Pathogens in our water systems

Gran: that nice man Joe is installing our new hot tub. What is hot tub lung?

Photo from Getty Images, https://people.com/health/4-people-now-dead-from-legionnaires-outbreak-linked-to-hot-tub-display-at-a-state-fair/

Nicholas J. Ashbolt

Faculty of Science and Engineering, Southern Cross University, Gold Coast, QLD, Australia

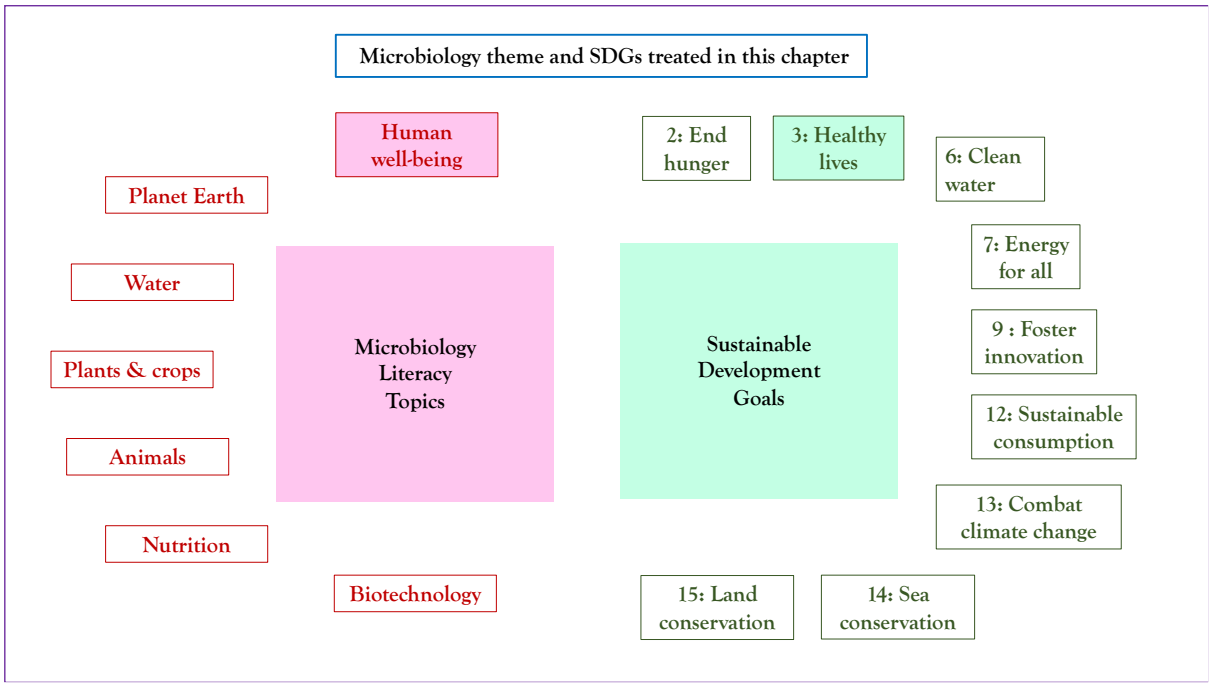
Pathogens in water systems

Storyline

Access to safe water for use in buildings is assumed if drinking water quality meets current guidelines/regulations. However, pools and hot tubs (also known as jacuzzies or spas, in which air is forced into the tub creating vast numbers of bubbles that burst at the surface, releasing small particles of water and microorganisms as aerosols), and building heating-cooling and hot water systems, may provide an environment for disease-causing organisms (pathogens) to grow. Waterborne pathogens of concern are generally either from human/animal excreta (called enteric pathogens, from pooh & wee, that generally die off rapidly in the environment), or water-based (also known as saprozoic) pathogens that grow naturally in the environment/water systems. When the source water is warm (meaning over 25 °C), then saprozoic pathogens, including free-living amoeba (such as *Naegleria fowleri*) and bacteria (such as *Legionella pneumophila*), proliferate in association with biofilms on natural environmental as well as engineered water system surfaces. In high income countries, this may result in more waterborne disease (largely lung and skin infections) than the traditional gastrointestinal waterborne pathogens.

