Health risks from *Legionella* in reclaimed water aerosols produced by cooling towers and spray irrigation

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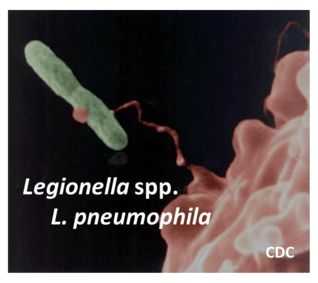


The use of reclaimed water brings new challenges for the water industry in terms of maintaining water quality while promoting sustainability. Increased attention has been devoted to opportunistic pathogens, especially *Legionella pneumophila,* due to its growing importance as a portion of the waterborne disease burden in the United States. Infection occurs when a person inhales a mist containing *Legionella* bacteria.

Introduction

Growing global water scarcity has intensified the need to recover water resources from wastewater, especially as population growth, economic development, and urbanization increase pressures on existing water supplies [1]. Reclaimed water is wastewater reused for beneficial purpose with treatment, where the level of treatment depends on the application[2] (Figure 1). The use of reclaimed water can alleviate stress on municipal water systems and augment existing water portfolios.

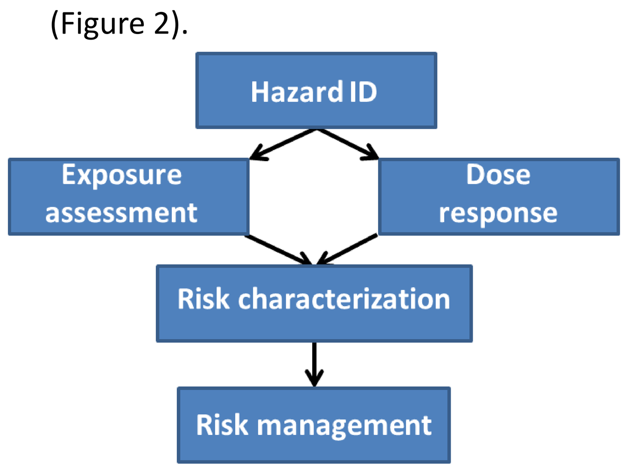
Agricultural and industrial water reuse represent the sectors with the largest reclaimed water usage in the United States[3]. Reclaimed water for cooling system purposes further represents the largest industrial water reuse application[4]. Cooling systems may consume 20-50% of a facility's water usage[5]. Common uses of reclaimed water such as spray irrigation or cooling towers can produce aerosols that are of concern because bacteria such as *Legionella pneumophila* can travel beyond the immediate vicinity of application[6]. To inform appropriate usages of reclaimed water and identify factors which have the greatest implication for best management practices, a quantitative microbial risk assessment (QMRA) is presented for scenarios of spray irrigation- and cooling tower- generated aerosols.

Figure 1. (left) Schematic for reclaimed water treatment; and (right) Example of reclaimed water system from Boca Raton, Florida[3]

Methodology

Quantitative microbial risk assessment (QMRA)

The QMRA framework was used to calculate the annual probability of infection for spray irrigation and cooling towers (Figure 2).



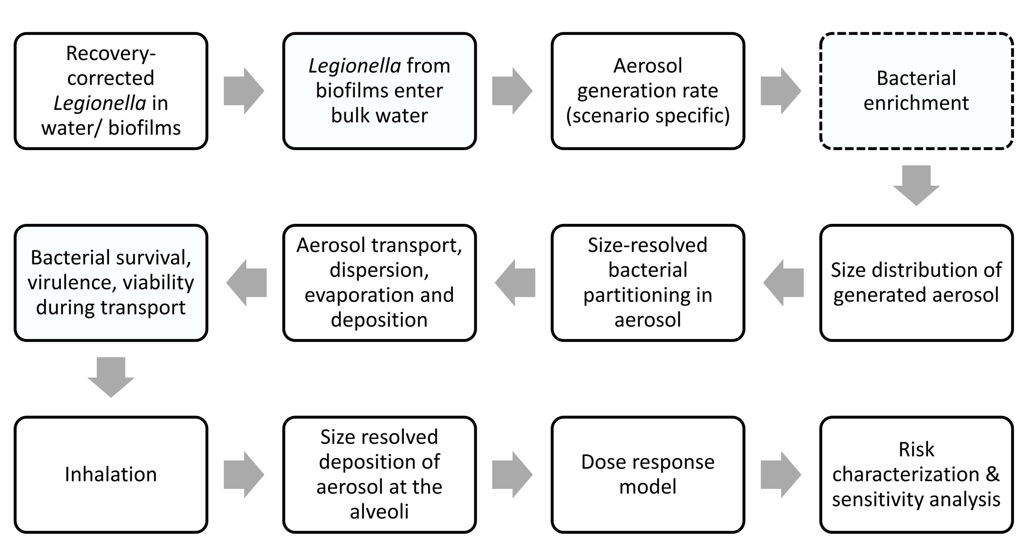


Figure 2. (left) An overview of the QMRA paradigm[7] and (right) processes specific to *Legionella* risk assessment[8].

