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Legionella Occurrence in Buildings: Implications of Public Water System Disinfectant and Residual

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ABSTRACT

Legionella pneumophila is an opportunistic drinking water microorganism of serious health concern. Anticipated revisions to U.S. EPA's Microbial and Disinfection Byproduct Rules may propose a numeric minimum disinfectant residual—rather than the current "detectable"—in part to better control *Legionella* in drinking water distribution systems and buildings served. Data to inform distribution system disinfectant residual concentration impacts on *L. pneumophila* concerns in buildings are scarce. In 2024, the General Services Administration tested water quality, including *Legionella*, at ~8250 federally owned and leased buildings. This study analyzed summary data from ~5600 buildings, detailed results from 40 buildings, and corresponding distribution system disinfectant residuals to assess links between residual levels and *Legionella* occurrence. Utilizing this largest and most nationally representative dataset available to date, findings varied by building and water system, with no clear numeric distribution system residual threshold consistently linked to lower *Legionella* occurrence in buildings.

1 | Introduction

1.1 | Public Health Risks of *Legionella pneumophila*

Legionella pneumophila (*L. pneumophila*) is an opportunistic drinking water microorganism that is of severe and sometimes fatal health risk, with case fatality rates ranging from 3% and 33% (National Academies of Sciences 2019). Inhalation of water aerosols containing *L. pneumophila* bacteria can cause Legionellosis, a respiratory infection that is now the most reported cause of waterborne outbreaks in the United States (Moffa et al. 2023). According to the Centers for Disease Control and Prevention, *Legionella* spp. was implicated in more than 90% of reported biofilm-associated drinking water outbreaks during 2015–2020, resulting in 786 cases of illness, 544 hospitalizations, and 86 deaths (Kunz et al. 2024). Despite its prominence in outbreak data and its potential severity, there are no US Environmental Protection Agency (EPA) regulatory requirements (e.g., treatment technique violations, Maximum Contaminant Level [MCL]) that directly regulate *L. pneumophila* in drinking water systems or buildings. There is a non-enforceable Maximum Contaminant Level Goal (MCLG) of zero for *Legionella* spp. in surface water supplied drinking water systems; however, this goal does not apply to groundwater-supplied drinking water systems.

To clarify terminology used throughout this paper, Table 1 defines key *Legionella* species classifications, including *Legionella* spp., *L. pneumophila*, non-*L. pneumophila*, and total *Legionella*.

1.2 | Proposed MDBP Regulation Revisions

The health risks posed by *L. pneumophila* are an underlying driver in the EPA's current efforts to revise the Microbial and Disinfection Byproduct (MDBP) rules. In response to direction

Article Impact Statement

Legionella occurrence findings vary by building and water system, with no clear numeric distribution system residual threshold consistently linked to lower *Legionella* occurrence in buildings.

TABLE 1 | Legionella classifications.

Term	Definition
Legionella spp. (also referred to as total *Legionella*)	All species in the genus *Legionella* (60+ species identified),[a] including *L. pneumophila* and non-*L. pneumophila*
L. pneumophila	Species most frequently associated with Legionellosis (esp. serotype 1); responsible for most reported outbreak cases
Non-*L. pneumophila*	All *Legionella* species except *L. pneumophila* (less commonly linked to disease)

[a]CDC (2025).

from the National Drinking Water Advisory Council (NDWAC), the MDBP Rule Revisions Working Group (WG) provided 13 recommendations for revising the current MDBP rules (NDWAC 2023). Among the most significant is the recommendation to replace the current non-specific requirement that residual disinfectant be "detectable" in distribution systems with a federal numeric minimum requirement.

Currently, 23 states already have a numeric minimum disinfectant residual (Samson et al. 2024). The WG has suggested raising the national standard to a specific value, with suggested minimum concentrations of up to 0.5 mg/L as Cl_2 for free chlorine and up to 0.7 mg/L as Cl_2 for total chlorine in chloraminated systems (NDWAC 2023). Based on stakeholder input, the EPA is considering several regulatory options, including but not limited to: (1) 0.2 mg/L as Cl_2 for free chlorine and 0.5 mg/L as Cl_2 for total chlorine, or (2) 0.5 mg/L as Cl_2 for free chlorine and 0.7 mg/L as Cl_2 for total chlorine (USEPA 2024). In parallel, a joint letter from American Water Works Association (AWWA), American Metropolitan Water Agencies (AMWA), and the Association of State Drinking Water Administrators (ASDWA) recommends adopting a minimum residual of 0.2 mg/L as Cl_2 for both free chlorine and total chlorine (AWWA et al. 2025). While this recommendation was submitted as part of the stakeholder input process, EPA has not publicly indicated which specific options will be advanced in the proposed rule.

These discussions reflect broader efforts to understand and control *L. pneumophila* exposure not only in public water system (PWS) distribution systems but also within building plumbing systems. However, nationally representative data remain limited, and there is considerable uncertainty about whether distribution system residual requirements at specific numeric thresholds would translate into reduced *Legionella* spp. occurrence in buildings.

1.2.1 | *L. pneumophila* Occurrence and Disinfectant Residuals in Distribution Systems

US distribution system studies have explored the relationship between disinfectant residual concentrations and *L. pneumophila* presence. When comparing the efficacy of chloramine and chlorine in controlling *Legionella* spp. growth in building water systems, several studies have found that chloramine may be more effective in controlling *Legionella* spp. growth (Flannery et al. 2006). For example, following a conversion from free chlorine to monochloramine disinfection, *Legionella* spp. colonization in hot water systems decreased from 60% to 4% (Donohue, Vesper, et al. 2019; Flannery et al. 2006).

A multi-utility study involving 10 water systems found that *L. pneumophila* growth may be limited when residual chlorine concentrations exceeded 0.1 mg/L as Cl_2 (LeChevallier 2019). From these 10 water systems, the samples were collected in the following locations for each water system: four raw water samples, four plant effluent samples, and 48 distribution system samples. The 2019 study of *L. pneumophila* occurrence was later expanded to include 57 PWSs (LeChevallier et al. 2025). The 57-PWS study dataset included over 9000 distribution system samples. The utilities chose the sample locations with an emphasis on sample locations with a low disinfectant concentration (i.e., <0.2 mg/L as Cl_2) and the sample locations were flushed for 3 to 5 min so that the sample would be representative of the distribution system, rather than building plumbing and about 66% of the sample locations were collected from dedicated sample stations plumbed directly to the distribution system. About 1.2% of samples were positive for *L. pneumophila* and 0.05% of the samples had concentrations greater than 1 MPN/mL. Most of the utilities measured *L. pneumophila* in house using Legiolert, which has an assay detection limit of 1 MPN/100 mL. The 2025 LeChevallier et al. risk assessment revealed that "the national estimate of risk for exposure to *L. pneumophila* from drinking water distribution systems would be exceedingly small ($<1\times10^{-7}$ annual risk of infection)" (LeChevallier et al. 2025).

Although the expected *L. pneumophila* exposure risk from distribution systems is low, PWS managers should still monitor distribution systems for *L. pneumophila* and aim to implement best management practices for *Legionella* spp. control. While these robust distribution system datasets provide insight regarding the impact of disinfectant residual concentration on *L. pneumophila* occurrence, there is a lack of data indicating how disinfectant residual and *L. pneumophila* concentrations evolve between the distribution system and the building water system.

1.2.2 | *L. pneumophila* Occurrence in Building Water Systems

L. pneumophila is rarely detected in distribution systems and is more commonly detected in building water systems. Recent studies have investigated the occurrence of *L. pneumophila* in building water systems and the role of disinfectant type and concentration on *L. pneumophila* detection (Dowdell et al. 2023;

Gamage et al. 2022). An international study of 26 buildings across 11 cities in the United States, Canada, and Switzerland examined *L. pneumophila* occurrence in relation to disinfectant type and concentration (Dowdell et al. 2023). The study found that buildings using free chlorine had a higher *L. pneumophila* culture-positivity rate (37%) than those using chloramine (1%). Furthermore, 78% of culture-positive samples had disinfectant residuals below 0.1 mg/L as Cl_2, while very few were positive when residuals exceeded 0.2 mg/L as Cl_2. While these findings suggest a link between low residual levels and increased *L. pneumophila* presence in buildings, the data were collected during the COVID-19 pandemic, when reduced building occupancy, lower water use, and higher water age likely contributed to lower residuals and may not reflect typical operating conditions (Proctor et al. 2020). This highlights the need for additional studies under normal usage scenarios to determine the impact of disinfectant residuals on building-level *Legionella* spp. occurrence.

Another examination of nationwide *Legionella* spp. prevalence was performed in a study of Veterans Health Administration (VHA) healthcare buildings on a quarterly basis for 4 years (Gamage et al. 2022). More than 800 buildings were sampled in the national VHA building study to examine the impact of building-level characteristics and control measures on *Legionella* spp. positivity rates across the healthcare buildings. The Gamage et al. study found a higher probability of *Legionella* spp. detection in older buildings, in taller buildings (likely due to poor water temperature management and lower chlorine residuals on higher floors), in hot water samples, and in samples with lower residual biocide (chlorine, monochloramine, chlorine dioxide, and copper-silver) concentrations. Lower probabilities of *Legionella* spp. positivity were observed with higher biocide concentrations for each of the studied biocides, but the effect was less pronounced for chlorine dioxide and copper–silver. Although the national VHA building water study analyzed and identified key building parameters (building age, building size, water temperature) that impact *Legionella* spp. positivity in buildings, there is still a gap in the national data informing the specific disinfectant concentration that can serve effectively as a minimum disinfectant residual to help control *Legionella* spp. growth in building water systems.

Even if distribution system chlorine concentrations were set at a minimum concentration of 0.2 mg/L as Cl_2, previous studies have indicated that the chlorine concentrations tend to be much lower or non-detect in building water systems due to their higher water age (Rhoads et al. 2014; Wang et al. 2012), elevated water temperatures (Angert et al. 2023; Ra et al. 2020; Salehi et al. 2020), pipe material (Wang et al. 2012), corrosion products, disinfectant residual type and dosage (Dowdell et al. 2023), and microbial activity (Li et al. 2019). As a result, even when minimum residuals are maintained in the distribution system, disinfectant levels may be much lower or not detectable by the time the water reaches taps, increasing the risk of *Legionella* spp. growth.

1.2.3 | Data and Regulatory Gaps

The MDBP Rule Revisions WG Report emphasized the need to address significant data and analysis gaps related to contaminant occurrence and management under the MDBP rules (National Drinking Water Advisory Council 2023). Recommendation 12, Part 3, 1 calls for national occurrence data for opportunistic pathogens (e.g., *Legionella* spp.) and Part 4, 1 calls for better understanding the relationship between distribution system water quality and building water quality, especially as related to opportunistic pathogens. A key concern is that current monitoring practices do not always capture the full range of distribution system conditions. To address these gaps, the WG Report recommended adopting monitoring plans that are more spatially representative, better integrated across all Safe Drinking Water Act (SDWA) distribution system sampling requirements, and supported by a revised compliance basis to prevent areas of the system from repeatedly experiencing low or no residual (NDWAC 2023; Sajdak et al. 2025). To implement disinfectant residual sampling plans that are more spatially representative, the WG Report recommends including the following monitoring locations: near distribution system water storage, historically challenging sites for maintaining residuals, near facilities such as hospitals, senior care facilities, daycare facilities, and schools, points of connection to consecutive systems, DBP sites, and increased sampling frequency (NDWAC 2023). The rule revision process is expected to yield criteria for disinfectant residual sample site selection. The new monitoring and assessment plans could consolidate current and existing distribution system sampling requirements (i.e., Lead and Copper Rule, disinfection residuals, Revised Total Coliform Rule [RTCR] and disinfection byproducts [DBPs]) to provide a more complete picture of water quality conditions in the distribution system.

Despite these proposed improvements, substantial uncertainty remains regarding whether establishing a numeric minimum disinfectant residual requirement in distribution systems will effectively reduce *Legionella* spp. occurrence in buildings. While the WG's recommendations would strengthen monitoring and compliance at the distribution level, existing studies have not yet provided sufficient, nationally representative evidence to confirm that such measures will translate into lower *Legionella* spp. risks within building plumbing systems. As summarized in Table 2, most prior studies have focused on *L. pneumophila* occurrence alone or have been limited to specific locations (distribution system or building plumbing) rather than spanning both. *L. pneumophila* is more likely to grow and proliferate in building plumbing rather than in the distribution systems because building plumbing provides a more hospitable environment for growth due to its higher surface area to volume ratios, longer stagnation times, low disinfectant residual, sediment and scale accumulation, and relatively warm water temperatures (Cullom et al. 2020). Regulatory revision dialogue has attempted to link disinfectant residual requirements with *Legionella* spp. control in buildings (NDWAC 2023; USEPA 2024). However, limited large-scale studies have jointly assessed disinfectant residual measurements in the distribution system paired with *L. pneumophila* occurrence in building systems, highlighting a critical gap that limits the evidence base for regulatory decision-making. Additional research is needed to evaluate *Legionella* spp. occurrence under typical water use conditions and to determine whether distribution-level disinfectant residual requirements will effectively reduce occurrence in building water systems.

TABLE 2 | Literature investigating role of disinfectant residual and *L. pneumophila* occurrence.

***Legionella* and disinfectant residual studies**			
Distribution systems	Occurrence of *Legionella* pneumophila in drinking water distribution systems (WRF 5156) • Focus; *L. pneumophila* and disinfectant residual in DS • Number of utilities: 57 Occurrence of culturable *Legionella pneumophila* in drinking water distribution systems (LeChevallier, 2019) • Focus: *L. pneumophila* and disinfectant residual in DS • Number of utilities: 12	Distribution systems and building plumbing	Few or no large-scale studies have examined the relationship between disinfectant residual in the distribution system and its impact on *L. pneumophila* detection in building plumbing.
Building plumbing	*Legionella pneumophila* occurrence in reduced-occupancy buildings in 11 cities during the COVID-19 pandemic (Dowdell et al. 2023) • Focus; *L. pneumophila* and disinfectant residual in buildings • Number of buildings: 26 Factors that affect *Legionella* positivity in Healthcare Building Water Systems from a Large, National Environmental Surveillance Initiative (Gamage et al. 2022) • Focus; *L. pneumophila* and disinfectant residual in buildings • Number of buildings: 814		

1.3 | GSA Building Water Quality Dataset

The US General Services Administration (GSA) conducted baseline drinking water quality tests starting in 2024 for approximately 1250 federally owned facilities and 6000 leased spaces. Baseline drinking water quality testing included building water sampling and analysis for *Legionella* spp., including *L. pneumophila* and other species, total coliform, *E. coli*, lead, and copper.