The Microbiology and Societal Context

The microbiology: biofilms; disinfectants; aerosols; infections; opportunistic pathogens; predation; alternative hosts; microbiology of the built environment. *Sustainability issues:* health and wellbeing.



Pathogens in water systems: the Microbiology

1. ***Slime in pipes & associated pathogens.*** In urban areas, treated source water is generally supplied via pipes (traditionally iron pipes but, increasingly for the smaller distribution pipes in streets and within buildings, also in various forms of plastic pipes). Whenever a surface is maintained moist, naturally-occurring bacteria adhere, generate slimes and form what we call biofilms with organic (microbial products) and inorganic matter (fine sediments and corrosion products) held in the slime layers.

The bacteria within these biofilm communities are eaten by slightly larger, free-living protozoa (single-cell amoebae or ciliates; see Fig) – in what has been an 'arms race' between predator and prey over millions of years. As a result of this 'arms race', both predators and prey have evolved to survive. For example, predators have evolved mechanisms to select for prey they can digest (hence recognising and not eating bacteria that may be harmful), while some bacterial prey have acquired genes that enable them to persist, undigested within their predator (then called a host cell). Some bacteria:host relationships have evolved to be mutually beneficial (i.e., symbiotic) and, in other cases, essential for both partners. However, some bacterial prey have developed traits that enable them to 'outwit' their predator, leading to bacterial growth within the host rather than being digested, often leading to death of their host – i.e., they become saprozoic pathogens of free-living protozoa.

As humans evolved and developed immune systems, the vast majority of bacteria associated with our moist surfaces co-evolved to be beneficial. However, some of our immune cells, such as phagocytes that keep our lungs relatively free of inhaled bacteria, are essentially the same as amoebae. Therefore, bacterial pathogens that have evolved to grow within amoeba, can often also grow within our lung phagocytes when we are not in a very healthy state. These pathogens are called opportunistic pathogens. Examples of this are growth of *Pseudomonas aeruginosa* in lungs of people genetically vulnerable to cystic fibrosis, growth of *Legionella pneumophila* leading to fluid on the lungs which, in turn, causes a pneumonia, known as legionellosis, typically seen in older people, and mycobacterial lung infections, particularly amongst individuals who have been heavy smokers (Table).

Both *P. aeruginosa* and *L. pneumophila*, along with a range of mycobacteria, grow naturally in warm water biofilm habitats, such as those in spas or piped hot water near points of use (such as at shower or tap outlets) where the water temperature is often near body temperature and selective (25-40 °C) for growth of these saprozoic pathogens in biofilm amoebae.

Table: Different diseases that can be caught from pools, hot tubs/jacuzzies/piped water (adapted from Ashbolt 2015, Pathogens **4**: 390-405)

