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Cooling tower *Legionella pneumophila* surveillance results: Vancouver, Canada, 2021

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ABSTRACT

Cooling towers have been linked to Legionnaires' disease cases and outbreaks. *Legionella pneumophila* results (from a culture-based method) are presented for 557 cooling towers across the City of Vancouver, Canada for 2021. Results of 10 CFU/mL or greater (defined as exceedances) were reported for 30 cooling towers (5.4%), including six >1,000 CFU/mL, and *L. pneumophila* serogroup 1 (sg1) was identified in 17 of these cooling towers (out of 28 with serogroup-level analysis). The data indicate highly localised *Legionella* issues, with exceedances concentrated within 16 facilities, including two hospitals. In the 3 months preceding each cooling tower exceedance, the nearest municipal water sampling station had a free chlorine residual of at least 0.46 mg/L and a temperature of <20 °C. There was not a statistically significant correlation between the *L. pneumophila* concentration of a cooling tower in exceedance and the municipal water free chlorine residual, temperature, pH, turbidity or conductivity. There was a statistically significant negative correlation between the concentrations of *L. pneumophila* sg1 and other *L. pneumophila* serogroups in cooling towers. This unique dataset underscores the pivotal role of building owners and managers in preventing the growth of *Legionella* bacteria and the value of regulations to verify operations and maintenance practices.

Key words: cooling tower, evaporative heat rejection system, *Legionella pneumophila*, Legionnaires' disease, opportunistic premise plumbing pathogens, water management program

HIGHLIGHTS

- In 2021, water samples from about 1-in-20 cooling towers in the City of Vancouver reported *Legionella pneumophila* concentrations of 10 CFU/mL or greater (defined as exceedances), including at two hospitals.
- The data point to building-scale *Legionella* issues. In cooling towers reporting exceedances, there was not a statistically significant correlation between conventional municipal water quality parameters and *L. pneumophila* concentration.
- There was a statistically significant negative correlation between the concentrations of *L. pneumophila* serogroup 1 and 'non-serogroup 1' *L. pneumophila* in cooling towers, hinting at a potentially competitive relationship.

INTRODUCTION

Legionnaires' disease is a serious type of pneumonia: Nearly all patients diagnosed with the disease, regardless of age, are hospitalised, and about 7% die (Barskey *et al.* 2020). There is no vaccine. For various reasons, it is likely underreported – even outbreaks may be missed – and up to 70,000 cases annually have been estimated in the United States (NASEM 2020; Spiegelman *et al.* 2020). It is the leading cause of reportable waterborne disease outbreaks in the United States associated with drinking water and its incidence has been rising over the last two decades (Barskey *et al.* 2022). The disease results from the exposure of a susceptible individual to a virulent strain of *Legionella* bacteria at an infective concentration in, most often, contaminated aerosols (NASEM 2020).

Legionella pneumophila, and more particularly *L. pneumophila* serogroup 1 (sg1), is associated with the majority of Legionnaires' disease cases in North America and Europe, but other serogroups and non-*pneumophila* species of *Legionella* can cause the disease (Yu *et al.* 2002; NASEM 2020). The dominance of *L. pneumophila* (and of sg1) may be an artefact of clinical diagnosis by the most commonly used urinary antigen test (UAT) kits, and recent advances in UAT kits may provide a diagnosis to a broader range of *Legionella* bacteria (Hamilton *et al.* 2018; Barskey *et al.* 2020; Kim *et al.* 2022).

Cooling towers

Aerosols are produced by building mechanical systems called 'cooling towers' – an imprecise but convenient shorthand used commonly in the literature for the various configurations of evaporative heat rejection or so called 'wet cooling' systems – which have been documented as sources of Legionnaires' disease cases from as far as 12 km away (Walser *et al.* 2014). Cooling towers were associated with 60% of Legionnaires' disease outbreak-associated deaths in a review over a decade (Hamilton *et al.* 2018). These building-scale mechanical systems are ubiquitous in (but not exclusive to) the urban environment. Bhopal *et al.* (1991) estimated that those living within 0.5 km of a cooling tower have a relative risk of *Legionella* infection over three times that of those living >1 km away, and Ricketts *et al.* (2012) estimated that 19.6% of non-outbreak, community-acquired cases may be associated with residential proximity to a cooling tower.

Legionella grows in building water systems that are not well maintained (Garrison *et al.* 2016). The general understanding that controlling *Legionella* at the building scale is an effective prevention strategy has catalysed the development of regulations, standards and guidance for mechanical systems such as cooling towers. A key recommendation of the NASEM (2020) consensus study report is the mandatory registration of cooling towers and regular monitoring of these systems for *Legionella*.

The fatal 2018 Legionnaires' disease outbreak in the City of Surrey, Canada (neighbouring the City of Vancouver) was associated with a cooling tower, but the public health response was hampered by the non-existence of a cooling tower registry (McCabe 2020). Similarly, when in 2020, the City of New Westminster, Canada (also neighbouring the City of Vancouver) recorded cases of Legionnaires' disease, no cooling tower registry was available to assist the same local health authority's investigation (personal communication). A number of European and North American jurisdictions have instituted mandatory cooling tower registries after an outbreak (Ricketts *et al.* 2008). Indeed, lamenting the absence of a cooling tower registry is a consistent theme of post-mortem outbreak reports (Walser *et al.* 2014; Paschke *et al.* 2019; Wüthrich *et al.* 2019); for jurisdictions with authority, a template for a cooling tower registry is available (USDN 2020).

City of Vancouver regulations

In the City of Vancouver, Canada, operating permits are compulsory for cooling towers, which are defined by the regulations (see 'Methods'). Operating permits are renewable annually and serve as a registry of cooling towers (http://www.vancouver.ca/operating-permit). Additionally, as a public health protection measure, the City implemented on 1 January 2021, an *L. pneumophila* standard of <10 CFU/mL in cooling towers (Vancouver Plumbing By-law 2019). This follows the Province of Quebec, Canada, which after a lethal cooling tower outbreak in 2012, adopted a province-wide registry and an *L. pneumophila* standard of <10 CFU/mL for cooling towers, verified by monthly culture-based testing (Racine *et al.* 2019). Similarly, Public Services and Procurement Canada (PSPC), an arm of the federal government, established an *L. pneumophila* standard of <10 CFU/mL for its nationwide portfolio of cooling towers, seven of which are in Vancouver, with water samples analysed monthly by a culture-based method to verify compliance (MD 15161-2013; NASEM 2020).

The <10 CFU/mL *L. pneumophila* standard is consistent with the NASEM (2020) report which recommended that, to prevent an outbreak, swift remediation should be initiated with a *Legionella* spp. concentration of 50 CFU/mL or more. The report advised that a lower 'action level' may be desirable for higher-risk populations, such as hospital patients (NASEM 2020). Indeed, in a review of 19 legionellosis outbreaks in a dozen countries, Walser *et al.* (2014) noted an *L. pneumophila* concentration of as low as 2 CFU/mL in an air scrubber associated with cases 10 km away.

In Vancouver, the <10 CFU/mL *L. pneumophila* standard is concordant with the detection limits of local commercial laboratories (see 'Methods'). Cooling tower results of 10 CFU/mL or more are termed 'exceedances.' With culture-based methods, the warning of Lucas *et al.* (2011) merits repetition: Environmental laboratories are likely to underestimate the actual level of contamination. Nevertheless, culture-based testing (ISO 11731 method), despite its limitations, was selected over molecular-based methods in Vancouver for compliance verification. Llewellyn *et al.* (2017) found that 84% of the cooling towers they sampled across the United States were PCR-positive for *Legionella* spp., and, unable to correlate DNA presence with the ability to culture the bacteria, concluded that DNA presence alone may not be an accurate gauge of the effectiveness of a cooling tower maintenance program.

