than DBPs.

5. Corrosion Control Effectiveness

Phosphates are often added to drinking water supplies to minimise the corrosion of piping materials [3][2][26]. Increased water age influences the effectiveness of such corrosion control inhibitors by the provision of poorly buffered waters, which challenges pH management [27][28]. Corrosion can reduce the lifetime of premise plumbing infrastructure and cause leaching of lead and copper into the water [29]. In addition, although there appears to be substantial interplay between corrosion control and disinfection, implications for microbial control are not fully understood.

Corrosion products react with some disinfectants to enhance or reduce their impact depending on the exact water chemistry and pipe materials [3][30]. For example, Al-Jasser [13] conducted a study showing that metallic pipes (cast iron and stainless steel) consumed more chlorine as they aged, which was likely due to the accumulation of corrosion products. Conversely, plastic pipes (polyvinylchloride and medium-density polyethylene) consumed less chlorine as they aged and exerted no demand after a decade of service.

‘Blue water syndrome’ i.e., blue staining occurs in waters with high levels of soluble and/or particulate copper. Although elevated levels of copper in water are not known to cause long-term health effects, it has been linked to gastrointestinal upset and exacerbation of problems associated with nitrate ingestion, especially in children [2]. Such occurrences are expected to be more frequent in certain situations with water conservation practices [3].

Copper corrosion failure (often referred to as pinhole leaks, and as non-uniform or pitting corrosion) is strongly attributed to frequent stagnation, as well as accumulation of debris during installation, and microbial activity [23][31]. Therefore, occurrence might be more frequent in green buildings associated with low flow velocities and low water use. Research by Lytle and Schock [32] determined free chlorine to be an important factor to induce pitting under certain conditions. Severe pitting corrosion can jeopardise the integrity of an entire plumbing system, for which costs of repair or replacement can be substantial.

Lead is a neurotoxin that can cause permanent, irreversible damage when consumed and is therefore a recognised threat to public health in water supply [33][34]. The corrosivity of the supply water is an important driver for lead into building plumbing systems [35]. System design and operation can also influence the rate of release [36]. Prolonged periods of stagnation and high-water age increase the contact time between water and lead-based plumbing components or solders, which can increase the rate of metal release [37]. Lytle and Schock [38] observed an exponential increase in lead levels with stagnation time in the first 20–24 h of exposure.

Lead pipe plumbing is not widespread in Australian homes relative to Europe and the US, where infrastructure is more dated [39]. Nowadays, the installation of lead-based piping and the use of lead-based solders is largely banned for new constructions and renovations. Despite this, the risk of lead exposure remains [40][41][42][43][44][45]. A field study by Elfland et al. [46] revealed that premise plumbing lines in green buildings with relatively low water demand had very high lead leaching from brass and bronze devices with lead coating.

6. Impact of Water and Energy-Efficiency Initiatives

As noted above, specific elements designed to achieve net zero or energy-efficient buildings have recently been subject to scrutiny for their potential to increase pathogen growth and aerosolisation. For example, multiple studies have demonstrated that metered faucets dispense higher levels of *P. aeruginosa* and *L. pneumophilia* than conventional faucets [47][48][49][50]. When the metered faucets are hands free, additional problems can arise due to the solenoid valve used to control the water flow. Such solenoid valves, when activated, force a soft polymer diaphragm against a sealing face to close the water supply. This soft ‘rubberised’ material can provide an ideal surface for colonisation as to the small volume of stagnant water beneath the diaphragm needed for it to operate. Notably, since the introduction of WELS in Australia, every tap now includes a mesh capture point on its outlet, which is suspected to be an ideal breeding ground for bacteria. The mechanisms driving these trends in outlet flow control devices in tap need to be better studied [51].

Solar water heaters and rainwater tanks require large storage volumes to meet sustainability goals, which increases holding time and microbial risk. Reducing hot water system temperatures in an attempt to conserve energy can also support conditions for pathogen growth in hot and cold-water systems [3][5][31]. Accordingly, critics of the Leadership in Energy and Environmental (LEED) rating system devised by the United States Green Building Council (USGBC) have reworked the acronym to stand for “Legionella Enabled Engineering Design”. As noted earlier, Green Star and the WELS rating system are the equivalent benchmarks for water efficiency drives in Australia.

The main benchmarks for sustainability, Green Star and the WELS rating system in Australia, have been aiming for simplicity in order to maximise their reach and subsequent adoption. This simplicity, combined with the current approach to sustainability as a kind of box to tick, has led to a disconnection between the design and construction of a building and its ongoing occupancy and management. While the performance of a building is a priority across all levels of Green Star, these benchmarks have created unforeseen consequences for the well-being of building users by failing to demonstrate an understanding of the knock-on effects when a building is not managed correctly. The current water efficiency solutions under sustainability benchmarks, combined with a lack of information available within building management services have created environments perfect for the growth and transmission of opportunistic pathogens in premise plumbing systems.

Green design principles are pivotal to sustainable development. It would be unwise to abandon water and energy conservation efforts. Instead, researchers and stakeholders associated with the drinking water distribution system should continue to advance their understanding of potential water quality issues and public health concerns to formulate better policies, codes, standards, risk assessment and management approaches.

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