This study leverages a unique opportunity to combine the GSA national building water *Legionella* spp. occurrence dataset with disinfectant residual data collected from individual PWSs serving the GSA buildings. To facilitate this study, AMWA submitted a Freedom of Information Act (FOIA) request to obtain results from the baseline drinking water quality tests from GSA. AMWA received a summary spreadsheet with results for GSA buildings and provided the dataset to the authors. In the spreadsheet, *Legionella* spp. results were limited to the number of total *Legionella* threshold exceedances per building, based on a threshold of 1 CFU/mL. GSA also agreed to provide detailed building and laboratory reports, inclusive of numeric results for *Legionella* spp. at all sample locations, for a total of 40 buildings. The authors reviewed the summary dataset and selected the 40 buildings, after which AMWA requested detailed reports for the 40 buildings which GSA provided.

This study linked GSA building locations to their respective PWS through geographic information system (GIS) analysis using EPA-collected and estimated water service area boundaries. By matching each building to its supplying PWS, two levels of analysis were conducted: a national analysis and a focused analysis. The national analysis used historical disinfectant residual data across the entire distribution system (2012–2020) to investigate relationships between historical disinfectant residual type and concentration and the rate of total *Legionella* exceedances in GSA buildings. However, this approach introduced a temporal mismatch, as GSA building water quality sampling occurred in 2024. Accordingly, results from the national analysis are interpreted as descriptive and contextual rather than as a temporally matched evaluation of relationships between disinfectant residual conditions and *Legionella* spp. occurrence.

To address this limitation, a focused analysis was conducted using individual disinfectant residual measurements from distribution system monitoring locations in seven PWSs near the 40 selected GSA buildings. These data were aligned to the same calendar quarter as the *Legionella* spp. sampling, allowing for direct temporal comparison. This analysis enabled a more robust evaluation of total *Legionella* exceedances and of *L. pneumophila* occurrence in relation to local disinfectant type, concentration, and other PWS-specific characteristics, albeit with a more limited dataset from just 40 buildings served by seven PWSs.

1.4 | Study Objectives

The overarching goal of this study was to develop a better understanding of *Legionella* spp. occurrence in US GSA building water systems and how disinfectant residual concentrations and type in their supplying PWSs relate to that occurrence.

The specific objectives of this study were to:

1. Evaluate the frequency of *Legionella* spp. occurrence in GSA buildings nationwide.
2. Investigate relationships between *Legionella* spp. occurrence in building water systems and PWS characteristics, including system size and source water type.

3. Evaluate the relationship between PWS disinfectant type and residual concentrations in the distribution systems and *Legionella* spp. occurrence in the GSA buildings they serve.

For all study objectives:

- Total *Legionella* (sum of all *Legionella* species) exceedance over 1 CFU/mL in GSA buildings nationwide was evaluated based on the summary dataset provided by GSA.
- Detailed *Legionella* concentrations and speciation were further assessed in a subset of 40 selected GSA buildings using paired, temporally aligned disinfectant residual data to support more direct comparison.

2 | Datasets and Methodology

2.1 | Building Water Quality Management and Sampling Requirements

The 2024 GSA building water sampling dataset is the largest and most nationally representative dataset on *Legionella* spp. occurrence in building drinking water served by PWSs. This dataset reflects GSA's proactive approach to identifying and mitigating public health risks associated with drinking water quality in federal workplaces.

According to GSA staff and a GSA order (GSA Order PBS 1000.7A), the GSA routinely reviews consumer confidence reports (CCRs) from PWSs serving GSA buildings. As part of the GSA order, targeted flushing and water quality sampling (lead, copper, and total coliform bacteria) must be conducted in federally owned buildings when new fixtures for drinking water purposes are installed (GSA 2023). To address stagnation concerns in all federally owned facilities, the facilities must implement the *Public Buildings Service (PBS) Guidance to Maintain or Restore Water Quality* if they meet the following criteria: (1) Buildings over 50,000 sq.ft. with water booster pumps (both conditions must apply); or (2) Buildings over six stories in height. As part of the guidance, the operations and maintenance (O&M) contractor must assess the building's plumbing system and is responsible for developing a water sampling and flushing plan for the buildings that meet these criteria. Buildings will use the PBS guidance unless a building-specific ASHRAE 514 water management program (WMP) or ASHRAE 188 water management plan has been implemented for the potable water system.

The CCRs are reviewed annually by the O&M contractor and if any issues are noted, then the affected occupant agency point of contacts are notified and the issues are documented in the PBS National Computerized Maintenance Management System (NCMMS). Although water testing in GSA buildings is not federally mandated, GSA staff also mentioned that testing is sometimes conducted in response to potential water quality issues, such as discoloration or local water system problems. When contaminant exceedances are detected, remediation measures—including flushing, temporary or localized disinfection of building plumbing (e.g., shock chlorination where appropriate), increasing water heater temperatures, and developing water management plans—are promptly implemented. Retesting is conducted until water quality meets required thresholds. GSA also prioritizes transparency and employee awareness by notifying affected individuals and conducting educational outreach regarding water quality risks.

Starting in 2024, GSA mandated baseline drinking water quality testing for federally owned facilities and leased spaces (USGSA 2024). It was projected that water testing would be conducted in 6400 federally leased spaces (6000 buildings) and 1250 federally owned buildings. GSA outlined specific requirements for testing that would help promote uniform procedures across the building sites. Testing requirements included hiring a professional with specific qualifications and providing the professional with a statement of work (USGSA 2024). Unilateral Lease Amendments (ULAs) were issued to the leased buildings in five phases beginning in February 2024, and lessors were given 90 days from receipt of the ULA to provide GSA building water test results conforming to the scope of work.

Required outlets for testing included outlets designed for human consumption and showers. Specifically, at least 10% of cold-water outlets primarily designed for human consumption, such as drinking fountains, bottle fillers, and kitchenette faucets, were required to be tested for lead, copper, and total coliform bacteria (including *E. coli*). Test results that exceeded the applicable federal, state, or local thresholds, were required to conduct remedial actions (mainly flushing and retesting) to reduce contaminant concentrations.

Separate fixture testing requirements were outlined for *Legionella* spp. testing (GSA 2023). A representative number of hot and cold-water outlets were required to be tested for *Legionella* spp. Either the CDC or ISO 11731:2017 culture-based methods were used to quantify and discriminate between total *Legionella* spp., *L. pneumophila* serotype 1, *L. pneumophila* serotype 2–15, and non-*L. pneumophila*. The GSA also recommended that professionals be hired to conduct the sample collection, and the professional must have experience in testing drinking water, including methods for detecting *Legionella* bacteria. The GSA stated a preference for contracting professionals with ASSE 12080 certifications. *Legionella* spp. sampling locations were required to encompass all of the following where applicable: (1) Incoming municipal water, (2) Storage tanks, (3) Expansion tanks, (4) Hot water circulation circuits, (5) Building common and private tenant showers (at least 1 sample for every 3 fixtures), (6) All point-of-use outlets that are primarily designed for human consumption in a childcare center for both hot and cold water, (7) All point-of-use outlets that are primarily designed for human consumption or treatment of patients in a Health Unit for both hot and cold water, and (8) 10% of all of the remaining point-of-use outlets primarily designed for human consumption, such as drinking fountains, bottle fillers, and kitchenettes focusing on distal locations for both hot and cold water with a minimum of five outlets for smaller facilities.

2.2 | GSA Building Water Quality Dataset

The summary dataset provided by GSA for use in this study included information regarding the building attributes including the building name, ID, address, ownership type (owned or leased), building use, and number of personnel. The dataset included a column for the number of outlets tested and number of tests performed in each building, although this information was largely missing. Specific water testing details included the scheduled sample date, number of *Legionella* exceedances based on total *Legionella* detected, lead and copper exceedances, and coliform exceedances. The summary dataset did not include details such as the concentrations of each contaminant detected within the building, results specific to *Legionella* speciation, the types of outlets tested in each building, or sufficient information to determine the percentage of samples or outlets with contaminant occurrence and/or exceedance. In addition, information on whether individual GSA buildings employed supplemental or localized disinfection within premise plumbing systems (e.g., booster disinfection or secondary treatment) was not available in the dataset and could not be evaluated as part of this analysis.

The dataset included analysis from 8477 GSA buildings across 50 states and 6 territories. Of the total amount of GSA buildings in the dataset, 7010 (83%) of these buildings met the GSA testing criteria, and 5409 (77% of those meeting testing criteria) GSA buildings included exceedance (> 1 CFU/mL) results for total *Legionella*.

GSA established the total *Legionella* exceedance threshold at 1 CFU/mL, which would trigger GSA notification and building remediation actions. The American Industrial Hygiene Association (AIHA) has provided a target risk concentration for *L. pneumophila*, where concentrations greater than 10 CFU/mL should trigger immediate steps to clean and disinfect the system (AIHA 2015). For context, the AIHA risk targets have been proposed for distribution system samples, where *L. pneumophila* concentrations between 1 and 10 CFU/mL should result in corrective actions (e.g., resampling, flushing) based on the percent positive detection rates (Bartrand et al. 2024). Additionally, the 2019 National Academies of Sciences, Engineering, and Medicine (NASEM) report on *Legionella* management recommends that a *L. pneumophila* concentration at or above 50 CFU/mL could indicate an imminent risk of an outbreak (NASEM 2019). Quantitative microbial risk assessments (QMRA) have proposed per-exposure disability-adjusted life years (DALY) exposure target *L. pneumophila* concentrations based on health risk: 1.06 CFU/mL for faucets and 0.014 CFU/mL for showers, using a per-exposure-corrected DALY metric (Hamilton et al. 2019). Notably, this QMRA-derived target exposure *L. pneumophila* limit for showers (0.014 CFU/mL) is much lower than the exceedance threshold set by GSA (1 CFU/mL), indicating that the exceedance threshold could have been set to a lower concentration to more fully protect public health.

GSA exceedance thresholds for other contaminants include 1.3 mg/L for copper, 15 μg/L for lead, and any detection for total coliforms (Table 5). The GSA exceedance thresholds for lead and copper are based on EPA's Lead and Copper Rule (USEPA 1991). The GSA threshold for total coliforms is based on EPA's drinking water MCLG of 0 organisms (USEPA 2013). Although GSA established the total *Legionella* exceedance threshold at 1 CFU/mL, this GSA exceedance threshold is not based on current USEPA guidance. The EPA has established a MCLG of 0 *Legionella* organisms, and regulatory control currently falls under the Surface Water Treatment Rule (SWTR) (USEPA 1989), which establishes a treatment technique requiring surface water supplies to be filtered and disinfected to achieve an effluent turbidity of 0.3 NTU, a 0.2 mg/L as Cl_2 disinfectant residual entering the distribution system, and a "detectable" residual within the pipe network in at least 95% of the measurements for two consecutive months. PWSs can maintain a distribution system disinfectant residual, but the responsibility for most PWSs ends at the meter or property line and PWSs have little control over how building owners operate and maintain their premise plumbing systems.

2.3 | GSA Building Metadata

GSA building metadata, which summarizes the inventory of both owned and leased properties and was available on the GSA website (GSA 2024a, 2024b), was downloaded and integrated into the analysis to address gaps in the GSA building water quality summary dataset. In particular, building age was not provided in the GSA water quality summary dataset and was therefore obtained from the building metadata. The metadata included information such as building size, year each building was constructed, and location. Building size and building age (Gamage et al. 2022) are building-specific factors that may contribute to a higher probability of *Legionella* spp. detection in building water. Locational data (latitude and longitude) were used in the GIS analysis to join GSA buildings with their corresponding PWS.

2.4 | Dataset and Study Limitations

While the GSA dataset represents the largest and most nationally representative building water system *Legionella* spp. dataset to date, several limitations should be noted.

First, the GSA reported results in a simplified summary format, focusing on the number of exceedances per building based on health-based risk thresholds rather than providing individual sample concentrations. While this streamlined reporting, it limited the ability to conduct more granular analyses, such as evaluating *Legionella* spp. concentrations and speciation, or differentiating results by sample location within buildings. Additionally, although the number of outlets tested in each building was recorded, this information was missing for approximately 85% of buildings with *Legionella* spp. results, hindering efforts to normalize exceedances by the number of outlets sampled.

Second, for the national analysis, disinfectant residual data were drawn from PWS compliance monitoring between 2012 and 2020, while GSA building water sampling occurred in 2024. This temporal mismatch limits the direct comparability of disinfectant residuals and total *Legionella* exceedance results. Moreover, only 57% of GSA buildings with total *Legionella* exceedance data could be linked to corresponding PWS disinfectant residual data due to incomplete reporting and challenges in spatially joining buildings to their serving PWS boundaries.

Third, building-level metadata had limitations. For leased spaces, reported building size often reflected only the GSA-occupied area (e.g., a single floor) rather than the entire building, complicating evaluation of building size effects. As a result, leased buildings were excluded from analyses that relied on total building square footage, while they were retained in other analyses where building size was not a determining factor.

Finally, for the focused analysis, detailed laboratory reports were provided for only 40 of over 5000 sampled buildings. These reports, used for quality control, revealed discrepancies with the summary dataset, such as mismatches in the number of exceedances, outlets tested, or tests performed. Some differences may reflect inclusion of retest results in lab reports that were not carried into the summary dataset. Manual extraction of data from these reports was labor-intensive, and expanding this approach to all buildings would be valuable but would require significant effort. Importantly, these detailed reports included sample-level information, such as the specific faucets and outlets tested, providing critical context for potential occupant exposure within each building. While chlorine residual and temperature were most often not reported at the time of *Legionella* spp. sampling, limiting insights into the direct relationship between disinfectant residual levels and *Legionella* spp. occurrence at the building level, these limited data likely represent the most substantial nationally representative dataset of such building level data and should be pursued. Additionally, disinfectant residual data were based on individual monitoring measurements from PWS distribution system sampling locations, typically within three miles of each building, rather than measurements collected at the building entry point or outlet. Because disinfectant residuals decay between the distribution system and building plumbing, this discrepancy may reduce the accuracy of building-level associations.

2.5 | Statistical Analysis

Statistical analyses were conducted using R software (R Core Team 2023). The Shapiro–Wilk normality test confirmed all data followed a non-normal distribution. Non-parametric tests were used to examine if there were significant differences between data groups. The two-sample Wilcoxon, Kruskal–Wallis, and Kolmogorov–Smirnov (K–S) tests were used to determine if there were statistically significant differences in central tendency and distributions of datasets. If the *p*-value of a statistical test was less than 0.05, the result was considered statistically significant.

Boxplots were used to visually summarize the statistical distribution of the data. Each box represents the interquartile range (IQR), spanning from the 25th to the 75th percentile. The horizontal line inside the box indicates the median (50th percentile), while the diamond marks the average (mean). Whiskers extend to the 5th and 95th percentiles, with values beyond this range shown as individual points. A legend explaining the boxplot elements is provided in Figure 1.

2.6 | GSA Building Water Quality Data and Summary Analysis

The analysis of GSA building water quality data evaluated relationships between building characteristics and measured water quality outcomes. Metadata describing building size, construction year, number of personnel, and building type were summarized to provide context for the dataset and to assess potential occupant exposure. Because reported square footage for leased buildings often reflects only the GSA-occupied portion of a building, leased buildings were excluded from analyses that relied on total building size but were retained for all other building-characteristic analyses. Exceedance rates for total *Legionella*, copper, lead, and total coliform bacteria were then examined in relation to these building attributes to identify potential patterns and influencing factors.