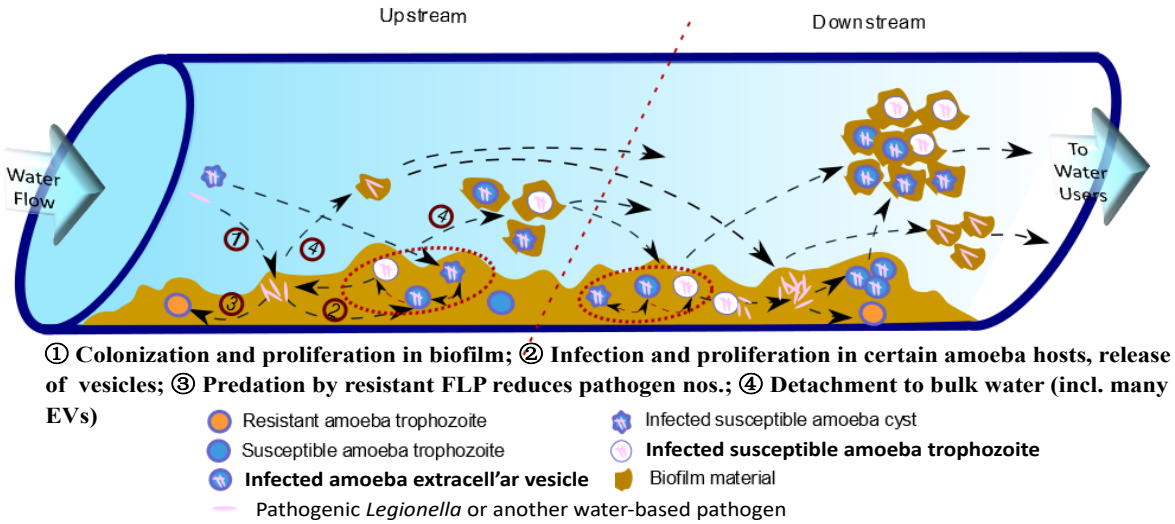
Agent	Disease	Problematic niche
Bacteria		
*Acinetobacter baumannii**	Range of nosocomial** respiratory & other infections (via biofilms) from drinking water, breathing tubes & urinary catheters; antimicrobial resistant strains	Free-living within biofilms of health-care water settings

*Aeromonas hydrophila**	Most strains do not appear to be of health concern (including enteric members), but some biofilm colonizers may cause wound infections.	Ubiquitous in aquatic environments, colonize engineered water systems
Various *Chlamydiales*	Community acquired pneumonia (CAP). Abortions in humans (and bovines)	Obligate amoeba-resisting bacteria of environmental biofilms
Legionella anisa, *L. longbeacheae* *L. micdadei* *L. pneumophila*	'Hot tub lung' or Legionellosis (from mild Pontiac Fever to severe Legionnaires' Disease); Community acquired pneumonia	Free-living within biofilms, but important pathogens within biofilm amoebae & other protozoa
Non-tuberculous mycobacteria (NTM) including: *Mycobacterium abscessus,* *M. avium* complex (MAC) *chelonae, M. Kansasii* complex & *M. ulcerans*	Community acquired pneumonia (CAP) Lymphadenopathy, skin and soft tissue infection	Free-living within biofilms, some appear facultative within biofilm amoebae and other free-living protozoa
Pseudomonas aeruginosa	Folliculitis & o*titis externa* from pools/spas and various nosocomial infections from plumbing biofilms	Ubiquitous in aquatic environments, colonize engineered water systems
Stenotrophomonas maltophilia	Range of nosocomial respiratory & other infections (via biofilms) in drinking water, breathing tubes & urinary catheters; antimicrobial resistant strains	Ubiquitous in aquatic environments, colonize engineered water systems
Protozoa		
Acanthamoeba spp.	Granulomatous amoebic encephalitis; keratitis (of eyes); lung & skin infections	Many strains appear to only grow saprophytically; ubiquitous in aquatic biofilms
Balamuthia mandrillaris	Granulomatous amoebic encephalitis; lung & skin infections	Relatively rare but present in source and treated waters of temperate regions
Naegleria flowleri	Primary amoebic meningoencephalitis	Relatively rare but present in source and treated waters over 28 °C if inadequate residual disinfectant
Vermamoeba vermiformis (*Hartmonnella* spp.) *Vahlkampfia* spp.	Keratitis (of eyes)	Many strains appear to only grow saprophytically; ubiquitous to aquatic biofilms
Viruses		
Mimivirus (Shan virus) *Mamavirus*	Suspected to cause minor pneumonia-like symptoms	In various biofilm amoebae, first described in *Acanthamoeba polyphaga*

* Facultative saprozoic (meaning can grow in environmental biofilms or within the gastrointestinal tract)
** nosocomial (meaning hospital acquired infection)

2. ***Minimising biofilms – minimising pathogens in piped waters.*** Biofilms are nearly impossible to eliminate – at best we can minimise them and their related problems. Even the space shuttle's piped water system (as will be the case in future moon and Mars expeditions) developed *P. aeruginosa* and other potential opportunistic bacterial biofilms, despite steam-sterilising spaceship water pipes between each mission. Hence, to manage saprozoic pathogens, like enteric pathogens, the focus is on good system design and management.