It is acknowledged that *Legionella* spp. rather than solely *L. pneumophila* could be better suited for a cooling tower standard: Non-*pneumophila* species of *Legionella* can also be pathogenic (Yu *et al.* 2002; NASEM 2020), and Llewellyn *et al.* (2017) cautioned that 'the risk of concurrent or future growth of [*L. pneumophila* sg1] should be considered high' if a non-*pneumophila* species of *Legionella* is isolated from a cooling tower. The City of Vancouver chose to harmonise with the <10 CFU/mL *L. pneumophila* standard established by the Province of Quebec and PSPC – an important co-benefit of which has been to preclude a regulatory patchwork in Canada for building owners and managers – with a phased implementation. In 2021, cooling towers in Vancouver were required to provide one *L. pneumophila* culture-based test result during the calendar year. Starting 1 January 2022, the cooling tower reporting frequency increased to once per calendar month of operation (Vancouver Plumbing By-law 2019). This article presents the 1 January–31 December 2021 dataset.

Water source

Cooling towers in the City of Vancouver, as in other jurisdictions, typically use municipally supplied potable water (though alternative sources may also be exploited, such as on-site groundwater, storm water, adjoining surface water or even reclaimed wastewater, though the latter source is prohibited in the City of Vancouver). Metro Vancouver supplies the City of Vancouver with treated surface water from protected watersheds and chlorinates for distribution. The City of Vancouver's municipal water distribution system comprises eight water pressure zones, and water can only flow between zones by passing through pressure-regulating valves. Water samples are taken weekly or every 2 weeks from the City of Vancouver's network of sampling stations for various field measurements and laboratory analyses.

In the present study, for those cooling towers which used municipal drinking water and reported *L. pneumophila* ≥10 CFU/mL, conventional distribution system water quality parameters – *Escherichia coli* and total coliform concentrations, free chlorine residual level, temperature, pH, turbidity and conductivity – were examined for the 3 months preceding each cooling tower exceedance, for possible correlations with the cooling tower *L. pneumophila* concentration.

Overall, the city-wide *L. pneumophila* surveillance data shared in this article are intended to facilitate insights into cooling tower operations and maintenance practices in the context of water supply and the potential public health implications. It is hoped that the City of Vancouver's transparency with these data is of assistance to other jurisdictions and researchers.

METHODS

'Cooling tower' definition

The City's regulatory definition of a 'cooling tower' is 'a direct (open circuit) cooling tower, indirect (closed circuit) cooling tower, evaporative condenser, adiabatic cooler which recirculates non-evaporated water or fluid cooler that is part of a recirculated water system incorporated into a building's cooling, industrial process, refrigeration or energy production system, and may comprise one or more cooling tower cells' (Vancouver Plumbing By-law 2019). The origin of this definition is The Rules of the City of New York (Title 24, Chapter 8).

Cooling tower data

Operating permit holders were responsible for sampling, arranging analysis with a commercial laboratory, and reporting their cooling tower *L. pneumophila* results online to the City of Vancouver. The regulations require that the commercial laboratory be accredited to ISO/IEC 17025, use the ISO 11731 culture-based method to quantify *L. pneumophila* (all serogroups), participate in a bi-annual external proficiency testing program such as CDC ELITE and agree to inform immediately the City of Vancouver and Medical Health Officer of any *L. pneumophila* result >1,000 CFU/mL (Vancouver Plumbing By-law 2019). When *L. pneumophila* was detected, most of the laboratories enumerated its serogroups and 'other *Legionella* species,' though this was not required by the regulations. The data are reproduced in Table 1 as they were presented in the laboratory reports. The commercial laboratories were coded and their self-reported method detection limits (MDL) for *Legionella* are as follows: L1 (10 CFU/mL); L2 (1 or 10 CFU/mL); L3 ('typical MDL = 0.04 CFU/mL'); L4 (10 CFU/mL); L5 (1 or 5 CFU/mL) and L6 (5 CFU/mL). *L. pneumophila* data in this article were current with the City's database as of 25 April 2022.

Permit holders entered their *L. pneumophila* sample date and result and uploaded their laboratory report via the City's permitting portal (Computronix POSSE Land Management System v7.4.0). More than half of the online entries for 2021 were audited by City staff. Errors were corrected by City staff; the most common was the entry of the laboratory report date instead of the sample date (a difference of 2–5 weeks). Much rarer was the entry of an *L. pneumophila* result without a corresponding laboratory report, and this was consistently for a 'not detected' result. In such cases, the entry was deleted by City staff if the permit holder could not supply the laboratory report. All *L. pneumophila* reports of 10 CFU/mL or greater were assigned to a Plumbing Inspector who, typically in collaboration with the local health authority, conducted one or more site inspections and followed up with the permit holder on the prescribed corrective actions (Vancouver Plumbing By-law 2019), sometimes into the 2022 calendar year.