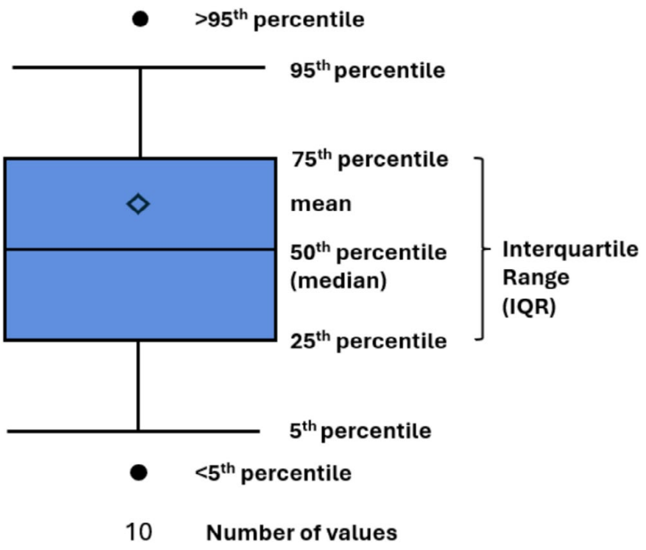

FIGURE 1 | Boxplot legend.

2.7 | Joined Analysis of GSA and PWS Data

The individual GSA property data were joined to their corresponding PWSs using EPA's Community Water System (CWS) Service Area Boundaries dataset (USEPA 2025a). This was achieved by conducting GIS spatial joins of GSA building locations with EPA-collected and estimated PWS service area boundaries. Each GSA location was assigned to a PWS if it fell within a service area boundary. However, these boundaries are approximations and are not guaranteed to be accurate. Approximately 40% of the boundaries were sourced from state databases, over 50% were modeled by EPA, and less than 10% were provided directly by water systems (USEPA 2025b). As such, spatial mismatches and inaccuracies may occur. Additionally, some GSA building locations fell outside of any known service area boundaries, which may reflect the presence of private wells, non-community water systems, or gaps or inaccuracies in the available data for PWSs. Buildings with no PWS match were excluded from the analysis.

Quality control efforts were conducted to validate the spatial join results and to ensure the integrity of the matched records. To further characterize system-level attributes, the PWS dataset was supplemented with EPA's Safe Drinking Water Information System (SDWIS) data (2024 Q4) to evaluate the impact of primary source type (e.g., surface water, groundwater, or groundwater under the influence of surface water [GWUDI]). The resulting merged dataset links GSA buildings to specific PWSs, enabling further analysis of *Legionella* spp. occurrence in individual buildings alongside their corresponding PWS characteristics, such as disinfectant type and concentration. The final dataset includes 4711 buildings sampled for *Legionella* spp., from the subset of 6079 buildings matched with a PWS.

2.8 | Joined Analysis of PWS Disinfectant Residuals and GSA Data

To analyze the relationship between national *Legionella* spp. occurrence and chlorine residual data, a joined analysis of PWS disinfectant residual levels (free and/or total chlorine, as reported in compliance monitoring) was conducted with GSA building *Legionella* spp. results. Historical disinfectant residual levels were collected and summarized for these PWSs. Disinfectant residual data consisted of individual compliance monitoring locations collected at approved distribution system sampling locations. The disinfectant residual data were retrieved from EPA's Fourth Six Year Review (SYR4) data set (2012–2019) and data collected from state regulatory agencies by the authors (2012–2020). The combined disinfectant residual dataset included data for 52,356 PWSs across 40 states, Washington D.C., and 6 Tribal areas or territories.

A temporal mismatch exists between these datasets: while disinfectant residual data reflect conditions from 2012 to 2020, GSA building water quality sampling, including *Legionella* spp. data, was conducted in 2024. As a result, disinfectant conditions at the time of *Legionella* spp. sampling may differ from those represented in the historical PWS data. However, the historical disinfectant residual data provide insight into how PWSs have historically managed distribution system residuals, which may influence building water system conditions in the buildings they serve.

In the period between 2012, the start of the disinfectant residual data set sampling, and 2024, when the *Legionella* spp. sampling occurred, several states implemented a numeric minimum disinfectant residual level for PWS distribution systems. These states include Louisiana (February 1, 2014), Colorado (April 1, 2016), Pennsylvania (April 28, 2019), and Illinois (July 26, 2019). Data for systems in these states collected before the numeric minimum disinfectant residual requirement was implemented were removed from the dataset because PWSs may have altered their operations to meet the new requirement. Thus, disinfectant residual data before these dates are likely less representative of disinfectant residual levels in 2024.

The disinfectant residual dataset was then filtered to only include data for PWSs serving GSA buildings with total *Legionella* exceedance data. This filtering process resulted in a dataset of disinfectant residual data for 874 PWSs in 40 states serving 3105 GSA buildings with total *Legionella* exceedance data. For each PWS, residual measurements from individual distribution system compliance monitoring locations were pooled across the historical period (2012–2020) and summarized using distributional statistics (e.g., 5th percentile, median, and 95th percentile concentrations) to characterize typical historical disinfectant conditions within each system. These PWS-level residual summarizes were then used to evaluate relationships between historical disinfectant residual conditions (2012–2020) and total *Legionella* exceedances in 2024 in GSA buildings served by those PWSs.

2.9 | Paired Analysis of Disinfectant Residual Data Provided by PWSs and GSA Data

In addition to the summary dataset provided by GSA, which reports the number of total *Legionella* exceedances per GSA-owned building or leased space, GSA provided detailed building-level laboratory reports for a subset of 40 buildings. These reports were used to conduct a focused, paired analysis linking building-level *Legionella* spp. results with disinfectant residual data from the seven supplying PWSs during the same sampling period in 2024.

For this paired analysis, disinfectant residual data were obtained from routine PWS distribution system monitoring locations proximal to each building and intended to represent local disinfectant conditions during the GSA sampling period. Seven PWSs participated in this effort, representing a range of primary source water types, disinfectant practices, state-mandated minimum disinfectant residual requirements, and observed total *Legionella* exceedance patterns. Participating PWSs provided 2024 disinfectant residual data, including sample location information. Key characteristics of these systems and the number of GSA buildings included for each system are summarized in Table 3.

For each of the seven systems, detailed building reports—including full sampling and laboratory results—were compiled for the 40 selected GSA buildings they serve. Table 3 provides context on sampling coverage by showing the number of buildings included in the paired analysis relative to the total number of GSA buildings sampled within each PWS, as well as the percentage of sampled buildings with at least one total *Legionella* exceedance.

Exceedances were defined based on total *Legionella* detections, encompassing both *L. pneumophila* and non-*L. pneumophila* species, consistent with GSA reporting. Accordingly, buildings were classified as having an exceedance regardless of the specific *Legionella* species detected. Although *L. pneumophila* is believed to pose a substantially higher health risk than other *Legionella* species, treating all detections equally may overstate the perceived health concern associated with these exceedances. Nevertheless, the total *Legionella*-based approach was retained for consistency with GSA's reporting method and to ensure comparability across both the national-scale and paired analyses.

Building selection for the paired analysis prioritized comparability of distribution system water quality conditions by focusing on buildings located in relatively close proximity within each PWS. Additional selection criteria were used to ensure representation across building size categories (small: $<$50,000 square feet; large: $\geq$50,000 square feet) and total *Legionella* testing outcomes (with and without exceedances). GSA-provided sampling schedules were also considered, with preference given to buildings sampled within the same calendar quarter to minimize seasonal variability.

Disinfectant residual data provided by each PWS were summarized for the same calendar quarter during which *Legionella* spp. samples were collected. Residual measurements were aggregated from distribution system monitoring locations within a defined buffer zone around each building (typically within three miles of the building), with a target of at least 30 routine monitoring samples to support statistical analysis.

TABLE 3 | Public water systems included in paired water quality analysis.

PWS number	Primary source water	Disinfectant type	State minimum disinfectant residual (mg/L as Cl2)	Number of buildings selected (of total sampled[a])	Percent of buildings with total *Legionella* exceedances[a]
PWS 1	Surface water	Free chlorine	Detectable	6 of 21	71% (15 of 21)
PWS 2	Surface water	Chloramine/mixed	0.2 (free); 0.5 (total)	6 of 24	38% (9 of 24)
PWS 3	Groundwater	Free chlorine	0.2 (free); 0.6 (total)	4 of 15	73% (11 of 15)
PWS 4	Surface water	Free chlorine	Detectable	6 of 61	44% (27 of 61)
PWS 5	Surface water	Chloramine	0.2 (free and total)	6 of 30	27% (8 of 30)
PWS 6	Surface water	Free chlorine	Detectable	6 of 22	77% (17 of 22)
PWS 7	Surface water (purchased)	Chloramine	Detectable	6 of 142	28% (40 of 142)

[a]GSA summary dataset.

Most *Legionella* spp. sampling occurred during the third quarter (Q3), corresponding to the summer months of July through September—when water temperatures are highest and disinfectant decay rates are greatest. During this period, residual disinfectant concentrations in distribution and building plumbing systems tend to be lower, while conditions are most favorable for *Legionella* spp. growth and persistence. As a result, the paired analysis primarily reflects seasonally conservative disinfectant residual conditions, under which exceedance potential may be higher than during cooler periods. Additional building-level details for the paired analysis are provided in Supporting Information (SI) Table S1.

A detailed process flow diagram of data sources and processing used to perform the analyses described in this section is provided in Figure S1.

3 | Results and Discussion

3.1 | GSA Building Water Quality Data and Summary Analysis

Federally leased and owned GSA buildings were required to have building water samples collected for *Legionella* spp., coliform, lead, and copper samples in 2024. Of the 8477 GSA buildings in the US, 85.5% (7244) are leased and 14.5% (1233) are federally owned. Figure 2 shows the geographic distribution of all GSA buildings, those sampled for *Legionella* spp., and those with at least one total *Legionella* exceedance. This map highlights the nationwide coverage of the dataset and contextualizes the subsequent analyses of exceedance rates and building characteristics.

Building metadata were summarized to characterize key attributes such as building size, building age, number of personnel, and building type, which provide important context for understanding the dataset and the potential scale of occupant exposure and associated health risk for occupants. Because reported square footage for leased buildings often reflects only the GSA-occupied portion of a building, leased buildings were excluded from summaries and analyses that relied on total building size. These key building characteristics are provided in Table 4.

Building size varied widely, from 552 square feet to over 2.8 million square feet, with a median of 50,847 square feet. Building construction years ranged from 1809 to 2025, with a median of 2000. The number of personnel ranged from 1 to 12,657, with a median of 29 personnel per building. A boxplot of building size distribution is provided in Figure S2.

In addition to these characteristics, building types were grouped into broader functional categories, including health and human services, land and outdoor use, operational support and maintenance, residential and institutional living, specialized and scientific facilities, miscellaneous or unclear use, administrative and office buildings, and infrastructure and communications. These building groups were then compared to the percentage of buildings with total *Legionella* exceedances. Among these categories, health and human services buildings had the highest exceedance rate, with over 40% of sampled buildings exceeding the threshold (Figure 3). However, sample sizes varied substantially across building type categories, and the health and human services category included a relatively small number of buildings ($n = 15$). As a result, outcomes should be interpreted cautiously. Nonetheless, the elevated exceedance rate in this category is notable given the potentially higher vulnerability of occupants in these facilities.

Building water samples were collected and analyzed for *Legionella* spp., copper, lead, and total coliform bacteria. Approximately 5400 buildings were reported in the summary dataset for these analytes. Rather than reporting the

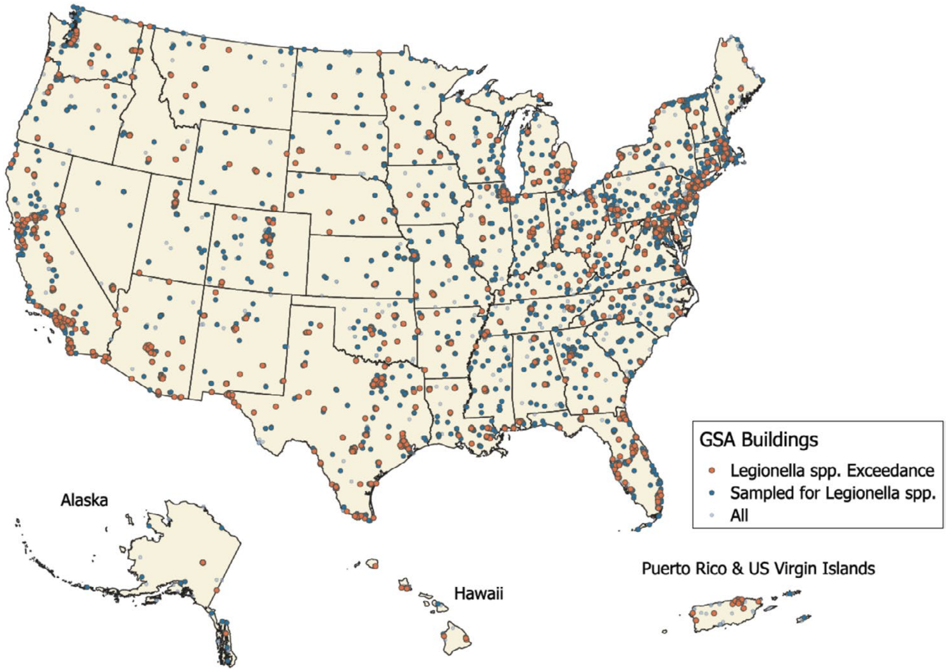

FIGURE 2 | Geographic distribution of GSA buildings sampled for *Legionella* spp. and exceedances.

TABLE 4 | Building characteristics.

Total number of buildings	Building size[a], sf—median (range)	Building Age[b]—median (range)	Number of Personnel[c]—median (range)
8477	50,847 (552–2,834,478)	2000 (1809–2025)	29 (1–12,657)

[a]Building size data for GSA-owned buildings were reported for 1226 of 1233 buildings (99.4%).
[b]Building age data were reported for 7920 of 8477 buildings (93.4%).
[c]Number of personnel was reported for 7236 of 8477 buildings (85.4%).

concentrations for thousands of samples, the GSA simplified the dataset by reporting these results in terms of numbers of exceedances per building, where the thresholds for exceedances represent health-based risk levels and are provided in Table 5.