The emission rate of aerosols for sprinklers and cooling towers was modeled from the top of the cooling tower (no plume rise) or the apex of the sprinkler arc (Figure 3) using a Gaussian plume model[9,10] (Figure 4), and equations 1 and 2:

$$Q_{Leg} = C_{Leg}FE \qquad (1)$$

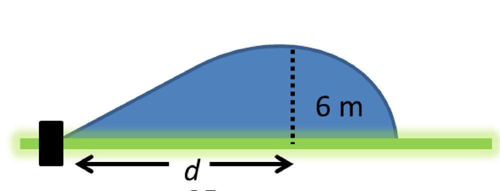


Figure 3. Sprinkler risks were modeled from the apex of the sprinkler stream

Where:

Q_{Leg} = *Legionella* emission rate (Number per second)
C_{Leg}= Concentration of *Legionella* in reclaimed water
F = flow rate (L/s)
E= aerosolization efficiency= fraction of sprayed reclaimed water or cooling tower mist (drift) that leaves the immediate vicinity of system as aerosols (0<E≤1)

$$Dose(x,y,z) = \frac{Q_{Leg}It}{2\Pi\mu\sigma_y\sigma_z} exp\left[\left(\frac{-y}{2\sigma_y}\right)^2\right]\left\{exp\left[\frac{-(z-H)^2}{2\sigma_z^2}\right] + exp\left[\frac{-(z+H)^2}{2\sigma_z^2}\right]\right\}\sum_{i=1}^{n} q_{i,s}DE_i exp^{\frac{-\lambda_s x}{\mu}} \qquad (2)$$

Where:

$Dose_{Leg}$ = Dose of Legionella at x, y, and z meters downwind from the source
x = distance downwind (m)
y = horizontal distance perpendicular to wind (m)
z = downwind receptor breathing zone height (1.5 m)
H = source height (m)
μ = wind velocity (m/s)
σ_y = horizontal dispersion coefficient (m)
σ_z = vertical dispersion coefficient (m)
λ = Decay rate (s^{-1}) for state s
s = in aqueous aerosol or evaporated
I = inhalation rate (m3 / min);
t = is the exposure duration (min)

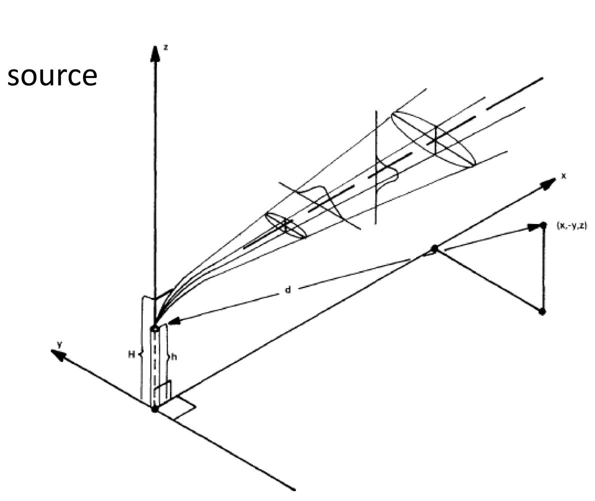


Figure 4. Cooling tower risks and sprinkler risks modeled according to a modified Gaussian plume model. An aerosol size distribution was simulated for both sprinklers and cooling towers.

Results & Discussion

Legionella concentrations

Data was provided from a study of *Legionella* spp. in 19 United States reclaimed water facilities (Table 1)[11]. Six of the nineteen facilities were followed up quarterly using 3 analytical methods: culture, quantitative PCR (qPCR), and ethidium-monoazide-qPCR (Figure 5). These data were used as input for the QMRA. 96% of cultured *Legionella* spp. were identified as *L. pneumophila*.