Table 1 | Cooling towers with *Legionella pneumophila* exceedances in 2021

Facility occupancy	Cooling tower index	Sample date (2021)	*L. pneumophila* Result (CFU/mL)	*L. pneumophila* Serogroup	Non-*pneumophila Legionella* species (CFU/mL)	Lab ID	Free chlorine residual (mg/L)	Turbidity (NTU)	Temperature (°C)	pH (Note 3)	n	Water main distance (m)	Station ID [Zone]
		Cooling tower *Legionella* spp. data (Note 1)					Municipal water sampling station data (Note 2)						
							Median and [range]						
Hospitals													
Hospital A Campus	C01a	Oct 21	**750**	sg1	150	L4	0.62 [0.54–0.65]	0.23 [0.13–0.34]	16.3 [11.3–18.0]	8.2 [8.2–8.3]	7	500	34 [499]
		Dec 13	ND	–	ND	L4							
	C01b	Oct 21	**880**	sg1	20	L4	0.62 [0.54–0.65]	0.23 [0.13–0.34]	16.3 [11.3–18.0]	8.2 [8.2–8.3]	7	500	34 [499]
		Dec 16	ND	–	ND	L1							
	C01c	Oct 21	**30**	sg1	50	L4	0.62 [0.54–0.65]	0.23 [0.13–0.34]	16.3 [11.3–18.0]	8.2 [8.2–8.3]	7	50	34 [499]
	C01d	Oct 21	**30**	sg2-15	ND	L4	0.62 [0.54–0.65]	0.23 [0.13–0.34]	16.3 [11.3–18.0]	8.2 [8.2–8.3]	7	700	34 [499]
		Dec 13	ND	–	ND	L4							
	C01e	Oct 21	**180**	170 CFU/mL sg1 + 10 CFU/mL unidentified sg (Note 4)	ND	L4	0.62 [0.54–0.65]	0.23 [0.13–0.34]	16.3 [11.3–18.0]	8.2 [8.2–8.3]	7	700	34 [499]
		Dec 13	**60**	sg1	ND	L4	0.58 [0.54–0.65]	0.21 [0.14–0.24]	10.8 [8.6–15.9]	8.3 [8.2–8.4]	6	700	34 [499]
	C01f	Oct 21	**600**	sg1	ND	L4	0.62 [0.54–0.65]	0.23 [0.13–0.34]	16.3 [11.3–18.0]	8.2 [8.2–8.3]	7	700	34 [499]
		Dec 13	ND	–	ND	L4							
	C01g	Dec 13	**70**	sg1	ND	L4	0.58 [0.54–0.65]	0.21 [0.14–0.24]	10.8 [8.6–15.9]	8.3 [8.2–8.4]	6	700	34 [499]
Hospital B Campus	C02a	Dec 15	**230**	220 CFU/mL sg1 + 10 CFU/mL sg2-15	ND	L4	0.73 [0.65–0.83]	0.21 [0.12–0.24]	9.3 [7.3–14.5]	8.3 [8.3–8.4]	7	500	15 [407]
	C02b	Dec 15	**180**	sg1 (Note 5)	ND	L4	0.73 [0.65–0.83]	0.21 [0.12–0.24]	9.3 [7.3–14.5]	8.3 [8.3–8.4]	7	500	15 [407]
		Dec 22	**70**	No sg analysis	ND	L1	0.73 [0.65–0.83]	0.21 [0.12–0.24]	9.3 [7.3–14.5]	8.3 [8.3–8.4]	7	500	15 [407]
	C02c	Dec 15	**180**	sg1 (Note 5)	ND	L4	0.73 [0.65–0.83]	0.21 [0.12–0.24]	9.3 [7.3–14.5]	8.3 [8.3–8.4]	7	500	15 [407]
		Dec 22	**10**	No sg analysis	ND	L1	0.73 [0.65–0.83]	0.21 [0.12–0.24]	9.3 [7.3–14.5]	8.3 [8.3–8.4]	7	500	15 [407]
	C02d	Dec 22	**30**	No sg analysis	ND	L1	0.73 [0.65–0.83]	0.21 [0.12–0.24]	9.3 [7.3–14.5]	8.3 [8.3–8.4]	7	500	15 [407]
	C02e	Dec 22	**20**	No sg analysis	ND	L1	0.73 [0.65–0.83]	0.21 [0.12–0.24]	9.3 [7.3–14.5]	8.3 [8.3–8.4]	7	500	15 [407]
10 or fewer storeys (excluding hospitals)													
Commercial	C03	Apr 6	**1,875**	175 CFU/mL sg1 + 1,700 CFU/mL sg2-14	ND	L5	0.74 [0.63–0.89]	0.22 [0.10–0.67]	5.9 [4.0–6.7]	7.7 [7.6–7.8]	7	1,000	14 [407]
		Apr 19	1	sg2-14	ND	L5							
Commercial	C04	Apr 27	**15**	sg1	ND	L5	0.72 [0.71–0.81]	0.14 [0.09–0.19]	4.9 [3.9–9.9]	7.8 [7.7–7.8]	7	1,100	15 [407]
		Jun 10	ND	–	ND	L2							
Education	C05	May 4	**10**	sg1	ND	L6	0.70 [0.60–0.79]	0.16 [0.09–0.34]	5.4 [3.3–9.9]	7.8 [7.6–7.8]	12	1,000	38 [570]
		May 17	ND	–	ND	L6							
		Aug 17	ND	–	ND	L3							
Public Utility	C06	Jul 14	**200**	sg2-14	ND	L5	0.70 [0.60–0.74]	0.23 [0.08–1.21]	12.5 [9.1–15.2]	7.8 [7.8–8.4]	13	1,200	60 [407]
Commercial	C07	Jul 29	**>1,500**	sg5 and 'not sg1-6' (neither quantified)	ND	L6	0.72 [0.67–0.79]	0.29 [0.16–2.79] (Note 6)	12.3 [8.7–15.8]	7.8 [7.8–8.4]	9	800	30 [407]
		Aug 16	ND	–	ND	L6							

(*Continued*.)

Table 1 | Continued

		Cooling tower *Legionella* spp. data (Note 1)					Municipal water sampling station data (Note 2)						
			L. pneumophila				Free chlorine residual (mg/L)	Turbidity (NTU)	Temperature (°C)	pH (Note 3)			
Facility occupancy	Cooling tower index	Sample date (2021)	Result (CFU/mL)	Serogroup	Non-*pneumophila* *Legionella* species (CFU/mL)	Lab ID	Median and [range]				n	Water main distance (m)	Station ID [Zone]
Residential	C08	Aug 19	**51**	sg2-14	ND	L5	0.81 [0.68–0.90]	0.25 [0.09–0.35]	12.9 [12.3–17.0]	8.2 [7.8–8.4]	7	2,500	39 [570]
		Sep 9	3	sg2-14	ND	L5							
Industrial	C09a	May 11	**1,245**	sg2-14	ND	L5	0.69 [0.61–0.83]	0.16 [0.09–0.45]	6.9 [3.9–11.3]	7.7 [7.7–7.8]	6	1,400	1 [442]
		Jun 1	**60**	sg2-14	ND	L5	0.69 [0.68–0.83]	0.11 [0.09–0.45]	8.3 [6.7–12.9]	7.7 [7.7–7.8]	5	1,400	1 [442]
		Jun 16	ND	–	ND	L5							
	C09b	May 11	**36**	1 CFU/mL sg1 + 35 CFU/mL sg2-14	ND	L5	0.69 [0.61–0.83]	0.16 [0.09–0.45]	6.9 [3.9–11.3]	7.7 [7.7–7.8]	6	1,400	1 [442]
		Jun 1	ND	–	ND	L5							
Warehouse	C10	Aug 19	**10**	sg2-14	ND	L5	0.62 [0.46–0.80]	0.16 [0.09–0.42]	17.3 [12.9–19.3]	8.3 [7.8–8.5]	14	2,300	4 [442]
> 10 storeys (excluding hospitals)													
Mixed Use	C11a	Aug 17	**1,015**	sg1	ND	L6	0.72 [0.63–0.80]	0.23 [0.14–0.40]	16.0 [12.9–18.7]	8.2 [7.7–8.4]	7	600	14 [407]
		Sep 1	ND	–	ND	L6							
	C11b	Aug 17	**25**	sg1	ND	L6	0.72 [0.63–0.80]	0.23 [0.14–0.40]	16.0 [12.9–18.7]	8.2 [7.7–8.4]	7	600	14 [407]
		Sep 13	ND	–	ND	L6							
		Oct 7	4	sg1	ND	L5							
	C11c	Sep 13	**10**	sg1	ND	L6	0.71 [0.59–0.80]	0.23 [0.13–0.80]	17.5 [14.0–18.7]	8.3 [8.2–8.4]	7	600	14 [407]
		Oct 7	2	sg1	ND	L5							
Commercial	C12	Sep 14	**33**	sg1	81	L5	0.75 [0.60–0.78]	0.22 [0.13–0.62]	14.9 [12.8–16.9]	8.2 [8.1–8.3]	7	1,000	15 [407]
Mixed Use	C13	Sep 14	**>1,500**	sg5	ND	L6	0.75 [0.60–0.78]	0.22 [0.13–0.62]	14.9 [12.8–16.9]	8.2 [8.1–8.3]	7	1,600	15 [407]
		Oct 1	ND	–	ND	L6							
Residential	C14	Oct 18	**1,800**	sg2-14	ND	L5	0.75 [0.71–0.83]	0.23 [0.14–0.62]	15.7 [12.5–16.9]	8.2 [8.2–8.3]	6	800	15 [407]
		Nov 2	**75**	sg2-14	ND	L5	0.73 [0.69–0.83]	0.21 [0.14–0.62]	14.5 [9.3–16.9]	8.3 [8.2–8.3]	7	800	15 [407]
		Nov 29	ND	–	No analysis	L2							
Hotel	C15a	Oct 21	**25**	sg5	ND	L6	0.69 [0.59–0.80]	0.23 [0.13–0.80]	17.6 [12.3–18.7]	8.4 [8.2–8.4]	6	500	14 [407]
		Nov 9	ND	–	ND	L6							
	C15b	Oct 21	**120**	sg5	ND	L6	0.69 [0.59–0.80]	0.23 [0.13–0.80]	17.6 [12.3–18.7]	8.4 [8.2–8.4]	6	500	14 [407]
		Nov 9	ND	–	ND	L6							
Mixed Use	C16	Dec 7	**115**	sg5	ND	L6	0.66 [0.60–0.72]	0.28 [0.16–0.80]	11.3 [7.8–17.6]	8.3 [8.3–8.4]	7	900	14 [407]

Notes: 1: *Legionella* data were provided by operating permit holders. Cooling tower index is a coded reference for this article. Abbreviations: CFU/mL, colony-forming units per millilitre; ND, not detected; sg, serogroup; spp., species; Lab ID, laboratory identification. See 'Methods' for self-reported method detection limits.