Out of the 5409 buildings with results for *Legionella* spp., 23.6% ($n=1274$) had at least one total *Legionella* exceedance. This building-level positivity rate is lower than the findings from a recent international study conducted during the COVID-19 pandemic, which reported *L. pneumophila* detection in 26.9% of buildings ($n=26$ buildings) sampled across the United States, Canada, and Switzerland (Dowdell et al. 2023). A disinfectant residual is required in most water distribution systems in the United States and Canada, whereas a disinfectant residual is not required in Switzerland. The building sampled in Switzerland with no disinfectant residual had a much higher *Legionella* positivity rate than the other buildings in the study (65% positivity). It is important to note that the Dowdell study utilized a combination of Legiolert, ddPCR, and qPCR, whereas the GSA study used ISO and CDC plate culture methods. Dowdell et al. (2023) suggested *Legionella* spp. growth was often associated with plumbing design and operational deficiencies, such as oversized water heaters and water softeners that deviated from industry best practices. The GSA dataset likely has a lower *L. pneumophila* specific positivity rate than 23.6%, as exceedances in this study were defined by total *Legionella* detections (inclusive of both *L. pneumophila* and non-*L. pneumophila* species). This broader definition may therefore overstate the perceived health concern, since non-*L. pneumophila* species are generally associated with lower health risk. Detailed species-level results were only available for the subset of 40 buildings included in the focused analysis.

The percentage of buildings with exceedances for other analytes was copper (8.8%; $n=473$), lead (7.2%; $n=392$), and total coliform (3.7%; $n=201$). Total coliform exceedances occurred in 3.7% of sampled buildings, significantly lower than the 23.6% exceedance rate for total *Legionella*. This disparity suggests that coliform bacteria are not a reliable indicator for *Legionella* spp. The lack of correlation between total coliform and total *Legionella* threshold exceedance (Pearson's correlation coefficient: $r=0.03$) likely reflects fundamental differences in environmental behavior. Opportunistic pathogens like *Legionella* spp. are ubiquitous in water and can proliferate under favorable conditions (e.g., warm temperatures, stagnation), while fecal pathogens typically require an external contamination event to be introduced into the water system. Furthermore, fecal-oral pathogens do not generally grow in water systems, unlike opportunistic pathogens (LeChevallier et al. 2024).

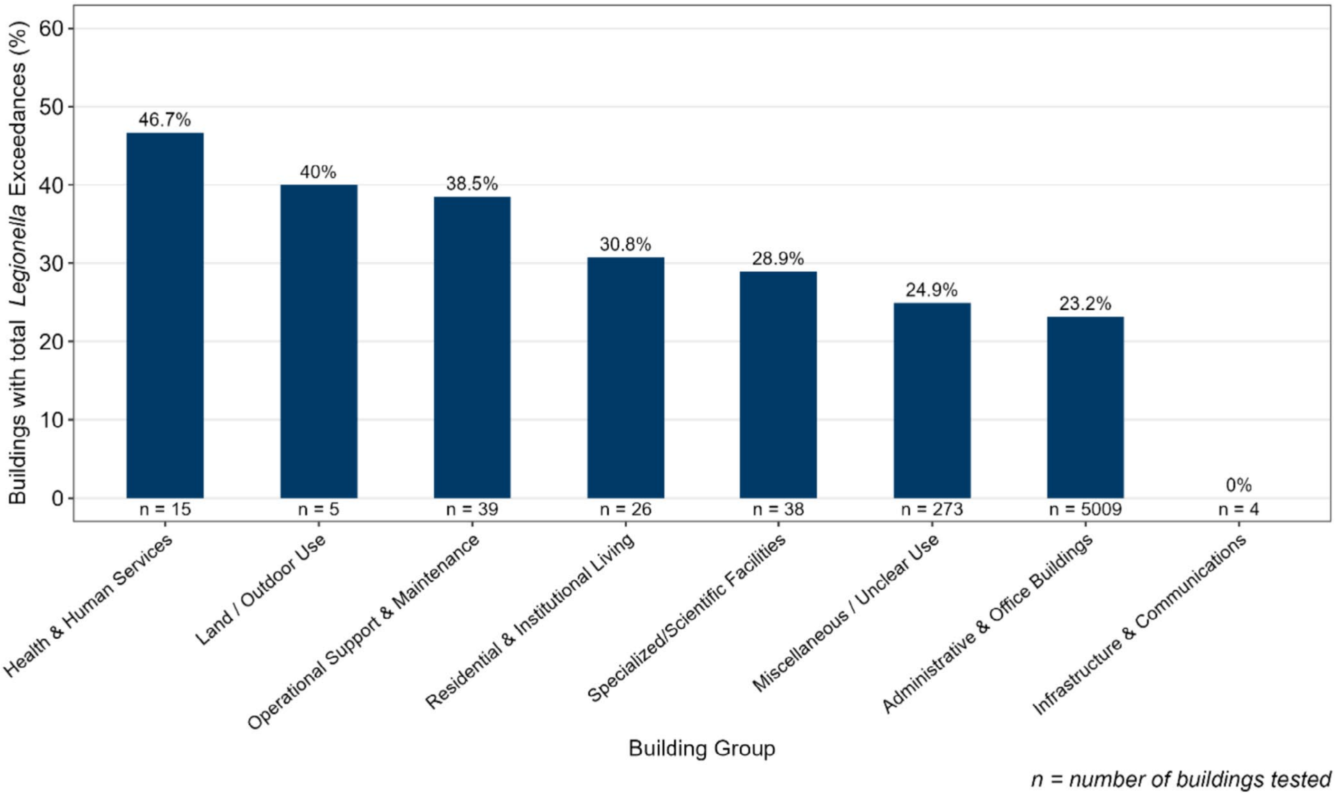

FIGURE 3 | Percentage of buildings with total Legionella exceedances by building group.

TABLE 5 | Summary of measured analytes and percentage of buildings with exceedances.

Contaminant	Exceedance threshold	Number of buildings reported	Number of buildings with exceedance(s)	Percent of buildings with exceedance(s)
Total *Legionella*	1 CFU/mL	5409	1274	23.6%
Copper	1.3 mg/L	5405	473	8.8%
Lead	15 µg/L	5409	392	7.2%
Total coliform	Detection	5403	201	3.7%

3.1.1 | Relationship Between Water Quality and Building Characteristics

The role of building characteristics including age and size was evaluated to determine their influence on the rate of total *Legionella* exceedances. Figure 4 shows the percentage of buildings with total *Legionella* exceedances grouped by the decade in which they were built. This figure represents 5377 of the 5409 buildings tested for *Legionella* spp. that also had reported year-built data, accounting for 99.4% of the total.

A chi-squared test of independence confirmed that the proportion of buildings with at least one total *Legionella* exceedance differs significantly by building decade ($p < 0.0001$). No distinct linear trend emerged between total *Legionella* exceedances and building decade. However, buildings constructed prior to the 1980s generally exhibited higher exceedance rates—often above 30% and reaching as high as 56% for those built in the first decade of the 1900s—compared to buildings from the 1980s onward, where exceedance rates typically remained below 30%.

This pattern may be attributed to older buildings having more complex and aging plumbing systems, under the assumption that original plumbing infrastructure has not been fully replaced or substantially renovated, which can create favorable conditions for *Legionella* spp. growth, such as oversized water heaters, water softeners, and increased water age that promotes disinfectant decay. In contrast, newer buildings often incorporate modern, water-efficient fixtures and appliances—which are designed to reduce water usage but may inadvertently increase hydraulic residence time (HRT). This extended HRT can affect overall water system dynamics and influence *Legionella* spp. proliferation (Julien et al. 2020). While the chi-squared test accounts for differences in sample sizes, the percentages for decades with relatively few buildings may be less stable and should be interpreted cautiously.

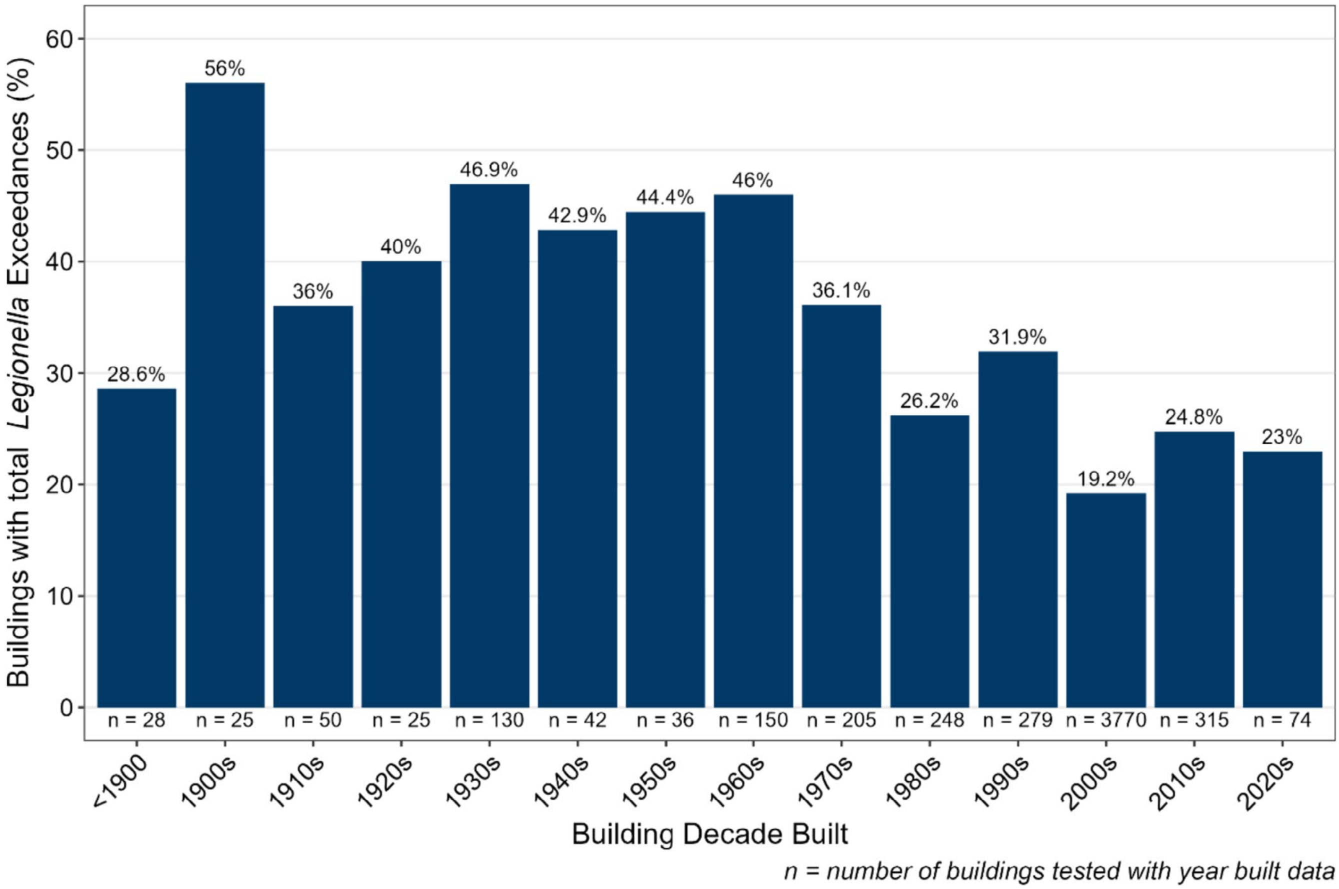

FIGURE 4 | Percentage of buildings with total *Legionella* exceedances by building decade built.

The relationship between building size and total *Legionella* exceedances was evaluated. Figure 5 shows the percentage of buildings with total *Legionella* exceedances, stratified by building size. For this analysis, building sizes were grouped into four categories: less than 5000 square feet, 5000 to 50,000 square feet, 50,000 to 500,000 square feet, and greater than 500,000 square feet. Larger buildings typically have more extensive plumbing systems, which can increase water age—especially if water usage is low—creating conditions favorable for *Legionella* spp. growth. The proportion of buildings with total *Legionella* exceedances rose with building size, with over 50% of buildings over 50,000 square feet, and nearly 70% of buildings over 500,000 square feet reporting at least one exceedance. It should be noted that larger buildings also tend to have a greater number of outlets and sampling locations, which may increase the likelihood of detecting at least one exceedance.

3.2 | Joined Analysis of GSA and PWS Data

3.2.1 | Legionella spp. Occurrence by Water System Characteristics

In addition to building-level factors, characteristics of the supplying PWS were evaluated for potential associations with total *Legionella* exceedances in GSA buildings. When stratified by system population size, exceedance rates appeared higher among systems serving more than 3300 people, while no clear trend was observed in smaller systems (Figure S3). However, these patterns should be interpreted cautiously due to substantial differences in sample size across system size categories, with larger systems serving more sampled buildings than smaller systems. In addition, spatial joins between GSA buildings and smaller PWS boundaries may be more sensitive to boundary estimation uncertainty, further limiting inference for the smallest systems. Accordingly, system size is not interpreted here as an independent predictor of total *Legionella* exceedance risk, and these results are presented for descriptive context only.

To further explore the higher exceedance rates in buildings served by larger systems, source water type and the size of buildings served were taken into consideration. Total *Legionella* exceedance rates by source water type are shown in Figure 6. Overall, exceedance rates were similar for buildings served by systems using surface water (24.5%; $n=3753$) and groundwater (21.7%; $n=958$). These source classifications reflect the reported primary source and may not capture potential blending or secondary sources that could affect water quality.

Within groundwater systems, buildings supplied by systems using purchased water had slightly higher exceedance rates (25.9%; $n=27$) than those supplied by systems using non-purchased groundwater sources (21.6%; $n=931$). Similarly, within surface water systems, marginally higher exceedance rates were observed for buildings supplied by systems using purchased surface water (25.1%; $n=850$) compared to those supplied by systems using non-purchased surface water (24.5%; $n = 2851$). Systems reporting purchased water sources operate as consecutive systems, receiving treated water from an upstream PWS rather than treating raw source water directly; as a result, water quality conditions in these systems may be influenced by upstream treatment practices and residual decay during transmission.

Among individual source water categories, buildings served by systems classified as GWUDI exhibited the lowest exceedance rate (15.4%; $n = 52$). Given the substantial differences in sample size across source categories—particularly for purchased groundwater and GWUDI systems—these comparisons should be interpreted cautiously. Taken together, the relatively modest differences observed suggest that source water type alone does not show a strong association with total *Legionella* exceedance rates in this dataset.

