Exposure

Will Robertson and Gordon Yasvinski

7.1 INTRODUCTION

A variety of microorganisms (viruses, bacteria and parasites) have the capacity to transmit disease through contact with contaminated water (US EPA 2009). Waterborne infectious diseases caused by these microorganisms can be fatal. Globally, over 1.5 million people die each year from unsafe water, inadequate sanitation and insufficient hygiene as a result of diarrhoeal diseases, schistosomiasis and others (Prüss-Üstün et al. 2008). In the USA alone, between 1971 and 2000 43 outbreaks involving almost 1800 cases associated with untreated recreational surface waters were attributed to zoonotic pathogens such as pathogenic E. coli, Leptospira, Giardia, Cryptosporidium and Schistosoma (dermatitis) (WHO 2004). Of these outbreaks, ten were attributed to animal and avian sources.

Catchment area loading with livestock wastes and the transport of this contamination to water bodies are of growing concern for their potential effects
on the quality of natural waters used for a variety of human contact activities. The question of the magnitude of these impacts on waters is one of significant importance to those involved in ensuring the safe use of these waters. The focus of this chapter is to provide discussion on the places that can be contaminated by livestock waste and the factors influencing the potential for human exposure, and possible infection and illness.

7.2 RELEVANT WATER TYPES

The water types of interest for these discussions are surface waters that are impacted by contamination from livestock waste (either directly or through transport) and that also support activities that can lead to human exposures to contaminated water. Contamination inputs within a catchment area can include both point and diffuse sources. Examples of point source inputs are intensive livestock operations (dairy/swine/poultry barns and feedlots) and animal processing facilities (slaughterhouses). Diffuse sources are pasturelands or grazing ranges, which can vary in size from large farms to households having a small number of domestic animals.

Specifically, the types of surface water encompassed by this definition include traditionally recognized water bodies such as coastal marine waters, and freshwater rivers, lakes and streams. Also certain less conventional water types such as rice paddies or flooded fields are covered by the definition, as are standing waters that have been created by flood events. In general these waters are located primarily in rural areas, but transport and weather-related pressures affecting pathogen movement can also contribute to the occurrence of exposures in urban areas.

The type of water use plays a large role in dictating which water areas may have an associated contamination exposure risk. This can be strongly influenced by geographical, social and economical factors. Uses for persons in developed countries where water is abundant, can be entirely different from uses for those living in developing countries or impoverished areas where water resources are far more scarce.

7.3 FACTORS INFLUENCING HUMAN EXPOSURE, INFECTION AND ILLNESS

In assessing the potential for the risk of human exposure to waterborne pathogens at the point of water contact, it is important to consider issues influencing the probability of human contact, infection and illness. Three
main components influence the probability of human infection by pathogenic organisms: the environment, the pathogen and the host. The principle behind each component and the considerations for contributing to exposures are the following:

- **Environment**: The environment must be favourable to permit the pathogen’s survival and pathogen-host interaction.
- **Pathogen**: The pathogen must be present and possess the specific virulence factors required for it to cause infection; and these factors must be successfully expressed in the host environment.
- **Host**: The host must take up the pathogen and be susceptible to infection.

If a pathogen is to be successful in initiating infection, all three of these components must be satisfied. Should infection be established, the resulting disease can range in severity from asymptomatic, through mild and severe to lethal.

The interaction between these factors is depicted in a simplified illustration in Figure 7.1. The full impact of the pathogen on the risk of exposure and illness can be expected to occur when environmental interaction, host susceptibility and pathogen virulence are considered high. Similarly, the pathogen’s impact is reduced if one or more of these determinants are lowered.