2: Data are for the 3-month period preceding the *L. pneumophila* sample date. All municipal water samples (except as described in Note 6) were analysed for *Escherichia coli* and total coliforms, and neither parameter was detected in any of the samples ($n = 114$). Conductivity was measured in all water samples and was consistently $<50\ \mu S/cm$ ($n = 115$). The Station ID is the City of Vancouver municipal water quality sampling station identification number, and the corresponding municipal water pressure zone is listed. Abbreviations: NTU, nephelometric turbidity units; *n*, number of municipal water quality samples. Water main distance is ± 50 m; see 'Methods' for details.

3: Effective 7 June 2021, Metro Vancouver henceforth adjusted the pH of drinking water supplied to the City of Vancouver, up from approximately pH 7.7 to a target of 8.3–8.5, and doubled the alkalinity to approximately 20 mg/L as $CaCO_3$. (Notice of this water quality change was communicated to the public by Metro Vancouver, and further broadcast by the City of Vancouver to all cooling tower operating permit holders.).

4: For correlation analyses involving C01e *Legionella* data from 21 October 2021 the *L. pneumophila* result was treated as 180 CFU/mL. But with the ambiguity of 10 CFU/mL of an unidentified serogroup, the C01e *L. pneumophila* sg1 datum for this date was treated as 170 CFU/mL, and the 'non-serogroup 1' *L. pneumophila* datum for this date was excluded from analyses.

5: The 15 December 2021 sample for C02b and C02c was taken from a common line between the two cooling towers; the same laboratory report was provided by the permit holder for each cooling tower. As these results were not measured independently, the C02c *Legionella* data for 15 December 2021 were excluded from correlation analyses.

6: The City of Vancouver sampler documented on 9 June 2021, an unexpected turbidity of 2.79 NTU, and resampled 5 min later to confirm that this was not a sampling error. The sampler returned on 10 June 2021 and recorded a turbidity of 0.18 NTU. On 10 June 2021, laboratory samples for *E. coli* and total coliforms were not taken, so $n = 8$ for those two parameters.

Municipal water distribution system data

Water quality data are presented for the 3 months preceding the sample date of a cooling tower *L. pneumophila* exceedance, from the municipal water sampling station closest to the corresponding building and in the same municipal pressure zone. This time-frame was informed by the predictive modelling of Racine *et al.* (2019) who had tested cooling tower basin water quality data against subsequent cooling tower *L. pneumophila* concentrations. In the present study, the distance between a building and a water quality sampling station was estimated ($\pm$50 m) by tracing the shortest horizontal path along water mains between the sampling station and the service line, up to the point of building entry (http://maps.vancouver.ca). For buildings with multiple service lines, this distance was estimated for each service line, and the largest of these estimates is presented.

Water quality data from sampling stations were extracted on 14 April 2022 from the City of Vancouver database (Infor Hansen v11.2). Water samples were field tested by City staff for free chlorine, turbidity, conductivity and pH using a Hach Pocket Colorimeter II, based on the USEPA DPD Method; a Hach 2100Q Portable Turbidimeter, meeting EPA Method 180.1; a Thermo Scientific Orion Star A222 Conductivity Portable Meter; and a VWR sympHony H10P meter, respectively. The latter also provided water temperature data. Samples from the municipal water distribution system were also collected aseptically by City staff in bottles containing sodium thiosulphate and delivered to the Metro Vancouver Microbiology Laboratory (Burnaby, BC, Canada) for analysis by membrane filtration and Chromocult® Coliform Agar (Austin 2020), with a detection limit of 1 CFU/mL for each of *Escherichia coli* and total coliforms. The City of Vancouver does not monitor for *L. pneumophila* in the distribution system. Available in the Supplementary Data are sampling station field measurements of total chlorine and heterotrophic plate count results for samples processed by the Metro Vancouver Microbiology Laboratory.

Correlation analyses

For statistical analyses, the dataset comprised each reported cooling tower exceedance in 2021 (Table 1). Spearman's rank-order correlation coefficient was used to evaluate the relationship between variables (two-tailed), with a significance level of 0.005 (IBM SPSS v29.0.0.0). This significance level is more rigorous than the conventional alpha of 0.05 and was selected to reduce false-positive results, acknowledging the increased potential of false-negative results (Miller & Ulrich 2019). For the *Legionella* data used in these analyses, 'not detected' reports were assigned a value of 0 CFU/mL, and the 'greater than' symbol was ignored (for example, >1,500 CFU/mL was treated as 1,500 CFU/mL). Notes 4 and 5 to Table 1 provide additional information on data preparation.

RESULTS

In 2021, of the 607 operating permits issued for cooling towers in the City of Vancouver, 557 provided at least one *L. pneumophila* laboratory report during the calendar year and 15 were not required to supply a report (because the cooling tower was not operational or not subject to the City's regulations), for an overall 94% compliance (557/592) with the sampling requirement. (Of the 35 operating permits which failed to meet this regulatory obligation, 24 provided an *L. pneumophila* report in early 2022, of which two cooling towers reported exceedances (data not shown).)

Some permit holders submitted more than one *L. pneumophila* report in 2021, such that Figure 1 summarises 787 reports for 557 cooling towers. For example, PSPC – a department of the federal government which is participating voluntarily in the operating permit program – uploaded multiple *L. pneumophila* reports for each of its seven cooling towers (none of which was in exceedance) throughout the calendar year, owing to their building water management program which prescribes regular sampling to validate maintenance practices.

Cooling tower reports

L. pneumophila results of $\geq$10 CFU/mL were reported in 2021 for 30 cooling towers (5.4%), of which six measured >1,000 CFU/mL. While more research is needed to correlate infection risk with measured *Legionella* concentrations and other factors in cooling towers, higher *Legionella* concentrations are associated with higher disease risk (NASEM 2020). All of the cooling towers in exceedance were on rooftops. For the City of Vancouver in 2021, there were no reported Legionnaires' disease outbreaks, and data on non-outbreak cases are unavailable.

With an exceedance, the City's regulations require another *L. pneumophila* sample after corrective actions (Vancouver Plumbing By-law 2019). The 30 cooling towers in exceedance are indexed in Table 1 to facilitate referencing in this article;