Key features that encourage pathogen growth in biofilms revolves around disinfectant concentrations and pipe materials, water stagnation and warm conditions. The concentrations of disinfectants, such as the chlorine added to drinking water to control microbial growth, diminish through reaction with biofilm matter (organics and imbedded pipe corrosion fragments) and warm water conditions. Hence, problematic biofilm growth increases near points of water use, such as at end fixtures (hot/cold water mixers and tap/shower outlets). In buildings, water use is intermittent, so hot- and cold-water pipes have flow and no/low flow periods, that may extend to some weeks in hotel or apartment buildings. This is in addition to the stagnant regions in 'dead-end' spare connection points in plumbing created to allow future evolution of piping systems.



Materials and conditions to control biofilm-pathogen issues from human exposures. With stagnation of water flow, disinfectant concentrations fall, water temperatures may rise and biofilms grow along with free-living protozoa (FLP, particularly amoebal hosts to various saprozoic pathogens such as *Legionella* spp.). Subsequent water flow and aerosolization near humans may then provide an infectious dose. Adapted from Shaheen *et al.* (2019) *Int J Hyg Environ Health 222:* 678-86.

To control the problem associated with stagnant/low water flow in healthcare buildings, hot water is recirculated through hot water pipes to maintain a temperature above 50 °C, a temperature too hot for known saprozoic pathogens to actively grow (although they may remain alive but dormant within host amoeba cysts at temperatures up to 65 °C). More recently, cold water is also recirculated to keep cold water well below 25 °C to manage legionellosis and other opportunistic diseases.

Iron and copper pipes are common in building water systems, yet these materials corrode and react with oxidizing disinfectants, such as chlorine, used to keep water safe. Plastic pipes, however, are not free of issues. The organics associated with plastic pipes (PVC, PEX or

polyethene) may leach matter into the biofilm environment, often supplying critically limiting organic carbon to support bacterial growth in drinking water systems.

Pipe biofilms may also capture and concentrate enteric pathogens. Enteric viruses, bacteria and parasitic protozoa do not proliferate outside of their corresponding hosts in water systems but may persist as infectious pathogens. Biofilms provide protection from chorine disinfection too. In particular, human enteric viruses not only sorb to the biofilm matrix and concentrate, but may also be accidentally preyed upon by free-living protozoa. It has been recently shown that preyed-upon virus particles remain infectious and generally are not digested within amoebae! These then may ultimately be released in concentrated 'biofilm or amoebal parcels' that slough/break off their underlying pipe surface and that may have increased likelihood of producing an infection upon human exposure.

3. ***Ubiquitous but not necessarily hazardous.*** Saprozoic pathogens are widely distributed as a result of their ability to proliferate in the environment. Yet it is the delivery of an infectious dose that is what needs to be controlled. Many saprozoic pathogens cause infection through our inhalation of aerosols or water droplets, not via ingestion. Other saprozoic pathogens, such as *P. aeruginosa,* may cause skin diseases such as a skin rash known as folliculitis, or acute ear infections (*otitis externa*), via dermal infections occurring through pool and hot tub exposures,. Hence, exposure points should be designed to minimise aerosol generation (i.e. droplets less than 10 µm in diameter) or pathogen concentrations in waters (i.e., < 100 *P. aeruginosa* per 100 mL of pool water). Avoidance of water conserving aerators on taps and high-velocity fine shower heads would reduce the generation of aerosols.

More problematic are spas, often maintained at temperatures close to 40 °C, and with only periodic aeration/circulation of use, providing a high potential to harbour opportunistic pathogens like, *P. aeruginosa* and *L. pneumophila* just waiting to be aerosolised or infect frail patients in healthcare settings. Luckily, unlike enteric pathogens that are transmitted from human-to-human with the potential for secondary spread and large community disease outbreaks, most saprozoic pathogens are unable to transmit from human-to-human and so the human represents a dead end in their lifecycle. Indeed, the life-cycle of pathogens such as *L. pneumophila* and *Mycobacterium avium* plays out within biofilms/free-living protozoa, which means that, when a case is identified, it has come from a water system.