**Figure 7.1** Risk triangle: Factors influencing exposure, infection and illness from zoonotic pathogens.
7.3.1 Environment

Preceding chapters have discussed the steps and conditions required for the transmission of viable zoonotic pathogens from livestock wastes to surface waters, and the factors required for understanding transport within these water bodies. Continuing this discussion as it relates to human exposure, it is recognized that various pressures within the water environment can influence the ability of a pathogen to reach points where human contact is possible. Different water types possess different intrinsic properties (sizes, depths, flow or circulation rates) that can affect pathogen movement. For example, coastal waters are affected by tides, inflows from discharging rivers, deep and shallow currents, and up- and down-welling effects caused by temperature and salinity differences. Inland lakes, especially smaller lakes can be considered relatively static water bodies. Inflows from rivers and streams can contribute to transport and mixing in these waters, and thermal stratification in stagnant lakes can lead to vertical movement of contaminants through up- and down-welling events. Larger lakes (for example, the North American Great Lakes) can be more comparable to coastal waters, having similar mixing pressures. Rivers, by comparison are very dynamic water bodies, where the primary mixing factors are the flow rate or mechanical speed and the turbulence effects (e.g. eddies) created by flow obstructions.

Sedimentation and resuspension are additional processes that operate alongside flow and circulation processes in determining microbial transport and distribution (Brookes et al. 2004). Attractive forces or the presence of substances such as extracellular polymers can allow microorganisms to attach to particles in the water column. Microorganisms attached to particles will settle more quickly than free, unattached microorganisms (Brookes et al. 2004, Characklis et al. 2005). Reciprocally, bottom sediment disturbances can result in the resuspension of settled microorganisms back into the water column. Jamieson et al. (2004) demonstrated that water quality in rural streams could be significantly influenced by faecal microorganisms in stream bed sediments. Disturbances can be the result of flow changes (currents, wave action or weather-induced flow changes) or due to human or animal activities within the watershed (motorized watercraft, canoeists, dredging activities or animals). This phenomenon of microorganism resuspension can create unexpected pathogen presence scenarios (Brookes et al. 2004).

Some transport and mixing pressures, like weather-related influences are common to all water types. Circulation and flows for coastal waters, lakes and rivers alike are aided by the action of winds.

Rainfall is an extremely important factor influencing the contamination of water bodies with faecal contamination from non-point sources. Faecal pathogen events in rivers, lakes and reservoirs have been shown to be associated with
rainfall events (Atherholt et al. 1998, Kistemann et al. 2002, Dorner et al. 2007). Krometis et al. (2007) observed that average stream water concentration of the faecal indicators thermotolerant coliforms and E. coli were highest in the earliest stages of a storm (referred to as the “first flush” phenomenon). The researchers additionally estimated that wet-weather events of short-term duration contribute to a much greater fraction of microbial loading of a waterway than lengthier dry weather events (Krometis et al. 2007). In an investigation of the effects of wet weather on pathogen and indicator concentrations in an agriculture-intensive watershed, Dorner et al. (2007) observed that during storm events, the peak Campylobacter concentration arrived earlier than the peak turbidity level. The authors speculated that this was because pathogens are generally in limited supply within a watershed and are therefore more likely to be flushed out of the stream before the turbidity level declines.

Research has recently highlighted evidence of a connection between extreme wet-weather events, microbial transport from non-point faecal sources and elevated risks of waterborne illness (Curriero et al. 2001). Flooding caused by heavy rains or disaster events such as hurricanes or tsunamis can create vast areas of standing water and with it new areas for potential pathogen exposures. It is expected that effects linked to climate change such as elevations in environmental temperatures and increases in extreme hydrological events may further contribute to water quality impairment by faecal pollution of livestock origin and thus further increase the potential for human exposures and illness.

Various physical, chemical and biological pressures can also have an effect on pathogen survival in the water column, including sunlight intensity (solar radiation), water temperature, salinity, pH, nutrient availability, the presence of toxic substances, predatory grazing by protozoa and other invertebrates, and competition from native microorganisms.