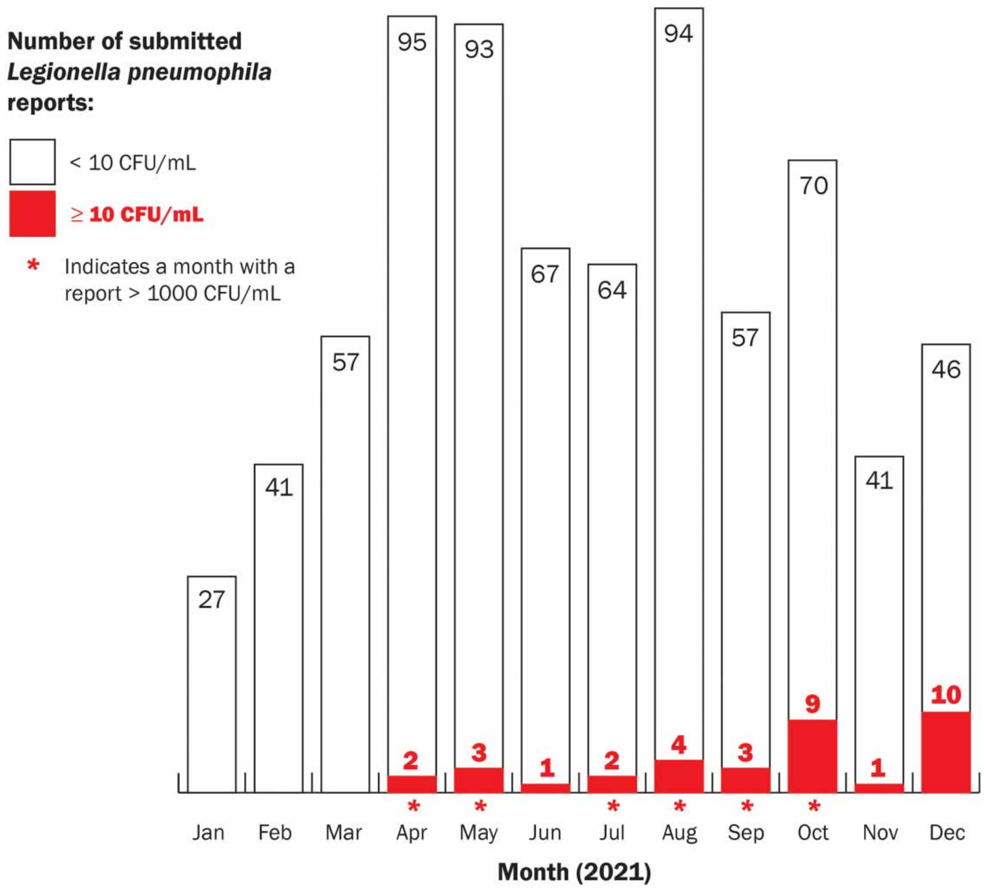

Figure 1 | Distribution of the 787 *Legionella pneumophila* laboratory reports (culture-based method) submitted for 557 cooling towers in the City of Vancouver, Canada during 2021, as a stacked bar chart (for example, in December, 56 reports were received). At least one *L. pneumophila* report was required during the 2021 calendar year for each cooling tower, and some permit holders submitted more than one report for a cooling tower. 30 cooling towers reported ≥10 CFU/mL, and five of these submitted two reports each of ≥10 CFU/mL. Six of the 30 cooling towers reported >1,000 CFU/mL (CFU/mL, colony-forming units per millilitre).

for five of these cooling towers (C01e, C02b, C02c, C09a, C14), a follow-up sample taken in 2021 after cleaning and disinfection was also ≥10 CFU/mL, giving a total of 35 reports of ≥10 CFU/mL in 2021 (Figure 1).

Follow-up samples were taken in 2021 for 21 of the 30 cooling towers which reported an *L. pneumophila* result of 10 CFU/mL or greater; the other 9 failed to resample in 2021, in some cases because the exceedance had been in late 2021 and the corrective actions were in progress at year's end (Table 1). Of the 21 which submitted a 2021 follow-up report, 16 met the City of Vancouver standard of <10 CFU/mL of *L. pneumophila*. Five were again in exceedance (noted above), but each with a lower *L. pneumophila* concentration than the initial report, prompting another round of corrective actions, including the retesting requirement. Two of these five were resampled in 2021 and met the City of Vancouver standard (C09a, C14); the other three (at the two hospitals) were expected to be retested in the new year.

Legionella population composition

L. pneumophila serogroups were enumerated in the laboratory reports for 28 of the 30 cooling towers with exceedances (Table 1). Of these 28, 17 cooling towers (61%) contained *L. pneumophila* serogroup 1 (sg1). This was intermingled with another serogroup (described collectively herein as 'non-serogroup 1' *L. pneumophila*) in only three, unambiguous cases (C02a, C03, C09b; C01e had an unidentified serogroup, which may or may not have been sg1) and with non-*pneumophila* species of *Legionella* in four other cooling towers (C01a, C01b, C01c and C12). Non-*pneumophila* species of *Legionella* were not detected when a cooling tower in exceedance contained 'non-serogroup 1' *L. pneumophila*.

There was a negative correlation between the concentrations of *L. pneumophila* sg1 and 'non-serogroup 1' *L. pneumophila*, and this was statistically significant ($r_s = -0.708$, $p < 0.001$, $n = 29$). There was not a statistically significant correlation between the concentrations of non-*pneumophila* species of *Legionella* and *L. pneumophila* ($r_s = 0.065$, $p = 0.716$, $n = 34$). When the latter was considered based on serogroup, the analyses were suggestive of associations, but with $\alpha = 0.005$, there was not a statistically significant correlation between the concentrations of non-*pneumophila* species of *Legionella* and either *L. pneumophila* sg1 ($r_s = 0.400$, $p = 0.029$, $n = 30$) or 'non-serogroup 1' *L. pneumophila* ($r_s = -0.400$, $p = 0.032$, $n = 29$). A caveat to these conclusions is their limitation to cooling towers containing at least 10 CFU/mL of *L. pneumophila*. Importantly, since the City of Vancouver cooling tower standard is based on *L. pneumophila*, a cooling tower containing non-*pneumophila* species of *Legionella* in the absence of *L. pneumophila* would not have been reported as an exceedance and would therefore not have been included in the correlation analyses.

Distribution of exceedances

The vast majority (94.6%) of reporting cooling towers met the <10 CFU/mL *L. pneumophila* standard, and a clear pattern emerged of highly localised, building-scale *Legionella* issues. The 30 cooling towers reporting exceedances were concentrated within 16 facilities – including two hospital campuses which together housed 12 of the cooling towers reporting exceedances. The other 14 facilities were diverse in both built form and occupancy classification and included a hotel, an industrial facility, a public utility, a warehouse and a variety of multi-storey commercial, residential and mixed-use buildings (Table 1). Taken together, the 16 facilities were dispersed geographically, encompassed by a circle with a 5 km radius and located within eight of the City's 22 local planning areas.

All of the cooling towers with exceedances used municipal water, and the associated 16 facilities were located in four of the City's eight water pressure zones (Table 1). Pressure zone 407 includes the entire downtown peninsula and hosts the majority of cooling towers in the City. In pressure zone 570, two cooling towers (C05, C08) reported exceedances, in buildings 2.3 km apart – and each recovered different *L. pneumophila* serogroups. Within pressure zone 442, three cooling towers reported exceedances, with two (C09a, C09b) co-located at an industrial facility 3.3 km away from a warehouse hosting the third cooling tower (C10). In pressure zone 499, exceedances were isolated to just one facility, Hospital A, accounting for nearly one-quarter of all exceedances in 2021. City-wide, there were only four cooling towers with exceedances that also reported non-*pneumophila* species of *Legionella*: Three of these were co-located at Hospital A, and the fourth cooling tower (C12) was in a commercial building 2.8 km away – and in a different municipal water pressure zone.

Municipal water quality

All of the municipal water quality results were compliant with applicable drinking water standards. During the 3 months preceding each of the reported *L. pneumophila* cooling tower exceedances, in the municipal water supplied to each of the corresponding 16 facilities: (1) neither *Escherichia coli* nor total coliforms were detected in any sample; (2) the free chlorine residual was ≥0.46 mg/L (and ≥0.54 mg/L for the two hospitals); (3) the water temperature was <20 °C; (4) the pH was 7.6–8.5; (5) the conductivity was <50 μS/cm; and (6) the turbidity was ≤0.71 NTU (and ≤0.34 NTU in the water used by the two hospitals), with three exceptions. On June 9, a turbidity of 2.79 NTU was measured at the municipal water sampling station nearest to C07, dropping to 0.18 NTU the next day; on June 24, a turbidity of 1.21 NTU was measured at the sampling station closest to C06, declining to 0.81 NTU when the next sample was taken a week later, and then to 0.31 NTU a week after that (Table 1). It is unknown what caused these temporary turbidity increases, but the free chlorine residual in the municipal water was ≥0.67 mg/L and ≥0.60 mg/L, respectively, during the 3 months preceding each cooling tower exceedance (Table 1).