Non-tuberculous mycobacteria (NTM), a range of *Mycobacterium* species that do not cause tuberculosis, but unfortunately do cause other lung and skin infections, are ubiquitous in the environment. NTM are as natural to groundwater systems as they are to colonising water filters and piped water biofilms, particularly when the competition is held back by higher concentrations of water disinfectants. However, it seems that only a subset of NTM has the potential to cause human infections and, as with other opportunistic pathogens, mostly in the vulnerable already having lung damage, genetic predisposition, or suppressed immunity. The *Mycobacterium avium* group of species are probably best characterised as potential human pathogens, but we have much to still learn about these pathogens.

4. ***Competing issues – needs a system understanding to reduce unintended consequences.*** In an attempt to save energy and reduce scalding of the elderly or young children, hot water heaters are often turned down. Rather than providing water above 60 °C, they are adjusted so water will not scald people, i.e. a temperature below 50°C, which of course saves energy too. Shower heads have been designed to aerosolise water more and therefore reduce the volume of

water use per minute of use. Both conservation measures are now understood to enhance the growth and transmission of saprozoic pathogens in aerosols, but codes of building practice and competing environmental issues take time to change.

Hence, as with any intervention trying to do the right thing, the broader system impacts need to be considered so we do not just exchange one problem for another.

5. ***Pools & Spas have a double whammy of issues.*** Swimming pools have filters designed to remove enteric pathogens that may be released by bathers (accidently as a 'floaties in the pool', small liquid releases or simply just from skin surfaces) – yep, there is always trace faecal matter on bathers, hence the reason to shower before bathing. Pool filters may also build up opportunistic pathogens, the best known being *P. aeruginosa* and why swimming pools have that species as a specific management measure (to be < 100 per 100 mL of pool water).

The chlorine or quaternary ammonium disinfectant commonly used in pools/spas is largely there to inactivate trace amounts of enteric pathogens that may end up in pool water and to inhibit the growth and inactivate bacterial pathogens like *P. aeruginosa*.

Yet there are disinfectant-resistant enteric pathogens. The most common of these causing pool outbreaks of gastro-enteritis is the parasitic protozoan *Cryptosporidium hominis*, which is excreted in faeces as a resistant structure known as an oocyst. Management of disinfection-resistant oocysts relies on effective pool water filtration. This highlights a core management goal: to have multiple barriers to manage pathogen risks. Unfortunately, most pools only have key pathogen barriers, disinfectant and a pathogen filtration system. Pool gastro-enteritis outbreaks often occur via disinfectant-resistant oocysts directly released into pool water rather than via enteric bacterial or viral pathogens that are better prevented by pool disinfectant and filtration barriers.

Spas, as discussed above, are particularly problematic to manage, due to their sporadic circulation/sparging use, and intervening periods suited to biofilm-pathogen growth, followed by release of sparging aerosols. Many documented outbreaks of legionellosis have been reported in older spa pool users, and even visitors nearby who inhale aerosols containing *L. pneumophila* that are circulated via building air circulation systems.

6. ***Cooling towers – a hot-spot for* Legionella*, but not the dominant health burden.*** The most commonly documented outbreaks of legionellosis are from cooling towers. These are engineered structures in which with hot water is circulated over biofilm-covered surfaces while a countercurrent of air is drawn up and out of the top of the tower. Cooling towers are specifically designed to achieve evaporative cooling to reduce the temperature of water used to remove heat in industrial processes, including air conditioning. The air leaving the top of a cooling tower is loaded with aerosols which may contain biofilm materials, which may themselves contain *Legionella*. Such aerosolised *L. pneumophila* has been reported to travel over several kilometres and cause legionellosis in people downwind!