Numerous studies have examined the effects of temperature on the survival of faecal microorganisms in the aquatic environment. Research suggests that Cryptosporidium oocysts can survive for periods of weeks to several months at temperatures frequently encountered in the environment (4–25°C) (Robertson et al. 1992, Medema et al. 1997, King et al. 2005) and are capable of maintaining a high level of infectivity at temperatures below 15°C (Fayer et al. 1998). Data have also been generated (Fayer & Nerad 1996) indicating that oocysts frozen for short periods of time (several days) at low freezing temperatures (−10°C) are able to maintain viability and infectivity. The capacity for oocysts to persist for very long periods in the environment at low temperatures remains uncertain. A recent study designed to replicate winter survival conditions in a northern aquatic environment (Robertson & Gjerde 2006) determined that no viable Cryptosporidium oocysts or Giardia cysts could
be detected (dye uptake method) after 20 weeks and one month, respectively. For faecal bacteria, data from temperature exposure experiments conducted with *E. coli* (Rhodes & Kator 1988, Sampson *et al.* 2006), *Campylobacter* (Obiri-Danso *et al.* 2001), *E. coli* O157:H7 (Wang & Doyle 1998) and *Salmonella* (Rhodes & Kator 1988) suggest these organisms are capable of surviving for days to several weeks at temperatures above 15°C. Similarly, water temperatures below 10°C can permit longer survival times. Thomas *et al.* (1999) reported that a *C. jejuni* population of greater than 4 log (initial concentration >6 log cfu/mL) could be maintained for more than 60 days in sterile river water at a temperature of 5°C. Sampson *et al.* (2006) observed less than a 1 log decline from a 5 log population of *E. coli* after storage for 30 days at 4°C in lake water. Information resulting from studies comparing the temperature-related survival of faecal indicator bacteria to bacterial faecal zoonotic pathogens has often been conflicting, with some studies observing prolonged survival for the pathogens (Roszak 1984, Rhodes & Kator 1988) and others showing equivalent or greater survival for the indicator species (McCambridge & McMeekin 1980, Korhonen & Martikainen 1991).

Sunlight intensity is another significant factor affecting the survival of faecal microorganisms in aquatic systems. Experiments with faecal zoonotic pathogens (*Cryptosporidium*, *Campylobacter*, *Salmonella*) and indicators (*E. coli*, faecal coliforms, enterococci) have demonstrated that inactivation is strongly influenced by the intensity of sunlight, with significantly greater die-off rates occurring under sunlight exposure than under dark conditions (Fujioka *et al.* 1981, Johnson *et al.* 1997, Obiri-Danso *et al.* 2001, Sinton *et al.* 2002, King *et al.* 2008, Nasser *et al.* 2007, Schultz-Fademrecht *et al.* 2008). Similarly, data have been provided to suggest more rapid inactivation under solar irradiation levels more typical of summer as compared to winter sunlight conditions (Noble *et al.* 2004, Sinton *et al.* 2002). Studies in which the survival ability of different faecal microorganisms have been directly compared have demonstrated a more rapid die-off for the bacterial species (*E. coli*, enterococci, *Salmonella*) as compared to the faecal protozoa *Giardia* and *Cryptosporidium* (Johnson *et al.* 1997, Medema *et al.* 1997, Nasser *et al.* 2007).

Also important in the consideration of the exposure environment are the activities which bring the human population in contact with the areas of pathogen presence. In those developed countries where water resources are in abundance, the primary human activities expected to facilitate contact with livestock-contaminated waters are recreational uses and potentially through drinking-water consumption.

For recreational water uses, it has been proposed that activities can be separated into two categories as defined by the degree of water exposure expected: primary-contact and secondary-contact (WHO 2003). In primary or whole-body
contact activities, the whole body, including the head is intentionally immersed in the water or wetted by spray. Hence, it is likely that some water will be swallowed (WHO 2003). The most common primary-contact activity is swimming, which includes related actions such as diving or jumping into the water. Other common examples are wading, surfing, water-skiing, windsurfing, scuba-diving and snorkelling. White-water sports such as canoeing, kayaking, tubing and rafting are also considered to fit in this category. In secondary or incidental contact activities only the arms and legs are intentionally exposed, and greater contact is unusual (WHO 2003). Examples of secondary-contact activities would be rowing, canoeing or kayaking; power boating and fishing. Another important consideration for the discussion of recreational contact relates to the location of potential exposures. Swimming activities occur near shorelines and thus users may be located in closer proximity to contamination inputs. Other activities like waterskiing or surfing can have immersion exposures that occur at significant distances from shore. Secondary contact activities such as recreational boating or canoeing may allow bathers to access possibly more polluted water closer to the source of contamination.

Drinking-water exposures in developed countries would be largely restricted to instances where livestock-contaminated source waters were untreated or incompletely treated prior to human consumption.