To explore whether building characteristics may contribute to the observed patterns, building size distributions were analyzed by PWS size (Figure S4). Median building size generally increased with PWS size for systems serving more than 3300 people. For smaller systems—those serving fewer than 3300 (i.e., ≤ 500 and 501–3300)—the median building sizes were relatively consistent, ranging from 8626 to 8645 square feet, respectively. In contrast, the median building sizes increased substantially for systems serving more than 3300, more than 10,000, and

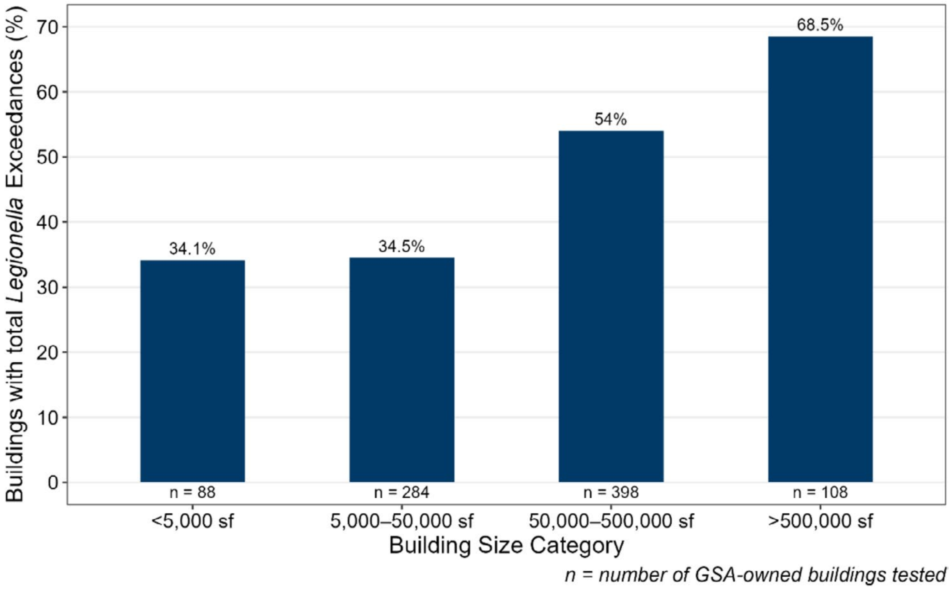

FIGURE 5 | Percentage of GSA-owned buildings with total *Legionella* exceedances by size category.

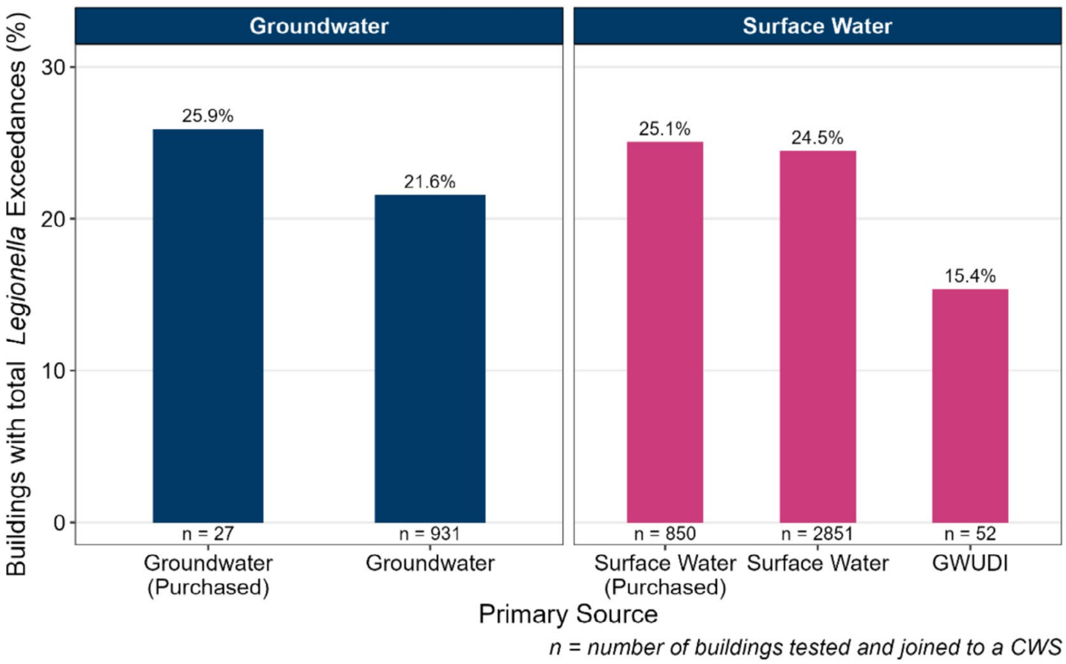

FIGURE 6 | Percentage of buildings with total *Legionella* exceedances by primary source water type.

more than 100,000 people, with median sizes of 27,284, 36,703, and 128,171 square feet, respectively. These results indicate that larger PWSs tend to serve larger buildings. Since larger buildings often have more complex plumbing—and a greater potential for water stagnation—this relationship may partially explain the higher rates of total *Legionella* exceedances observed in buildings served by larger systems.

3.3 | Joined Analysis of PWS Disinfectant Residual and GSA Data

3.3.1 | Scope and Interpretation of the National-Scale Analysis

The analyses presented in this section rely on historical PWS disinfectant residual data collected between 2012 and 2020, whereas GSA building-level *Legionella* spp. sampling occurred in 2024. As a result, these national-scale analyses are not intended to represent temporally matched evaluations of disinfectant residual concentrations at the time of *Legionella* spp. sampling. Instead, they provide contextual insight into whether broad, long-term distribution system disinfectant practices and regulatory frameworks are consistent with observed building-level *Legionella* spp. occurrence patterns at a national scale. Interpretation of results from this section should therefore be considered descriptive and contextual rather than causal or predictive.

The primary purpose of this analysis is to assess whether regulatory constructs—such as state-mandated minimum disinfectant residual requirements, disinfectant type (free chlorine vs. chloramine), and low-percentile residual metrics—emerge as consistent indicators of building-level total *Legionella* exceedances when evaluated across a large, nationally representative dataset. Direct, temporally aligned evaluation of disinfectant residuals and *Legionella* occurrence is addressed separately in Section 3.4.

3.3.2 | Impact of State Minimum Disinfectant Residual Requirements on Legionella Occurrence

As mentioned previously, 23 states have currently defined a required distribution system numeric minimum disinfectant residual level (Samson et al. 2024). As part of the proposed MDBP Rule revisions, there have been suggestions to mandate a numeric minimum disinfectant residual rather than the current "detectable" requirement for distribution systems. This analysis aimed to evaluate whether buildings served by PWSs in states with numeric minimum disinfectant residual requirements had significantly different rates of total *Legionella* exceedance compared to those in states with only a detectable residual requirement.

To support this analysis, PWSs were categorized by disinfectant type (free chlorine or chloramine). Chloramine systems were identified using EPA's SYR4 Treatment Process Table, linking treatment by facility to a corresponding PWSID with the "Water System Facility Plant Table," "Water System Facility Table," and "Water System Table." Additionally, any system that reported disinfectant residual data under the analyte name "Chloramine" was classified as a chloramine system. While the classification of disinfectant type may not be perfect for all systems, the method is suitable for a national level analysis and helps to inform the relationship between PWS distribution system disinfectant residual levels and total *Legionella* exceedance rates in buildings served by the PWS.

The resulting dataset included 978 PWSs with available historical disinfectant residual data (2012–2020) that served GSA buildings. This dataset verified that systems identified as using chloramines for secondary disinfection maintain higher disinfectant residual levels throughout distribution systems as compared with systems using free chlorine (Figure S5).

Disinfectant residual concentrations also varied by PWS size. When residual levels were stratified by the same PWS population size categories used in the preceding analyses, larger systems maintained significantly higher residual concentrations than smaller systems (Kruskal–Wallis test, $p < 0.001$). This pattern reflects, in part, the greater prevalence of chloramine use observed among larger PWSs, which typically maintain higher and more stable distribution system residuals than free chlorine systems.

Of the 978 PWSs with available historical disinfectant residual data, 874 served buildings with total *Legionella* exceedance results. For each of these 874 PWSs, the percentage of associated GSA buildings with exceedances was calculated, and these PWS-level percentages were compared across state minimum disinfectant residual requirements and disinfectant types.

Results indicated no statistically significant difference in the percentage of buildings with total *Legionella* exceedances when comparing states with a detectable residual requirement to those with a numeric minimum residual requirement—this was true for both free chlorine systems (Wilcoxon Test, $p = 0.97$) and chloramine systems ($p = 0.48$) (Figure S6). Additionally, there was no correlation between the numeric minimum values (e.g., 0.2 mg/L as Cl_2, 0.5 mg/L as Cl_2) associated with state requirements and the percentage of buildings served by the PWS with total *Legionella* exceedances. Thus, state minimum disinfectant residual requirements were not associated with statistically significant differences in the percent of buildings with total *Legionella* exceedances served by PWSs within this national-scale dataset.

3.3.3 | Impact of PWS Distribution System Disinfectant Residual Type and Concentration on Legionella spp. Occurrence

The study investigated whether the type and concentration of disinfectant residual maintained in PWS distribution systems were associated with the occurrence of total *Legionella* exceedances in buildings. To evaluate the differences between disinfected system types, the analysis was conducted at the PWS level using 874 PWSs with available historical disinfectant residual data (2012–2020) that also served GSA buildings with total *Legionella* exceedance results. For each PWS, the percentage of associated GSA buildings with one or more total *Legionella* exceedances was calculated, and these PWS-level percentages were compared between systems using chloramines and systems using free chlorine. The analysis was performed at the

PWS level because disinfectant residual type is a distribution-system characteristic shared across all buildings served by the same utility. Aggregating results at the PWS level avoided disproportionately weighting large systems serving many GSA buildings and allowed comparisons between distribution systems and their disinfectant strategies rather than between individual buildings.

Results showed no statistically significant difference in PWS-level building exceedance percentages between systems using chloramines and those using free chlorine (Wilcoxon Test: $p = 0.09$). For both disinfectant types, the median PWS-level exceedance rate was 0%. The average PWS-level exceedance rate was slightly higher in chloraminated systems (18%; $n = 197$ PWSs) compared to free chlorine systems (17%; $n = 677$ PWSs) (Figure S1).

To assess the potential influence of undisinfected water, groundwater PWSs without reported disinfection (identified from 2024 Q2 SDWIS data) were linked to GSA buildings with total *Legionella* results. Unlike the PWS-level comparison above, this analysis was conducted at the building level rather than the PWS level because the number of buildings supplied by undisinfected systems was very small and most undisinfected PWSs were linked to only a single GSA building. As a result, calculating PWS-level exceedance percentages would be strongly influenced by very small sample sizes.

Figure 7 therefore compares building-level exceedance rates across disinfectant categories. Among the 6079 GSA buildings joined to a PWS, 23 are supplied by undisinfected groundwater systems. Of these 23 buildings, 19 had total *Legionella* testing results, and six (31.6%) showed total *Legionella* exceedances. For comparison, buildings served by free chlorine systems had a building-level exceedance rate of 23.2% ($n = 2224$ buildings), while those served by chloraminated systems had an exceedance rate of 19.4% ($n = 824$ buildings), indicating broadly similar exceedance rates across disinfected systems. Statistical comparisons using the K-S Tests comparing building-level exceedance distributions between disinfectant categories identified no statistically significant differences between any disinfectant category pairs (all $p > 0.05$). However, comparisons involving the undisinfected category should be interpreted cautiously because the undisinfected group included a substantially smaller number of buildings ($n = 19$) than the free chlorine and chloramine categories.

To further assess the potential impact of both distribution system disinfectant residual type and concentrations, the percent of buildings served by PWSs with total *Legionella* exceedances was compared to the historical (2012–2020) 5th percentile disinfectant residual concentration for each PWS, stratified by disinfectant type. The 5th percentile was selected as an appropriate metric, as federal and state regulatory requirements stipulate that 95% of disinfectant residual samples must meet the minimum requirement monthly. This percentile also represents an indicator of low distribution system residual levels, which may result in conditions that increase risk for microbial growth.

No significant correlation was found between the 5th percentile disinfectant residual concentration and the percentage of buildings with a total *Legionella* exceedance for either disinfectant type (Pearson's $r = -0.10$ for free chlorine systems; $r = -0.20$ for chloraminated systems) (Figure S8).

Additionally, systems were grouped by total *Legionella* exceedance status, defined as whether the PWS served at least one building with a total *Legionella* exceedance. Figure S9 presents boxplots comparing the historical (2012–2020) 5th percentile residuals for each group, with potential minimum residual thresholds (0.2 mg/L as Cl_2, 0.5 mg/L as Cl_2, 0.7 mg/L as Cl_2 for chloramine systems only) shown for reference. No statistically significant differences in historical 5th percentile residual concentrations were observed between PWSs that served buildings with exceedances and those without exceedances (Wilcoxon Test: $p = 0.09$ for free chlorine systems; $p = 0.31$ for chloramine systems).

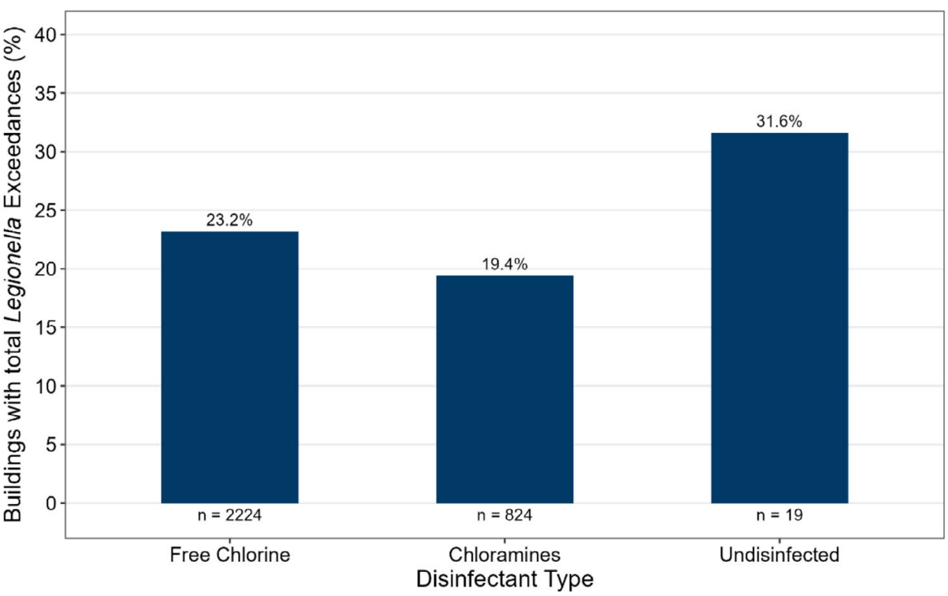

FIGURE 7 | Percentage of buildings with total *Legionella* exceedances by disinfectant type. n = number of buildings.

To further explore the potential relevance of specific regulatory threshold values, additional analyses comparing building-level total *Legionella* exceedance rates across historical minimum disinfectant residual thresholds (detectable, 0.2, 0.5, and 0.7 mg/L as Cl_2) were conducted and are provided in Figure S10. Results were consistent with the primary findings and did not indicate systematic differences in exceedance rates across threshold categories.

3.4 | Paired Analysis of Disinfectant Residual Data Provided by PWSs and GSA Data

This study examined the relationship between disinfectant residual concentration and type, and total *Legionella* exceedances in a subset of 40 selected GSA buildings. A paired analysis was conducted by linking *Legionella* spp. sampling results from these buildings with disinfectant residual data provided by the corresponding PWSs, collected during the same quarter in which the *Legionella* spp. samples were taken. The selected buildings were chosen to represent different attributes, including size (small and large) and total *Legionella* exceedance status (with and without exceedances), and were distributed across seven participating PWSs.