No statistically significant correlation was found between the cooling tower concentration of *L. pneumophila* and any of the following municipal water quality parameters over the 3 months preceding each cooling tower exceedance: free chlorine residual (median or minimum), turbidity (median or maximum), temperature (median or maximum), pH (median) or conductivity (median or maximum) (Table 2). Considering *L. pneumophila* based on serogroup 1 and testing these parameters, there were two statistically significant associations: a negative correlation between turbidity (maximum) and *L. pneumophila* sg1 ($r_s = -0.602$, $p < 0.001$, $n = 30$) and a positive correlation between turbidity (maximum) and 'non-serogroup 1' *L. pneumophila* ($r_s = 0.669$, $p < 0.001$, $n = 29$). A statistically significant correlation was not found between the cooling tower concentration of non-*pneumophila* species of *Legionella* and any of the aforementioned municipal water quality parameters (Table 2).

Table 2 | Correlation analyses for municipal water quality parameters and microbial concentrations in cooling towers

Spearman's rank-order correlation coefficient (*p* value) (Note 1)

Measured municipal water quality parameter (Note 2)		Measured microbial concentration in cooling towers with exceedances (Note 3): *L. pneumophila* ($n = 34$)	*L. pneumophila* sg1 ($n = 30$)	'Non-serogroup 1' *L. pneumophila* ($n = 29$)	Non-*pneumophila Legionella* species ($n = 34$)
Free chlorine residual	Median	0.096 (0.587)	−0.180 (0.342)	0.358 (0.056)	−0.181 (0.307)
	Minimum	0.075 (0.675)	−0.241 (0.200)	0.394 (0.034)	−0.359 (0.037)
Turbidity	Median	0.323 (0.062)	−0.037 (0.848)	0.131 (0.498)	0.210 (0.233)
	Maximum	0.287 (0.099)	− **0.602** (<**0.001**)	**0.669** (<**0.001**)	−0.048 (0.786)
Temperature	Median	0.010 (0.954)	−0.017 (0.930)	−0.155 (0.422)	0.306 (0.078)
	Maximum	−0.058 (0.745)	0.021 (0.911)	−0.255 (0.182)	0.232 (0.187)
pH	Median	−0.230 (0.190)	0.010 (0.960)	−0.178 (0.356)	−0.056 (0.751)
Conductivity	Median	−0.072 (0.684)	0.018 (0.924)	−0.228 (0.234)	0.179 (0.310)
	Maximum	−0.051 (0.773)	−0.162 (0.394)	−0.009 (0.965)	0.062 (0.727)

Notes: 1: Table values shown are the Spearman's rank-order correlation coefficient r_s followed in parentheses by the *p* value. Results are from two-tailed analysis; statistically significant results ($\alpha = 0.005$) are bolded and underlined.

2: Data are for the 3-month period preceding each reported cooling tower exceedance, from the municipal water sampling station closest to the corresponding building. *Escherichia coli* and total coliforms are absent from this table as they were consistently undetected in municipal water samples.

3: A cooling tower in exceedance signifies a cooling tower reporting ≥10 CFU/mL *Legionella pneumophila*. See Table 1.

DISCUSSION

There were no reported Legionnaires' disease outbreaks in the City of Vancouver in 2021, but just as alluded to by Spiegelman *et al.* (2020) in the context of the City of Toronto, Canada, not all cases of pneumonia in the City of Vancouver are subject to urinary antigen and *Legionella* culture-based testing – especially in 2021, in the midst of widespread respiratory illness caused by the coronavirus SARS-CoV-2.

Nonetheless, that two hospitals had systemic cooling tower *L. pneumophila* issues – identifying up to 880 CFU/mL of serogroup 1 (sg1) – was concerning (Table 1). Seven registered cooling towers at Hospital A and five at Hospital B were in exceedance, accounting for 40% of exceedances in the City in 2021. All of these cooling towers underwent cleaning and disinfection. Follow-up samples were provided for seven of these cooling towers in 2021, and in three instances, there was again an *L. pneumophila* exceedance, of 10–70 CFU/mL (C01e, C02b, C02c, Table 1). Through 2022, the cooling towers at Hospitals A and B will be followed closely by inspectors.

The most lethal Legionnaires' disease outbreak in Canadian history was in the City of Toronto in the fall of 2005, with a cooling tower at a long-term care home implicated in 23 deaths (Walker *et al.* 2005). Reviewing 19 cooling tower outbreaks in 12 countries (of which the Toronto 2005 outbreak was one), Walser *et al.* (2014) concluded that an avoidable public health risk is *Legionella*-contaminated cooling towers in proximity to medical care facilities: The authors described an outbreak fatality rate averaging 6.3%, but in the two medical facility outbreaks reviewed, the rate was about 4.5 times higher than this average. Indeed, summarising 27 Legionnaires' disease outbreak field investigations, Garrison *et al.* (2016) noted that all of the outbreaks were caused by *L. pneumophila* sg1 and that 85% of deaths were healthcare associated.

Of the Legionnaires' disease cases in 2016–2017 in the United States, Barskey *et al.* (2020) found that 20–21% resulted from healthcare exposure and 15–16% were associated with travel accommodations. To the latter, there are 74 hotels in the City of Vancouver (as of April 2022, and not all have cooling towers). Only one hotel, representing approximately 1% of total hotel rooms, reported exceedances in 2021, for both of its cooling towers, and follow-up samples after cleaning and disinfection did not detect *L. pneumophila* (C15a, C15b, Table 1).

Surveillance surveys

Overall, 5.4% of cooling towers reporting *L. pneumophila* ≥10 CFU/mL was on the lower end when compared – imperfectly, due to differing contexts, such as climate – to other surveillance datasets derived from a culture-based test. Representing the lower end of the expected range is PSPC, with its well-established, robust *Legionella* prevention program. For the nationwide PSPC portfolio, 10 of its approximately 200 cooling towers 'required unscheduled cleaning and disinfection' in 2018, presumably because testing revealed ≥10 CFU/mL of *L. pneumophila* (NASEM 2020). Another domestic dataset is from a water treatment company servicing cooling towers in the Province of Quebec. *L. pneumophila* results of ≥10 CFU/mL were reported (on a quarterly basis) in 11–14% of 323 cooling towers in 2015, and in 8–12% in 2016; presumably, had this dataset also incorporated cooling towers without professional water management, the percentages would have been higher (Racine *et al.* 2019). Internationally, Mouchtouri *et al.* (2010) reported that 23% of 96 cooling towers tested in Greece 'required remedial action,' either because *Legionella* spp. was ≥10 CFU/mL or the 'aerobic count' was >100,000 CFU/mL. The results of the present study are for *L. pneumophila*, which is of course a subset of *Legionella* spp., so a comparison is inexact. Similarly, Hong Kong reported that 24% of water samples from cooling towers in 2021 had *Legionella* spp. ≥10 CFU/mL and 2.4% had >1,000 CFU/mL ($n = 875$, EMSD 2022). These samples were collected by inspectors and it is unlikely that the cooling towers were selected on a random basis; conversely, Vancouver's samples were collected city-wide by permit holders and self-reported, so a comparison is once again approximate. Lastly, and cited for completeness, cooling tower *L. pneumophila* surveys have been conducted using other enumeration methods, but such results cannot be assumed to be comparable to those derived from a culture-based method. For example, with a direct fluorescent antibody method, Gilpin & Gilpin (2014) surveyed 472 cooling towers across the United States over a 4-year period, with some cooling towers sampled repeatedly. Of the 1,336 samples acquired, 54% had *L. pneumophila* counts ≥10/mL and 3.1% had counts >1,000/mL (Gilpin & Gilpin 2014).