Table 1. *Legionella* concentrations via three analytical methods in all positive samples from six reclaimed water facilities[11]

Method	*Legionella* spp. (#/mL) in positive samples [Mean ± SD (range)]	% Positive
Culture	25 ± 19 (3 - 80)	48
EMA-qPCR	307 ± 336 (2 - 1,438)	89
qPCR	1,014 ± 683 (1 - 2,550)	90

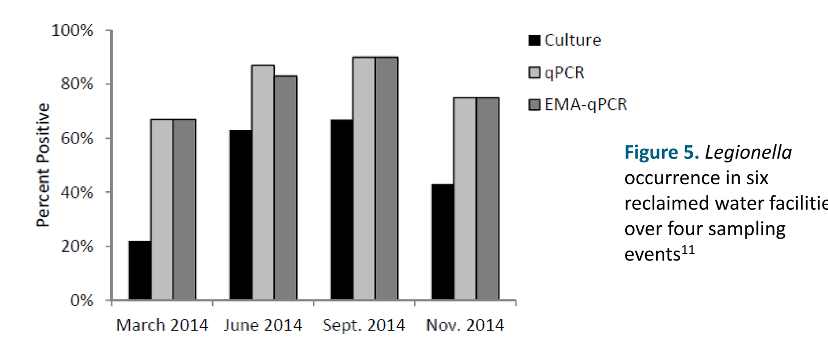


Figure 5. *Legionella* occurrence in six reclaimed water facilities over four sampling events[11]

Sprinkler annual risks for varying conditions

Annual infection risks were modeled for various meteorological conditions including 4 stability classes and 3 relative humidity (RH) values. The highest risks occurred with a wind speed of 7 m/s and 65% RH (Figure 6), however, the risk did not vary substantially by meteorological condition. Risks using the clinical severity dose response model were up to 2.5 orders of magnitude lower than infection risks, and occupational (8 hour exposure) risks were up to 1 order of magnitude higher than residential (1 hour exposure) risks. The greatest differences in annual risks for each scenario were due to: 1) differences in analytical method; 2) the population at risk considered (residential or occupational); and 3) the dose response model used (infection or clinical severity). The sensitivity analysis indicated that the most influential factors for variability in sprinkler risks were the concentration of *Legionella*, dose response parameter, and aerosolization efficiency. Setback distances necessary to achieve an annual infection risk level[12] of 10^{-4} for spray irrigation ranged from approximately 600 m (culture) up to > 7,500 m (qPCR).

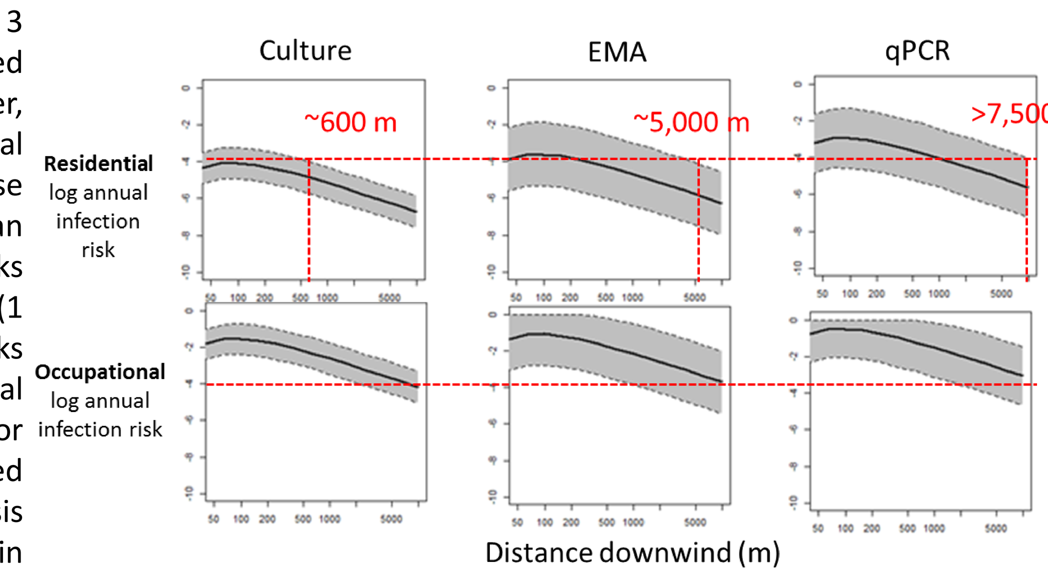


Figure 6. Sprinkler risk models shown for wind speed = 7 m/s and RH = 65% (most conservative scenario). Red lines are associated with the drinking water annual infection risk benchmark for reference (10^{-4}).[12]