To ensure that the analysis reflected local disinfectant conditions, residual data was aggregated from distribution system monitoring locations within a defined buffer zone around each building, with a target of at least 30 monitoring samples per building to support statistically meaningful comparisons. This approach ensured that disinfectant residual concentrations represented conditions near the buildings sampled for *Legionella* spp., rather than broader system-level summaries.

A summary dataset was compiled to enable direct comparison between building-level *Legionella* spp. results and the disinfectant residual levels reported by the PWSs serving those buildings. Figures 8 and 9 display residual disinfectant levels in free chlorine and chloraminated systems, respectively, plotted against proposed national minimum residual thresholds. In both figures, PWSs are grouped by total *Legionella* exceedance status, which is defined as whether the system served at least one building in the analysis with a total *Legionella* result exceeding the GSA threshold of 1 CFU/mL. This grouping allows for visual comparison of residual levels in PWSs associated with exceedance versus non-exceedance buildings, revealing system-specific differences in residual distributions that are explored in greater detail in the subsequent subsection.

It should be noted that all seven participating PWSs maintained disinfectant residuals at or above their respective state-mandated minimum requirements for most samples collected during 2024. While localized residuals measured near buildings—most of which were sampled during Q3—were sometimes lower due to seasonal and hydraulic conditions, the overall distribution of reported values was consistent with systems operating within regulatory expectations.

3.4.1 | Impact of Disinfectant Residual Concentration on Legionella spp. Occurrence

The median and distribution of disinfectant residuals were analyzed across two groups—buildings with and without total *Legionella* exceedances—to evaluate whether relative differences in residual levels near buildings were associated with exceedance patterns. Residual concentrations were also compared across systems to assess broader trends. The Wilcoxon Rank-Sum Test was used to compare median residuals between groups, and the K–S Test was used to assess differences in the overall distribution of residuals. Table 6 compares disinfectant residuals by total *Legionella* exceedance status for each of the seven systems.

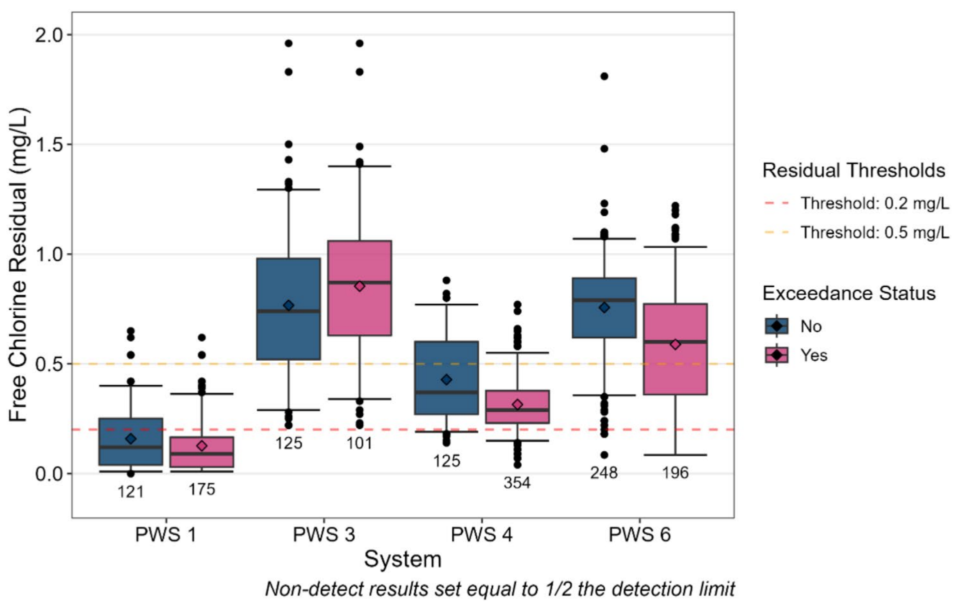

FIGURE 8 | Residual disinfectant levels in free chlorine systems by *Legionella* exceedance status. n = number of PWS disinfectant residual data points near selected GSA buildings, during the same quarter in which *Legionella* spp. samples were collected.

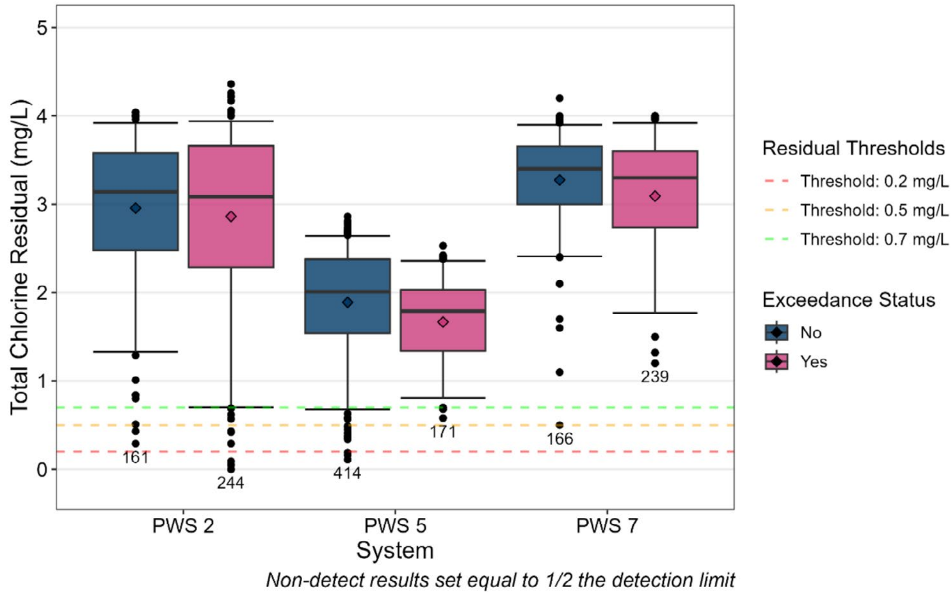

FIGURE 9 | Residual disinfectant levels in chloramine systems by *Legionella* exceedance status. n = number of PWS disinfectant residual data points near selected GSA buildings, during the same quarter in which *Legionella* spp. samples were collected.

Across the seven systems evaluated, residual concentrations near buildings varied by system, reflecting localized and seasonal (Q2–Q3) conditions within the distribution systems. In four systems (PWS 4–7), buildings with total *Legionella* exceedances were associated with comparatively lower nearby residuals, and these differences were significant ($p < 0.05$). In PWS 3, buildings with exceedances were associated with higher median nearby residuals, a difference that was statistically significant based on the Wilcoxon test. In PWS 1 and PWS 2, buildings with exceedances were also associated with lower nearby residuals, but the differences were not statistically significant. Taken together, these inconsistent patterns indicate that distribution system disinfectant residual measurements—even when localized and temporally aligned by calendar quarter—do not reliably predict building-level *Legionella* spp. exceedance outcomes. These findings also likely reflect the fact that residuals measured in the distribution system do not directly represent residuals maintained within building plumbing, and that residual and *Legionella* spp. data, while matched by calendar quarter, were not collected on the same sampling day. As a result, localized water age, stagnation, temperature, and premise plumbing conditions may decouple distribution system residual measurements from building-level *Legionella* occurrence.

3.4.2 | Impact of Disinfectant Residuals on Legionella spp. Occurrence

To evaluate disinfectant performance relative to minimum residual standards, the 5th percentile disinfectant residual was determined for each of the seven systems serving the 40 selected GSA buildings. The 5th percentile represents the lower end of the residual distribution within the distribution system near the buildings and indicates whether at least 95% of samples met or exceeded applicable state minimum requirements. This metric was based on residual measurements collected during the same quarter in which *Legionella* spp. samples were obtained, enabling direct temporal comparison. The 5th percentile values were compared against both state-mandated minimum residual requirements and proposed national thresholds to assess whether systems were generally maintaining residual levels consistent with regulatory expectations—and whether total *Legionella* exceedances occurred even when those thresholds were met. Results are summarized in Table 7, which presents the 5th percentile residuals by system and exceedance group (buildings with and without total *Legionella* exceedances), along with a comparison to applicable state and proposed minimum residual thresholds. Because these data represent localized residuals measured near GSA buildings, they should not be interpreted as system-wide compliance determinations but rather as indicators of relative disinfectant levels during the study period.

Total *Legionella* exceedances were observed in four of the seven systems, even when the proposed minimum disinfectant residual thresholds were met in measurements taken near the buildings. These systems included PWS 2, PWS 3, PWS 5, and PWS 7, where both exceedance and non-exceedance buildings had 5th percentile residuals at or above the proposed thresholds. In contrast, in systems where proposed thresholds were not met, low residuals were also observed near buildings without exceedances, suggesting that residual levels alone may not fully explain exceedance patterns. This was evident in PWS 1 and PWS 4, where 5th percentile residuals near buildings fell below the 0.2 mg/L as Cl_2 threshold regardless of exceedance status. PWS 6 was the only system where a clear distinction was observed: buildings with exceedances were associated with residuals below both the state and proposed thresholds, while buildings without exceedances had nearby residuals that met or exceeded the proposed 0.2 mg/L as Cl_2 threshold.

As a contextual check on the temporal representativeness of the historical disinfectant residual data used in the national-scale analysis, relative to conditions observed in 2024, statistical comparisons were conducted for the subset of utilities included in

TABLE 6 | Disinfectant residuals in the distribution system near buildings with and without total *Legionella* exceedances.

PWS number	Disinfectant type	State min residual req. (mg/L as Cl_2)	Data quarter(s)	Wilcoxon *p*	K–S *p*	Median residual (mg/L as Cl_2)—near buildings with exceed.[a]	Median residual (mg/L as Cl_2)—near buildings with no exceed.[a]	Interpretation
PWS 1	Free chlorine	Detectable	Q3	0.084; > 0.05	0.24; > 0.05	0.090	0.12	Lower residuals near buildings with exceedances, but not statistically significant
PWS 2[b]	Chloramines/ mixed	0.2 (free); 0.5 (total)	Q2–Q3	0.74; > 0.05	0.68; > 0.05	3.08	3.14	Lower residuals near buildings with exceedances, but not statistically significant
PWS 3	Free chlorine	0.2 (free); 0.6 (total)	Q3	0.039; < 0.05	< 0.16; > 0.05	0.87	0.74	Higher residuals near buildings with exceedances; statistically significant when comparing medians only
PWS 4	Free chlorine	Detectable	Q3	< 0.001; < 0.05	< 0.001; < 0.05	0.29	0.37	Lower residuals near buildings with exceedances; statistically significant
PWS 5	Chloramines	0.2	Q2–Q3	< 0.001; < 0.05	< 0.001; < 0.05	1.79	2.01	Lower residuals near buildings with exceedances; statistically significant
PWS 6	Free chlorine	Detectable	Q2–Q3	< 0.001; < 0.05	< 0.001; < 0.05	0.60	0.79	Lower residuals near buildings with exceedances; statistically significant
PWS 7	Chloramines	Detectable	Q3	0.007; < 0.05	0.033; < 0.05	3.30	3.40	Lower residuals near buildings with exceedances; statistically significant

[a]Median residuals represent localized measurements near GSA buildings from distribution system monitoring sites near GSA buildings during the same sampling quarter as *Legionella* spp. testing and are intended for comparative analysis only.
[b]For PWS 2, only residual measurements from chloraminated portions of the distribution system were included in the analysis.

TABLE 7 | Comparison of 5th percentile disinfectant residuals (near buildings) to state and proposed minimum thresholds.

PWS number	Disinfectant type	State min residual req. (mg/L as Cl_2)	Proposed min residual(s) (mg/L)	Data quarter(s)	5th percentile residual (mg/L as Cl_2)—near buildings with exceed.[a]	5th percentile residual (mg/L as Cl_2)—near buildings with no exceed.[a]	Interpretation
PWS 1	Free chlorine	Detectable	0.2, 0.5	Q3	0.010	0.010	State minimum (detectable) met; but well below proposed 0.2 mg/L as Cl_2 across both groups
PWS 2[b]	Chloramines/mixed	0.2 (free); 0.5 (total)	0.2, 0.5, 0.7	Q2 – Q3	0.70	1.3	State minimum (0.5 mg/L as Cl_2) met; both groups exceed proposed 0.7 mg/L as Cl_2
PWS 3	Free chlorine	0.2 (free); 0.6 (total)	0.2, 0.5	Q3	0.34	0.29	Both groups exceed state minimum and proposed 0.2 mg/L as Cl_2
PWS 4	Free chlorine	Detectable	0.2, 0.5	Q3	0.15	0.19	State minimum (detectable) met; but below proposed 0.2 mg/L as Cl_2 across both groups
PWS 5	Chloramines	0.2	0.2, 0.5, 0.7	Q2–Q3	0.81	0.68	Both groups exceed state minimum and proposed 0.2 mg/L as Cl_2
PWS 6	Free chlorine	Detectable	0.2, 0.5	Q2–Q3	0.085[c]	0.36	Exceedance group does not meet state minimum (detectable); non-exceedance group above proposed 0.2 mg/L as Cl_2
PWS 7	Chloramines	Detectable	0.2, 0.5, 0.7	Q3	1.8	2.4	State minimum (detectable) met; well above proposed 0.7 mg/L as Cl_2 across both groups

[a] 5th percentile residuals represent localized measurements near GSA buildings and are intended for comparative analysis only; they do not constitute system-wide compliance determinations.
[b] For PWS 2, only residual measurements from chloraminated portions of the distribution system were included in the analysis.
[c] Non-detects reported at half the detection limit (0.17 mg/L as Cl_2) indicates many non-detects or very low residuals in distribution samples near buildings.

the paired analysis. Median and distributional differences between historical (2012–2020) and 2024 disinfectant residuals were evaluated using Wilcoxon rank-sum and K-S tests. For all utilities with available data (excluding PWS 3 and PWS 6, where historical residual data were unavailable), disinfectant residual concentrations in 2024 were statistically higher than those observed historically ($p < 0.05$ for all comparisons). These results demonstrate that the absence of a relationship between disinfectant residuals and *Legionella* exceedances in the national-scale analysis is not driven by the use of historical data. Even under higher disinfectant residual conditions observed in the paired analysis, exceedances occurred and no consistent residual–exceedance relationship was observed.

3.4.3 | Impact of Disinfectant Residual Type on Legionella Occurrence and Speciation

This analysis evaluated the relationship between distribution system disinfectant residuals and total *Legionella* exceedances in buildings, as well as whether disinfectant type was associated with differences in *Legionella* species composition.