With the aim of characterising cooling tower microbial communities, Llewellyn *et al.* (2017) surveyed 196 cooling towers located in multiple U.S. climate regions using PCR as a screening tool and then a culture-based method. Llewellyn *et al.* (2017) reported that when *L. pneumophila* sg1 was recovered, 72% of samples also contained another *L. pneumophila* serogroup or non-*pneumophila* species of *Legionella*. In comparison, this was true for less than half of the samples in the present study (with a sample set limited to cooling towers from one climate region, with *L. pneumophila* ≥10 CFU/mL and for which serogroup-level analysis was available). Additionally, the present study identified a negative correlation between the concentrations of *L. pneumophila* sg1 and 'non-serogroup 1' *L. pneumophila* in cooling towers, hinting at a potentially competitive relationship. This proposition has a basis in laboratory research: Levin *et al.* (2019) discovered that *L. pneumophila* can antagonise the growth of *Legionella* bacteria – including other *L. pneumophila* – through secretion of an inhibitor called homogentisic acid (HGA). Levin *et al.* (2019) found that 'high-density, established' *L. pneumophila* communities were resistant to HGA and postulated that HGA was deployed 'to protect against low-density, invading *Legionella* competitors' in the contest for an ecological niche. Outside of the laboratory, Wéry *et al.* (2008) demonstrated from a study of a facility's cooling towers that *L. pneumophila* proliferation was associated with a decrease in the concentration (and diversity) of non-*pneumophila* species of *Legionella* (a correlation that was not statistically significant in the present study across cooling towers reporting exceedances). The speculation of Wéry *et al.* (2008), predating the HGA discovery, was that this might have been due to an antagonistic relationship, divergent temperature growth ranges or differences in amoebal hosts. Such 'active' or 'passive' competition (Bauer *et al.* 2018) could also be the basis for the results of the present study. This is explored further, below.

Water source

Overall, that 94.6% of cooling towers in the City of Vancouver did not contain *L. pneumophila* ≥10 CFU/mL in 2021 may suggest a general proficiency of building owners and managers in operating and maintaining their mechanical equipment. However, to assert this necessitates more than a single water sample from each cooling tower and demands acknowledgement that *L. pneumophila* concentrations can fluctuate – sometimes rapidly – with weather conditions and operational decisions (Bentham & Broadbent 1993; Wéry *et al.* 2008; Gilpin & Gilpin 2014; Llewellyn *et al.* 2017; Racine *et al.* 2019). It is noteworthy that through the policy development process culminating in the City of Vancouver's *Legionella* prevention regulations, the local tourism industry and the local association of building owners and managers were supportive, hosting educational seminars for their members and writing to City Council in favour of the measures (which were passed unanimously by City Council).

The low number of exceedances in 2021 may also be attributable partly to the high quality of municipal water that supplied nearly all of the City's registered cooling towers. Illustrative of an extreme is the 2014–2015 Legionnaires' disease outbreak in the City of Flint, Michigan contemporaneous with changes to the municipal water supply. Nevertheless, Smith *et al.* (2019) noted that while the Flint water distribution system could have fostered *Legionella* growth with its low chlorine and high iron content, residential proximity to only certain cooling towers – but not to others – was associated with some of the Legionnaires' disease cases, and for this and other reasons concluded that a key barrier to outbreaks is building-scale design and maintenance of water systems.

This being said, maintaining a minimum disinfectant residual in municipal drinking water systems is recommended so that the best water quality is delivered to buildings (NASEM 2020). The City of Vancouver and the local health authority have agreed that a minimum free chlorine residual of 0.2 mg/L in the municipal potable water is to be delivered to the property line (but this is not formally established as a system permit condition). This is a defensive measure intended to eliminate any faecal pathogen contamination downstream of the treatment plant and to forestall opportunistic pathogen growth. In the City of Vancouver in 2021, there was a free chlorine residual of $\geq$0.46 mg/L in the municipal water serving each of the cooling towers reporting an exceedance; moreover, for the six cooling towers reporting *L. pneumophila* >1,000 CFU/mL, the free chlorine residual in the municipal water was even higher, at $\geq$0.60 mg/L. These levels surpass the recommendation of LeChevallier (2019) for a minimum free chlorine residual of 0.1 mg/L in municipal distribution systems. LeChevallier (2019) had conducted surveillance exercises with several American water utilities and detected *L. pneumophila* in distribution systems only when water temperature exceeded 18 °C; furthermore, in positive samples, *L. pneumophila* was consistently <0.1 MPN/mL except when the free chlorine residual was <0.1 mg/L.

NASEM (2020) also suggests regular monitoring of *L. pneumophila* in municipal distribution systems, 'triggered once water temperatures consistently exceed 20 °C.' This condition was not met: For the 3 months preceding each cooling tower exceedance, the municipal water temperature never exceeded 20 °C. In fact, the highest measured temperature was 19.3 °C, and this municipal water, at pH 8.4, still had a robust 0.56 mg/L free chlorine residual. For reference, illustrating the susceptibility of *L. pneumophila* to free chlorine inactivation, Buse *et al.* (2019) reported a Chick–Watson *Ct* value of 0.3 min·mg/L for 99.99% (4-$\log_{10}$) reduction of *L. pneumophila* by free chlorine at pH 8 and 21 °C.

No statistically significant correlations were found between cooling tower *Legionella* populations and conventional municipal water quality parameters measured in the 3 months preceding cooling tower exceedances, with the exception of turbidity. For cooling towers reporting exceedances, as the maximum measured turbidity increased in municipal water (range: 0.19–2.79 NTU), *L. pneumophila* serogroups exhibited divergent tendencies: *L. pneumophila* sg1 levels tended to decrease while 'non-serogroup 1' *L. pneumophila* concentrations tended to increase, and overall *L. pneumophila* concentration appeared to be uncorrelated. If these associations are not due to chance or an artefact, they of course do not imply causation; understanding what the relationship might be would be of public health interest, as *L. pneumophila* sg1 has been shown to be overwhelmingly dominant in culture-confirmed legionellosis (Yu *et al.* 2002). There is furthermore a general implication for studies on *L. pneumophila*: aggregating its serogroups may mask real differences (in the present study, laboratory reports did not facilitate the resolution of individual serogroups within the aggregate 'non-serogroup 1' *L. pneumophila*). *L. pneumophila* serogroups are defined by the architecture of lipopolysaccharide (LPS) associated with the outer leaflet of the bacteria's outer membrane (Shevchuk *et al.* 2011) and these serogroups may interact differentially with the environment. For example, Buse *et al.* (2018) observed a wide range in surface charge amongst *L. pneumophila* serogroups, with LPS diversity likely contributing to this; the researchers noted that surface charge impacts mobility, surface adherence and disinfectant resistance, and the variability observed may affect survival and ecological distribution. In another study, Buse *et al.* (2022) reported differences in *L. pneumophila* sg1, sg4 and sg6 inactivation by UV-C light-emitting diodes and cited the importance of understanding outer membrane properties. From the present study, one could conjecture that within the context of a potentially competitive relationship in cooling towers between *L. pneumophila* sg1 and other *L. pneumophila* serogroups, the long-term competitive outcome might be affected by a selective pressure (Bauer *et al.* 2018) exerted by unidentified suspended solids on the outer membrane, disadvantaging *L. pneumophila* sg1. Further investigation is warranted.