Cooling tower annual risks for varying conditions

The greatest differences in derived setback distances were based on analytical method rather than the meteorological parameters or system operating conditions chosen such as cooling tower stack height or the presence of drift eliminators. Risks peaked further downstream with a 100 m compared to a 10 m stack height. However, peak risks for the higher cooling tower were up to ~1 log lower. Setback distances necessary to achieve an annual infection risk level of 10^{-4} for cooling towers was greater than 5,000 m for all scenarios. Increasing the stack height shifted the peak annual risk downwind distance. For "bad performance" drift eliminators (efficiency 0.01 - 0.1 %), risks are ~1 log higher at all downwind distances. The sensitivity analysis indicated that the concentration of *Legionella* and aerosolization efficiency were the most influential parameters.

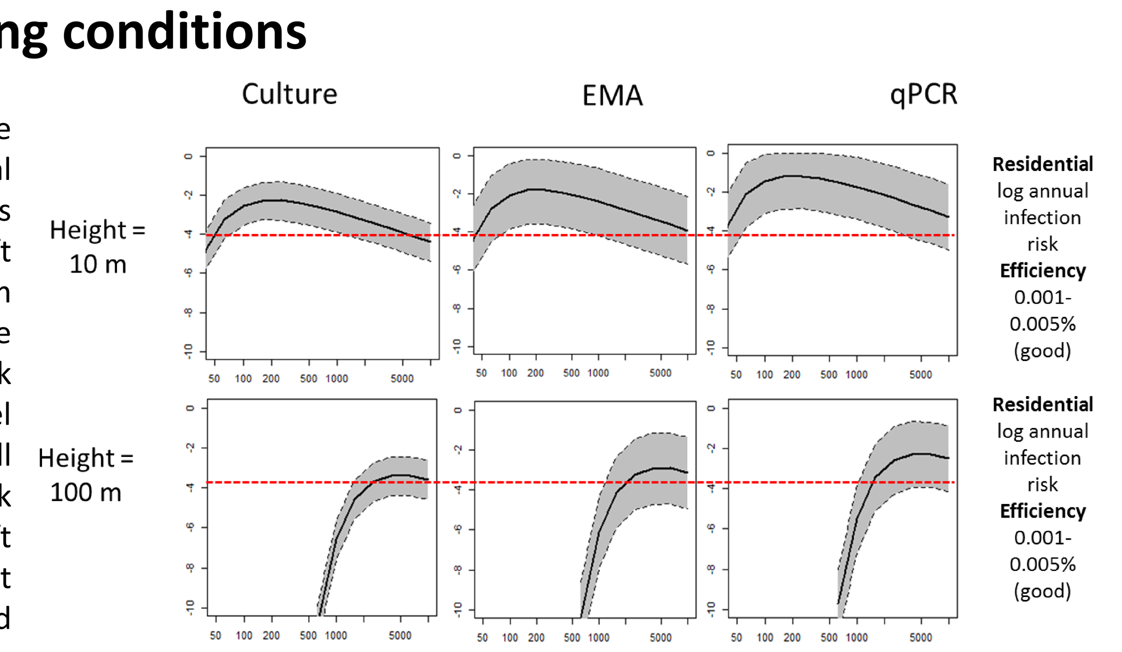


Figure 7. Cooling tower risk models shown for wind speed = 7 m/s and RH = 65% (most conservative scenario). Red lines are associated with the drinking water annual infection risk benchmark for reference (10^{-4}).[12]

Conclusions & Future Work

- *Legionella* risks are non-trivial at potentially large distances for spray irrigation and cooling towers, indicating that other simultaneous management practices may be needed to manage risks.
- The setback distance associated with a 10^{-4} annual risk varies depending on analytical method, meteorological conditions, dose response model used, and operating conditions. The analytical method used made the greatest difference in the scenario analyses.
- The concentration of *Legionella* in water was the most influential model parameter for model variability, highlighting the importance of managing disinfectant residual and other measures to control *Legionella* occurrence.
- Other management practices can be applied to reduce the setback distances needed for cooling tower health risk protection such as lowering cooling tower stack heights, using windbreaks or walls to limit aerosol dispersion, and installing more efficient drift eliminators.
- For spray irrigation, using irrigation nozzles that produce sprays with larger diameter aerosols, or limiting irrigation times to those when exposure is less likely to occur can reduce risks.

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