Cooling tower aerosols are sometimes located too close to air intake structures of buildings, thereby directly feeding *Legionella*-aerosols into air conditioning systems, resulting in the classic cause of cooling tower outbreaks of Legionnaires' Disease!

That most *outbreaks* of legionellosis are associated with cooling towers (and indeed, now better regulated to manage this issue), does not mean it is the reason for most *cases* of legionellosis. What is emerging is that outbreaks of legionellosis, such as from cooling towers,

may only account for less than 25% of all documented cases. *Legionella* (aerosols) largely cause sporadic cases (less than two people identified as being infected from the one source). Many of these sporadic cases are amongst previously smoking males over 65 years of age with underlying health issues – illustrating the general opportunistic pathogen nature of legionellosis.

Where do these sporadic cases arise? It seems that many occur in healthcare settings through growth of *L. pneumophila* in hot water and its mixing with cold water prior to aerosolization and human exposure from aerated tap outlets and shower heads!

Relevance for Sustainable Development Goals and Grand Challenges

- **Goal 3. Ensure healthy lives and promote well-being for all at all ages**. Water systems are not only a potential delivery system for pathogens, they can also serve as a habitat for the growth of pathogens, so represent a source of health risks. This means that special attention must be paid to their construction and maintenance, in order to reduce risk to a minimum.

Potential Implications for Decisions

1. ***Individual***
    a. Given the particular risks of a hot tub, should you acquire one?
    b. If so, , what risks should you be aware of?
    c. In particular, are you prepared to maintain it in a safe way and what does that mean on a daily basis and less frequently?
    d. If you have a skin wound, is it safe to swim and, if so, where? Or should you use a hot tub?
    e. Going on a vacation to a hotel where the rooms are maybe less frequently used, what risks should you be concerned about from the room plumbing, and its pool or spa?
    f. What should you look out for (or want to smell) to know if the pool/spa water is disinfected?
    g. When visiting a site where a bloom or aerosols (steam mist) is exiting a cooling tower, what type of pathogen risk is there and how do you minimise such risk?

2. ***Community policies***
    a. To minimise enteric pathogen risks in pools/spas, should pre-showering be required by operators or municipal agents responsible?
    b. Will pre-showering impact on saprozoic pathogens associated with a spa?
    c. What are the needs to reduce saprozoic pathogen risks in community pools and spas?

3. ***National policies***
    a. Regulations/guidelines relating to built environment waterborne pathogens, particularly focussing on cooling towers and heating and cooling systems within buildings.
    b. Clear identification of those responsible for hot water system maintenance within buildings.
    c. Clear identification of the roles of the municipal drinking water supplier.
    d. Proper education/instruction of those responsible for supplying and maintaining water systems

Pupil Participation

1. ***Class discussion of the issues associated with waterborne pathogens***, separately for enteric pathogens and saprozoic pathogens.

2. ***Pupil stakeholder awareness***
   a. Do you wish to take on known risks with a home hot tub or join others in a communal hot tub?
   b. What mitigation measures should you ask about or take yourself?
   c. What would you advise in an old age home related to use of a hot tub?

3. ***Exercises***
   a. Describe the signs of possibly poor maintenance of hot and cold water systems in a hotel and what could be undertaken to improve matters.
   b. Discuss the pros and cons of energy conservation initiatives that impact water systems.

The Evidence Base, Further Reading and Teaching Aids

For the teaching aids, the following short videos are suggested:

CDC: *Legionella Ecology and an Introduction to Environmental Health and Engineering* https://www.youtube.com/watch?v=RV0bmdliQjQ

UNC: Nontuberculous Mycobacterial Lung Disease Today and Tomorrow
https://www.youtube.com/watch?v=EVCX_cTcnPw

Key references (Open Source)

Ashbolt, N. J. (2015). "Environmental (saprozoic) pathogens of engineered water systems: Understanding their ecology for risk assessment and management." Pathogens **4**(2): 390-405.

Ashbolt, N. J. (2015). "Microbial contamination of drinking water and human health from community water systems." Current Environmental Health Reports **2**(1): 95-106.