Figure 10 shows the relationship between 5th percentile chlorine residuals from the distribution system near each building and the percentage of total *Legionella* samples exceeding the threshold, grouped by system and disinfectant type. PWS 1, PWS 3, PWS 4, and PWS 6 all use free chlorine; these systems had the highest percentages of exceedances, with some buildings exceeding 50%. In contrast, PWS 2, PWS 5, and PWS 7 are all chloramine systems and had lower exceedance rates, with all buildings below 50%. Previous studies have indicated that monochloramine may be more effective than free chlorine for the control of *L. pneumophila* growth in drinking water systems and buildings (Dowdell et al. 2023; Lytle et al. 2021; NASEM 2019). Monochloramine may be more effective at controlling *L. pneumophila* growth because it can more effectively penetrate biofilms (LeChevallier et al. 1988; Lee et al. 2011). However, in the 2019 Donohue study, *L. pneumophila* was detected at the same frequency for buildings with water disinfected with free chlorine or monochloramine, but the concentrations were lower in the buildings receiving water disinfected with monochloramine (Donohue, Vesper, et al. 2019).

Figure 11 compares chlorine residuals from monitoring locations near buildings with and without total *Legionella* exceedances, stratified by disinfectant type, and evaluates these residuals against proposed minimum threshold values. For chloramine systems, median residuals were slightly higher in exceedance buildings (2.87 mg/L as Cl_2) than non-exceedance buildings (2.41 mg/L as Cl_2). The 5th percentile residuals were also higher in exceedance buildings (0.94 mg/L as Cl_2 vs. 0.84 mg/L as Cl_2), and both groups exceeded the 0.7 mg/L as Cl_2 threshold. For free chlorine systems, median residuals were lower in exceedance buildings (0.32 mg/L as Cl_2) compared to non-exceedance buildings (0.60 mg/L as Cl_2). The 5th percentile residuals were very low in both groups (~0.03–0.04 mg/L as Cl_2), well below the 0.2 mg/L as Cl_2 threshold. Statistical comparisons using the Wilcoxon Test (medians) and K–S Test (distributions) indicated significant differences ($p < 0.05$) between exceedance and non-exceedance groups for both disinfectant types.

These contrasting patterns suggest that the relationship between disinfectant residuals and total *Legionella* exceedances differs by disinfectant type. Higher residuals in chloramine systems were not protective against exceedances, while in free chlorine systems, lower residuals were associated with exceedances, though both groups had similarly low 5th percentile values. However, these apparent differences between free chlorine and chloramine systems may also reflect confounding factors such as building size, age, and use type, rather than disinfectant alone. Larger or more complex buildings can have greater water age and more extensive plumbing networks that promote disinfectant decay and *Legionella* spp. growth independent of disinfectant type.

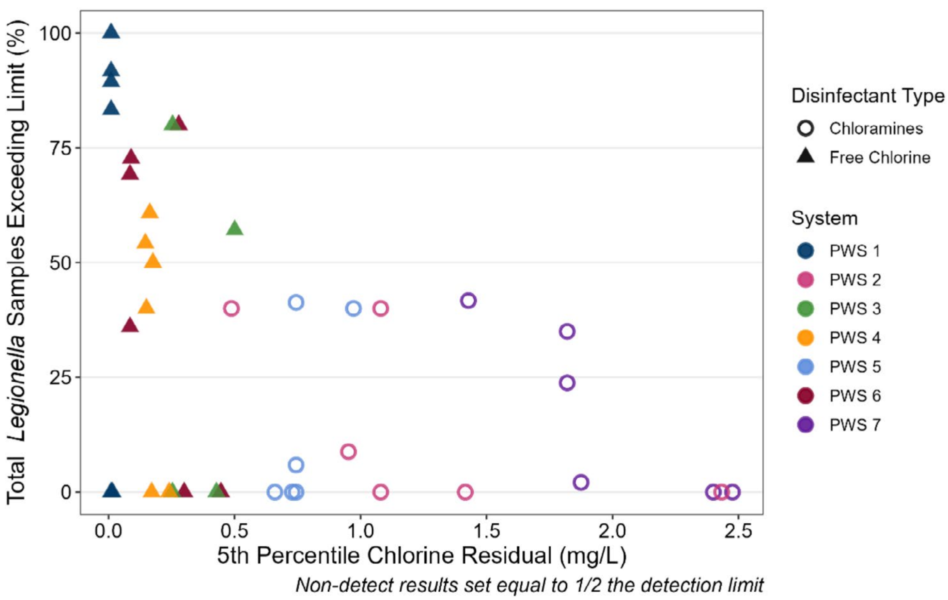

FIGURE 10 | 5th percentile chlorine residuals near buildings and percentage of total Legionella samples exceeding limit. Data points represent GSA buildings within each PWS.

Unlike the national analysis, which examined whether buildings had any total *Legionella* exceedances, the focused analysis allowed assessment of the proportion of samples within each building that exceeded the total *Legionella* threshold. This building-level exceedance rate provides a measure of exceedance severity within individual buildings, rather than a binary exceedance indicator. While disinfectant type did not appear to prevent exceedances, buildings served by free chlorine tended to exhibit higher exceedance rates than those served by chloramine. These findings provide additional context to the national results, illustrating how residual type may influence the extent of exceedance within buildings, even when exceedances occur under both disinfectant types. However, the limited number of data points precludes a statistically meaningful assessment of the relationship between disinfectant residual levels and total *Legionella* exceedance rates, and these results should be interpreted as exploratory.

In addition to overall occurrence, *Legionella* species distributions were examined to determine whether disinfectant type influenced the composition and concentrations of *Legionella*. Data from all participating PWSs were combined and stratified by disinfectant type (free chlorine vs. chloramines) and species group (*L. pneumophila* vs. *non-L. pneumophila*). Cumulative distribution plots (Figure 12) were generated to visualize concentration patterns across these groups. Detection limits across the combined dataset ranged from 0.05 to 5 CFU/mL. This variability reflected differences in laboratories and analytical volumes.

Median concentrations were the same for *L. pneumophila* and non-*L. pneumophila* within each disinfectant type but differed between disinfectants: 0.05 CFU/mL in chloraminated systems and 0.5 CFU/mL in free chlorine systems. This indicates that within a given disinfectant type, species groups exhibited similar central tendencies, yet overall concentrations tended to be higher in free chlorine systems compared to chloraminated systems.

The relative distributions of species differed between disinfectant types. In buildings supplied by free chlorine systems, *L. pneumophila* concentrations were generally greater than those of non-*L. pneumophila*, whereas in buildings supplied by chloraminated systems, non-*L. pneumophila* concentrations were higher. Statistical comparisons using the K-S Test confirmed significant differences ($p < 0.05$) in concentration distributions between disinfectant types for both species groups. Taken together, these findings suggest that free chlorine and chloramines are associated with different patterns of *Legionella* colonization and species dominance in building water systems.

4 | Conclusions

4.1 | GSA'S Proactive Approach to Drinking Water Quality and Legionella spp. Monitoring

The GSA baseline water quality testing dataset represents one of the largest and most nationally representative collections of *Legionella* spp. occurrence data in buildings served by PWSs. This proactive, non-mandated testing approach demonstrates GSA's commitment to identifying and mitigating drinking water risks. Systematic remediation and communication following exceedances further highlight a strong public health focus.

4.2 | National Legionella spp. Positivity Rate in Buildings

When examining the national dataset, 23.6% ($n = 1274$) of buildings had total *Legionella* exceedances, consistent with recent studies reporting *L. pneumophila* detection in 26.9% of buildings

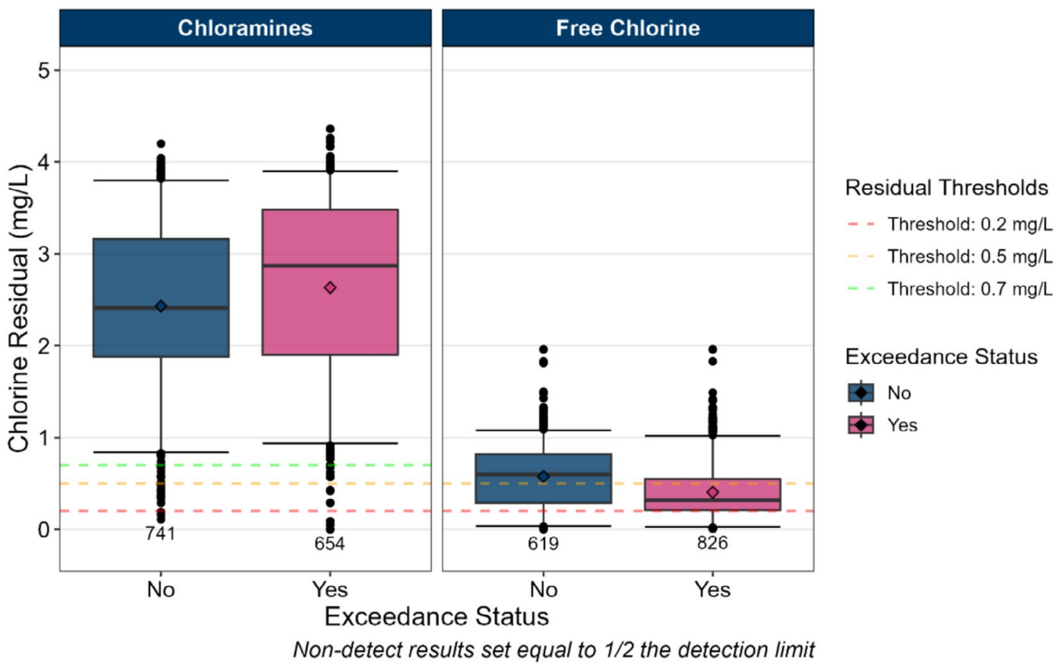

FIGURE 11 | Chlorine residuals near buildings by disinfectant type and exceedance status. n = number of PWS disinfectant residual data points near selected GSA buildings during the same quarter in which *Legionella* spp. samples were collected across 40 selected GSA buildings.

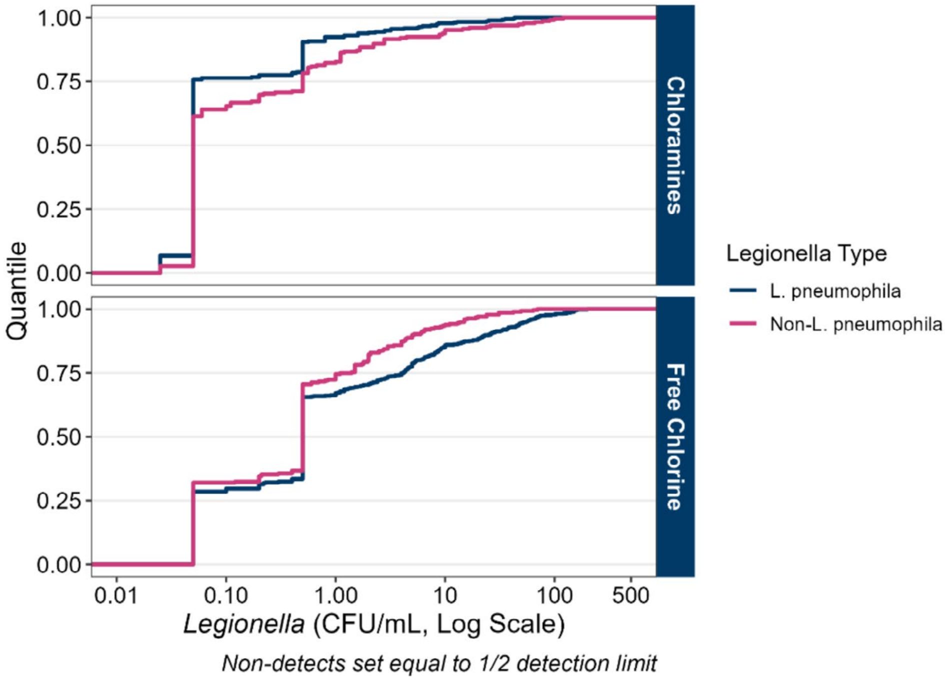

FIGURE 12 | Cumulative distribution plot of *Legionella* concentrations by disinfectant type and species.

(Dowdell et al. 2023) and 35%–42% in US residences and offices (Donohue, King, et al. 2019). Because exceedances in the GSA dataset were based on total *Legionella* detections (including both *L. pneumophila* and non-*L. pneumophila* species), the reported rate may be somewhat higher than if exceedances were limited to *L. pneumophila* alone. Previous studies may have had higher rates of detection because other methods were employed (qPCR) and qPCR can detect DNA from non-viable or viable but not culturable (VBNC) cells that may not have resulted in positive detections for culture-based methods.

4.3 | Role of Building Characteristics

Exceedance rates for total *Legionella* were associated with:

- *Age*: Older buildings, particularly those constructed prior to the 1980s, tended to show higher exceedance rates. This pattern may reflect aging plumbing infrastructure and more complex plumbing systems—assuming that building age is broadly correlated with premise plumbing age and materials—which can promote disinfectant decay and microbial growth.
- *Size*: Larger buildings had higher exceedance rates. Exceedances exceeded 50% among buildings over 50,000 square feet, with the highest rates observed in facilities greater than 500,000 square feet. The likely drivers are more extensive plumbing networks and lower flow in distal areas of the system. Larger buildings also typically have more outlets and sampling locations, which may increase the likelihood of detecting at least one exceedance.
- *Type*: Health and human services facilities had the highest proportion of exceedances (>40%), underscoring their heightened vulnerability.

These findings emphasize the need for proactive water quality management in older, larger, or intermittently occupied buildings.

4.4 | Influence of PWS Characteristics

Total *Legionella* exceedances increased with PWS size, particularly for systems serving populations greater than 3300, while source water type had minimal influence. Larger PWSs also tended to serve larger buildings, indicating that the observed increase in exceedances is closely aligned with building size rather than PWS characteristics alone.

4.5 | Disinfectant Residual Requirements

State-level minimum disinfectant residual requirements and disinfectant type (chlorine vs. chloramine) were not significantly associated with total *Legionella* exceedances. This finding is notable given that larger PWSs—where higher exceedance rates were observed—generally maintained higher disinfectant residual concentrations, in part due to a greater prevalence of chloramine use. As such, the increased occurrence of exceedances in buildings served by larger PWSs is unlikely to be explained by lower distribution system residual levels.

A small subset of buildings served by undisinfected groundwater systems showed a higher proportion of exceedances; however, the limited number of buildings in this category constrains broader interpretation. Nonetheless, this pattern suggests that undisinfected systems may represent a potential vulnerability and warrant further evaluation in future, targeted studies.

4.6 | Building-Level Disinfectant Residuals

Analysis of 40 GSA buildings with detailed data revealed that lower residuals near some buildings correlated with exceedances, but this pattern was not consistent. Because *Legionella* spp. sampling for most systems occurred during the third quarter (summer) when disinfectant residuals are typically at their seasonal minimum and conditions favor disinfectant decay, reducing microbial control and increasing the potential for *Legionella* spp. growth, these findings likely reflect seasonally conservative residual conditions rather than broader system performance. Across all participating systems, disinfectant residuals were generally maintained at or above their respective state-mandated minimum requirements for most samples, although localized measurements near buildings were sometimes lower due to seasonal and hydraulic variability. Exceedances occurred even when residuals met regulatory thresholds; however, exceedance occurrence alone does not capture the full range of *Legionella* risk, as concentration—particularly of *L. pneumophila*—and exceedance extent are also important considerations.