Building-specific factors

The cooling tower exceedances observed in the City of Vancouver in 2021 are most likely attributable to the building-specific design, maintenance and/or operational factors. Logan-Jackson & Rose (2022) concluded that 'water management in the building is the most critical factor that contributes to the growth of *Legionella* species.' Various studies have shown associations between *L. pneumophila* colonisation and growth in cooling towers and building-specific factors such as a cooling tower's exposure to sunshine, age and permanently-wet surface area-to-volume ratio; operator training; the existence of a risk management plan; biocide levels; and basin water temperature, pH and microbial community composition (Yamamoto *et al.* 1992; Bentham & Broadbent 1993; Mouchtouri *et al.* 2010; Llewellyn *et al.* 2017; Racine *et al.* 2019). Moreover, airborne construction debris, freeway pollution and wildfire particulates can challenge cooling tower water treatment regimens (Scanlon *et al.* 2020; personal communication with the Los Angeles Department of Water and Power). Intriguingly, Wüthrich *et al.* (2019) postulated from an outbreak investigation that contaminated aerosols from one cooling tower could potentially colonise another with *Legionella* bacteria.

An example is illustrative of the potential consequences of building-specific factors on *L. pneumophila* concentration. In the present study, a newly installed cooling tower (C13) reported >1,500 CFU/mL of *L. pneumophila*, and the municipal water had a free chlorine residual of ≥0.60 mg/L in the 3 months preceding the exceedance. The service provider explained that, owing to partial occupancy of the new building, valves to certain condenser loops had been closed, and the cause of *L. pneumophila* growth might have been the uncirculated water held in these loops (after corrective actions, no *L. pneumophila* was detected). No reasonable level of free chlorine residual in the municipal water delivered to this building could have been expected to thwart such a plumbing configuration.

Accordingly, Holsinger *et al.* (2022) encourage building-scale water management programs, concluding from their review of 184 legionellosis outbreaks that water utility '[d]isinfectant management alone should not be considered to control *Legionella*.' Indeed not all cooling towers use municipally supplied potable water. Additionally, in various jurisdictions, there are pressures such as drinking water scarcity, rising utility costs and sewer capacity limitations compelling building owners to improve water efficiency (for cooling towers, by increasing the 'cycles of concentration') and to consider alternative water sources – placing even more importance on building-scale water management programs to control *Legionella*. Some new developments in the City of Vancouver, for example, are intending to supply their cooling towers with captured rainwater as their contribution to assuaging combined sewer overflows. The NASEM (2020) consensus study report recommends that authorities with jurisdiction, such as building departments, codify requirements for water management plans in all public buildings, and recommends regulations to register and monitor cooling towers.

Limitations

No inferences are drawn from the ostensible proportion of cooling towers in exceedance in each calendar month (Figure 1), because permit holders were free to choose the month in 2021 for their one required sample (such that a cooling tower reporting an exceedance in a given month may well have also had *L. pneumophila* ≥10 CFU/mL earlier in the year). The *L. pneumophila* data presented in this paper are subject to several other limitations. The registration of cooling towers, collection of water samples, organisation of testing by a competent laboratory, and reporting of results were the responsibility of building owners. While pragmatic from the City of Vancouver's perspective, this arrangement introduced an inherent variation in proficiency and engendered a conflict-of-interest. There are possibilities of unregistered cooling towers, unrepresentative samples, unreported exceedances and incorrect sample dates or *L. pneumophila* results in online reports, and there is no reason to assume equivalent *Legionella* recovery or enumeration accuracy amongst the six commercial laboratories which conducted culture-based testing, which has its own methodological limitations (Lucas *et al.* 2011). It is acknowledged that a more robust dataset might have been derived by third parties such as City inspectors collecting cooling tower water samples, with appropriate quality assurance and quality control measures like travel blanks, field duplicates, and reference samples, but available resources precluded such arrangements. For statistical analyses, a stringent significance level (0.005) was chosen to reduce chance findings, but at the cost of potentially failing to identify real correlations.

The City of Vancouver regulations pertain to *L. pneumophila* concentrations, and permit holders were not required to supply information about other *Legionella* species that may have been detected. When *L. pneumophila* was detected, serogroup-level analysis was not required (but nonetheless five of the six laboratories provided such analysis). Ideally, information about sequence types could have facilitated a more refined analysis of *Legionella* distribution amongst the City's cooling towers, and even a comparison to past clinical isolates by the health authorities (Wüthrich *et al.* 2019).

Municipal water quality data were extracted from the closest sampling station in the same water pressure zone as a building that had reported a cooling tower exceedance, and the estimated distance between each building and its corresponding sampling station ranged from 50 to 2,300 m (±50 m, Table 1). The further a sampling station is from a building, the less indicative its data are for the municipal water supplied to that building.

Future research

As of 1 January 2022, as part of the phased implementation of *Legionella* prevention regulations, all cooling towers in the City of Vancouver require monthly *L. pneumophila* reporting, with the same sample collection, testing and reporting arrangements as for the data presented here. The 2022 dataset would facilitate a seasonal analysis of *L. pneumophila* positivity and concentrations, and its larger sample size would support more robust correlation analyses to validate the conclusions reached in the present study. Because cooling towers colonised by *Legionella* spp. have been found to be 'at higher risk of future positivity' (Racine *et al.* 2019), there is an opportunity to also validate this finding by tracking the subsequent results of cooling towers through 2022. Lastly, Mouchtouri *et al.* (2010) found that, when *Legionella* spp. testing was not conducted regularly (for the authors, this meant at least quarterly), there was a positive association with *Legionella* spp. colonisation of cooling towers. The City of Vancouver 2022 dataset would help to test the hypothesis of others that regular *Legionella* testing of cooling towers drives down *Legionella* positivity, perhaps by the increased sense of awareness and accountability (Mouchtouri *et al.* 2010; Gilpin & Gilpin 2014; Racine *et al.* 2019; NASEM 2020).

CONCLUSIONS

As the present study illustrates, even when high-quality municipal water is supplied to a facility, this may not counteract issues with building-scale design, operations or maintenance that facilitate *Legionella* growth. In totality, for the City of Vancouver in 2021, cooling tower and municipal water quality data suggest highly-localised, building-scale *L. pneumophila* issues. There was almost a 95% compliance of cooling towers with the *L. pneumophila* standard of <10 CFU/mL; the 30 cooling towers which did report exceedances were clustered within 16 facilities that were scattered geographically, and *Legionella* results considered in the context of the City's municipal water pressure zones and water quality data do not point to a municipal water distribution system issue.

An unexpected finding was that 12 of the registered cooling towers at two hospitals measured an *L. pneumophila* concentration of between 10 and 880 CFU/mL. Without a cooling tower registry and a regulatory requirement to report *L. pneumophila* concentrations, it is unknown for how long these issues, and those of the other 14 facilities with cooling towers in exceedance, would have persisted. To this point, while there was no reported Legionnaires' disease outbreak in Vancouver in 2021, Wüthrich *et al.* (2019) established that a strain recovered from a cooling tower during a Swiss outbreak investigation had been causing infections over several years. In 2021, all of the cooling towers in exceedance were required by the City of Vancouver's regulations to undergo corrective actions including cleaning, disinfection and retesting.

This is the first article, to the best of the authors' knowledge, summarising environmental surveillance data for *L. pneumophila* (analysed by a culture-based method) in cooling towers city-wide, coupled to information from the municipal water quality distribution system. It underscores the crucial role of building owners and managers in the design, operations and maintenance of mechanical systems such as cooling towers which have the potential for growing and spreading lethal waterborne pathogens. It also demonstrates the public health protection benefits from implementing proactively recommendations to catalogue, monitor and establish minimum operational expectations for cooling towers.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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