Disinfectant type influenced species distribution: free chlorine systems had higher *L. pneumophila* concentrations, whereas chloraminated systems had higher non-*L. pneumophila* concentrations. However, neither disinfectant type nor concentration prevented exceedances, though buildings served by free chlorine tended to exhibit higher proportions of samples exceeding the total *Legionella* threshold than those served by chloramine. These apparent differences by disinfectant type may also be influenced by building-level factors such as size, age, and occupancy patterns, which can affect water age and disinfectant decay independent of disinfectant type. While the paired residual dataset provided sufficient resolution for meaningful comparison across systems, the smaller number of building-level data points limited statistical evaluation of the relationship between 5th percentile residuals and exceedance rates.

4.7 | Recommendations

This study found no consistent association between distribution system disinfectant residual levels and *Legionella* spp. occurrence in GSA buildings; however, this finding should be interpreted in light of the temporal and spatial mismatch between available disinfectant residual data and building-level *Legionella* spp. sampling. Together, these results underscore the limited value of relying solely on distribution-level residual requirements for *Legionella* spp. management, recognizing that exceedance occurrence alone does not fully reflect building-level conditions and that concentration and extent of detections are also relevant considerations. Because disinfectant decay and building-specific factors strongly influence conditions within premise plumbing, future regulatory and policy development should prioritize building-centered approaches. While PWSs are responsible for maintaining water quality to the point of delivery, building owners are responsible for conditions within premise plumbing systems, emphasizing the need for coordinated management across both scales.

In addition, the GSA should make its full building-level dataset publicly accessible, including detailed information on building water disinfectant residuals, fixture types, building water system design, and other plumbing characteristics. Such transparency would allow for more comprehensive analyses, enable independent researchers to identify additional drivers of exceedance risk, and ultimately support more effective water quality management strategies. Last, improving the documentation, retention, and compilation of individual disinfectant residual monitoring datapoints—rather than only aggregated compliance metrics—by both water systems and state programs would substantially strengthen future nationally representative evaluations of the relationship between disinfectant residuals and *Legionella* spp. occurrence.

Author Contributions

Emily von Hagen: formal analysis, validation, investigation, visualization, methodology, writing – original draft, project administration, writing – review and editing. **Christian Mathews:** formal analysis, validation, investigation, visualization, methodology, writing – original draft, writing – review and editing. **Carleigh Samson:** conceptualization, data curation, formal analysis, supervision, funding acquisition, validation, investigation, visualization, methodology, writing – original draft, project administration, writing – review and editing. **Chad Seidel:** conceptualization, data curation, formal analysis, supervision, funding acquisition, validation, investigation, visualization, methodology, writing – original draft, project administration, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study were obtained from public sources including the U.S. General Services Administration (GSA) through a Freedom of Information Act (FOIA) request; U.S. EPA SDWIS water system inventory, Six Year Review Four occurrence data, and water system boundaries; statemanaged compliance data; and directly from participating water utilities. The data are not shared as part of this publication.

References

AIHA. 2015. "Recognition, Evaluation, and Control of Legionella in Building Water Systems." https://www.aiha.org/education/marketplace/legionella-guide.

Angert, D. M., C. Ley, K. Ra, et al. 2023. "Water Quality During Extended Stagnation and Flushing in a College Residential Hall." *Environmental Science: Water Research & Technology* 9, no. 12: 3484–3496. https://doi.org/10.1039/D3EW00038A.

AWWA, AMWA, and ASDWA. 2025. "Joint Letter of Recommendations for Opportunities for Revising Microbial and Disinfection Byproduct (MDBP) Rules From AWWA, AMWA, and ASDWA."

Bartrand, T. A., M. W. LeChevallier, J. L. Clancy, and G. A. Burlingame. 2024. "Protocol for Responding to the Detection of *Legionella pneumophila* in Drinking Water Distribution Systems." *AWWA Water Science* 6, no. 2: e1370. https://doi.org/10.1002/AWS2.1370.

CDC. 2025. "Clinical Overview of Legionnaires' Disease." June 9, 2025. https://www.cdc.gov/legionella/hcp/clinical-overview/index.html.

Cullom, A. C., R. L. Martin, Y. Song, et al. 2020. "Critical Review: Propensity of Premise Plumbing Pipe Materials to Enhance or Diminish Growth of Legionella and Other Opportunistic Pathogens." *Pathogens* 9, no. 11: 1–34. https://doi.org/10.3390/pathogens9110957.

Donohue, M. J., D. King, S. Pfaller, and J. H. Mistry. 2019. "The Sporadic Nature of Legionella Pneumophila, Legionella Pneumophila Sg1 and Mycobacterium Avium Occurrence Within Residences and Office Buildings Across 36 States in the United States." *Journal of Applied Microbiology* 126, no. 5: 1568–1579. https://doi.org/10.1111/jam.14196.

Donohue, M. J., S. Vesper, J. Mistry, and J. M. Donohue. 2019. "Impact of Chlorine and Chloramine on the Detection and Quantification of Legionella Pneumophila and Mycobacterium Species." *Applied and Environmental Microbiology* 85, no. 24: e01942-19. https://doi.org/10.1128/AEM.01942-19.

Dowdell, K. S., H. G. Healy, S. Joshi, et al. 2023. "*Legionella pneumophila* Occurrence in Reduced-Occupancy Buildings in 11 Cities During the COVID-19 Pandemic." *Environmental Science: Water Research & Technology* 9, no. 11: 2847–2865. https://doi.org/10.1039/D3EW00278K.

Flannery, B., L. B. Gelling, D. J. Vugia, et al. 2006. "Reducing Legionella Colonization of Water Systems With Monochloramine." *Emerging Infectious Diseases* 12, no. 4: 588–596. https://doi.org/10.3201/EID1204.051101.

Gamage, S. D., C. Jinadatha, J. D. Coppin, et al. 2022. "Factors That Affect Legionella Positivity in Healthcare Building Water Systems From a Large, National Environmental Surveillance Initiative." *Environmental Science & Technology* 56, no. 16: 11363–11373. https://doi.org/10.1021/ACS.EST.2C02194/SUPPL_FILE/ES2C02194_SI_002.TXT.

GSA. 2023. "GSA Order: Public Building Service 1000.7A." November 17, 2023.

GSA. 2024a. "FY23 Federal Real Property Profile (FRPP) Public Dataset – Catalog." https://catalog.data.gov/dataset/fy23-federal-real-property-profile-frpp-public-dataset.

GSA. 2024b. "Inventory of Owned and Leased Properties (IOLP) – Catalog." https://catalog.data.gov/dataset/inventory-of-owned-and-leased-properties-iolp.

Hamilton, K. A., M. T. Hamilton, W. Johnson, et al. 2019. "Risk-Based Critical Concentrations of *Legionella pneumophila* for Indoor Residential Water Uses." *Environmental Science & Technology* 53: 4528–4541. https://doi.org/10.1021/acs.est.8b03000.

Julien, R., E. Dreelin, A. J. Whelton, et al. 2020. "Knowledge Gaps and Risks Associated With Premise Plumbing Drinking Water Quality." *AWWA Water Science* 2, no. 3: e1177. https://doi.org/10.1002/AWS2.1177;SUBPAGE:STRING:FULL.

Kunz, J., H. Lawinger, S. Miko, et al. 2024. "Surveillance of Waterborne Disease Outbreaks Associated With Drinking Water — United States, 2015–2020." *MMWR Surveillance Summaries* 73, no. 1: 1–23.

LeChevallier, M. W. 2019. "Occurrence of Culturable *Legionella pneumophila* in Drinking Water Distribution Systems." *AWWA Water Science* 1, no. 3: e1139. https://doi.org/10.1002/aws2.1139.

LeChevallier, M. W., T. A. Bartrand, and J. L. Clancy. 2025. "Risk Assessment of *Legionella pneumophila* in Drinking Water Distribution Systems." *AWWA Water Science* 7, no. 4: e70028. https://doi.org/10.1002/AWS2.70028;SUBPAGE:STRING:FULL.

LeChevallier, M. W., C. D. Cawthon, and R. G. Lee. 1988. "Inactivation of Biofilm Bacteria." *Applied and Environmental Microbiology* 54, no. 10: 2492–2499. https://doi.org/10.1128/AEM.54.10.2492-2499.1988.

LeChevallier, M. W., T. Prosser, and M. Stevens. 2024. "Opportunistic Pathogens in Drinking Water Distribution Systems—A Review." *Microorganisms* 12, no. 5: 916. https://doi.org/10.3390/MICROORGANISMS12050916.

Lee, W. H., D. G. Wahman, P. L. Bishop, and J. G. Pressman. 2011. "Free Chlorine and Monochloramine Application to Nitrifying Biofilm: Comparison of Biofilm Penetration, Activity, and Viability." *Environmental Science and Technology* 45, no. 4: 1412–1419. https://doi.org/10.1021/es1035305.

Li, R. A., J. A. McDonald, A. Sathasivan, and S. J. Khan. 2019. "Disinfectant Residual Stability Leading to Disinfectant Decay and By-Product Formation in Drinking Water Distribution Systems: A Systematic Review." *Water Research* 153: 335–348. https://doi.org/10.1016/J.WATRES.2019.01.020.

Lytle, D. A., S. Pfaller, C. Muhlen, et al. 2021. "A Comprehensive Evaluation of Monochloramine Disinfection on Water Quality, Legionella and Other Important Microorganisms in a Hospital." *Water Research* 189: 116656. https://doi.org/10.1016/J.WATRES.2020.116656.

Moffa, M. A., C. Rock, P. Galiatsatos, S. D. Gamage, K. J. Schwab, and N. G. Exum. 2023. "Legionellosis on the Rise: A Scoping Review of Sporadic, Community-Acquired Incidence in the United States." *Epidemiology and Infection* 151: e133. https://doi.org/10.1017/S0950268823001206.

NASEM. 2019. "Management of Legionella in Water Systems." *Management of Legionella in Water Systems*. National Academies Press. https://doi.org/10.17226/25474.

National Drinking Water Advisory Council. 2023. "Report of the Microbial and Disinfection Byproducts Rule Revisions Working Group." https://www.epa.gov/system/files/documents/2023-11/report-of-the-mdbp-rule-revisions-working-group-to-the-ndwac-november-2023_0.pdf.

NDWAC. 2023. "Report of the Microbial and Disinfection Byproducts Rule Revisions Working Group."

Proctor, C. R., W. J. Rhoads, T. Keane, et al. 2020. "Considerations for Large Building Water Quality After Extended Stagnation." *AWWA Water Science* 2, no. 4: e1186. https://doi.org/10.1002/aws2.1186.

R Core Team. 2023. "R: A Language and Environment for Statistical Computing." https://www.R-project.org/.

Ra, K., T. Odimayomi, C. Ley, T. G. Aw, J. B. Rose, and A. J. Whelton. 2020. "Finding Building Water Quality Challenges in a 7 Year Old Green School: Implications for Building Design, Sampling, and Remediation." *Environmental Science: Water Research & Technology* 6, no. 10: 2691–2703. https://doi.org/10.1039/D0EW00520G.

Rhoads, W. J., A. Pruden, and M. A. Edwards. 2014. "Survey of Green Building Water Systems Reveals Elevated Water Age and Water Quality Concerns." *Environmental Science: Water Research & Technology* 2: 164. https://doi.org/10.1039/c5ew00221d.

Sajdak, N., C. Samson, G. Trejo, and A. Pifer. 2025. "Innovative Tools Provide Disinfectant Residual and Legionella Control in Drinking Water Systems." *Journal AWWA* 117, no. 6: 64–66. https://doi.org/10.1002/AWWA.2471.

Salehi, M., T. Odimayomi, K. Ra, et al. 2020. "An Investigation of Spatial and Temporal Drinking Water Quality Variation in Green Residential Plumbing." *Building and Environment* 169: 106566. https://doi.org/10.1016/J.BUILDENV.2019.106566.

Samson, C., C. Seidel, and S. Masters. 2024. "Impacts of Setting a Numeric Minimum Disinfectant Residual for Public Water System Distribution Systems." *AWWA Water Science* 6, no. 3: e1379. https://doi.org/10.1002/AWS2.1379.

USEPA. 1989. "Surface Water Treatment Rules." https://www.epa.gov/dwreginfo/surface-water-treatment-rules.

USEPA. 1991. "Lead and Copper Rule." https://www.epa.gov/dwreginfo/lead-and-copper-rule.

USEPA. 2013. "Revised Total Coliform Rule and Total Coliform Rule." https://www.epa.gov/dwreginfo/revised-total-coliform-rule-and-total-coliform-rule#rule-summary.

USEPA. 2024. "Potential Revisions to the Microbial and Disinfection Byproduct National Primary Drinking Water Regulations | Executive Order 13132 Federalism/Unfunded Mandates Reform Act Consultation Meeting." December 5, 2024.

USEPA. 2025a. "Community Water System Service Area Boundaries." https://www.epa.gov/ground-water-and-drinking-water/community-water-system-service-area-boundaries.

USEPA. 2025b. "EPA Community Water System Service Area Boundaries Introduction to Service Area Boundaries."

USGSA. 2024. "Water Quality: Federally Owned Facilities." November 19. https://www.gsa.gov/real-estate/facilities-management/water-quality-management/federally-owned-facilities.

Wang, H., S. Masters, Y. Hong, et al. 2012. "Effect of Disinfectant, Water Age, and Pipe Material on Occurrence and Persistence of Legionella, Mycobacteria, Pseudomonas Aeruginosa, and Two Amoebas." *Environmental Science & Technology* 46: 11566–11574. https://doi.org/10.1021/es303212a.

Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Table S1:** Summary of building characteristics and sampling data for 40 selected GSA buildings by PWS. **Figure S1:** Data pipeline overview. **Figure S2:** Boxplot of building size (GSA-owned). **Figure S3:** Percentage of buildings with total Legionella exceedances by PWS size. **Figure S4:** Boxplots of distribution of building size (GSA-owned) by system size. **Figure S5:** Boxplots of PWS system-wide median disinfectant residuals by disinfectant type. The median disinfectant residual concentration for each PWS with available historical data (2012–2020) is represented in the boxplots. **Figure S6:** Comparison of state minimum disinfectant residual requirements and total Legionella exceedance rates by residual type. **Figure S7:** Comparison of disinfectant residual type and total Legionella exceedance rates. **Figure S8:** Percent of buildings with total Legionella exceedance vs. PWS 5th percentile chlorine residual. **Figure S9:** Boxplots of PWS 5th percentile disinfectant residuals by total Legionella exceedance status and disinfectant type. **Figure S10:** Distributions of building-level total Legionella exceedance by PWS disinfectant residual threshold compliance (free chlorine and chloramine systems).