In developing countries, contact circumstances can be expected to be entirely different from the developed world. Numbers published by the WHO and UNICEF suggest that as of 2000, 1.1 billion people lacked basic access to a water supply within 1 kilometre of their home (Howard & Bartram 2003). In poor rural communities water resources can be shared by multiple households and would support a variety of sanitary or hygienic and household uses. Expected water contact activities would be bathing and laundering, and other uses such as drinking or handwashing may also occur if there is inadequate household access to water (Howard & Bartram, 2003). It is also expected that in certain countries a greater number of exposures may arise through occupational circumstances. Examples include domestic farmers working in rice paddies, and military personnel on manoeuvres in rural areas. Rescue workers providing relief in floodwaters produced by natural disasters are a noteworthy example of occupational exposure created by unpredictable circumstances. This scenario would have importance in both the developing as well as the developed world. In interpreting the degree of water exposure associated with this range of activities, it is possible that the WHO contact definitions can also be applied here. For the examples described, bathing might be considered a primary-contact activity, while laundering and occupational exposures may be more representative of secondary contact.
An area of emerging interest that perhaps can be considered a subcategory of water contact relates to contact with pathogens that may be present in contaminated sands or sediments directly adjacent to surface waters. Sands and soils have been noted as a potential medium for human contact with microorganisms (including faecal microorganisms) that have been transported to this environment (Bolton et al. 1999, Obiri-Danso & Jones 1999, WHO 2003, Whitman & Nevers 2003, Edge 2008). Numerous studies have demonstrated the extended persistence of faecal microorganisms in sand and sediments of environmental waters (Davies, et al. 1995, Byappanahalli & Fujioka 1998, Desmarais et al. 2002, Brookes et al. 2004, Byappanahalli et al. 2006). Greater nutrient availability and increased protection from predation in this environment have been suggested as explanations for this effect. Contact activities important for this issue would be those occurring near shore to contaminated surface waters or in shallow water areas. Potential areas of relevance could include contaminated beach sands, rice paddies and flooded agricultural fields.

7.3.2 Pathogen

Various waterborne zoonotic bacteria and protozoa can cause gastrointestinal illness in humans. Yet for a variety of reasons it is not practical to routinely monitor them in faecally-contaminated water including those impacted by livestock wastes and used for various water contact activities (WHO 2003). Instead, these waters, particularly those used for primary contact recreational use, are routinely tested for faecal indicator organisms. The presence of faecal indicator organisms (FIOs) in water indicates that it has been subject to recent faecal contamination and may therefore contain zoonotic pathogens and present a risk to bathers. Other studies have measured FIOs or zoonotic pathogens in surface waters usually as part of research programmes directed towards microbial risk assessments or the development and evaluation of best management practices. Our knowledge of their presence, persistence and infectivity is limited. A number of notable studies where zoonotic pathogens and waterborne FIOs have been measured in waters with known livestock impacts are presented in Tables 7.1 and 7.2.

In general Tables 7.1 and 7.2 illustrate that FIOs are definite indicators of the presence of livestock wastes in surface waters and that livestock wastes can contribute zoonotic pathogens to surface waters. In addition, there does not appear to be a good correlation between FIOs and the presence of waterborne zoonotic pathogens, although the data are limited (Dorner et al. 2007, Till et al. 2008). There may be several reasons for this discrepancy. For example, FIOs are present in much greater concentrations in livestock wastes and in contaminated
Table 7.1  Notable studies: Areas with livestock impacts – pathogen monitoring.

<table>
<thead>
<tr>
<th>Location</th>
<th>Organism</th>
<th>Results</th>
<th>Comments</th>
<th>Reference</th>
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</thead>
<tbody>
<tr>
<td>Japan</td>
<td><em>C. parvum</em></td>
<td>Overall: 50% of sites&lt;br&gt;Dairy farming areas: 88% of sites&lt;br&gt;Horse-rearing areas: 0% of sites</td>
<td>Rivers – significant dairy farming and horse rearing.</td>
<td>Tsushima <em>et al.</em> 2001</td>
</tr>
<tr>
<td>USA</td>
<td><em>Cryptosporidium</em> spp.</td>
<td>0–40% of sites&lt;br&gt;36% of samples</td>
<td>Watershed with small, concentrated dairy industry; drinking water source.</td>
<td>Sischo <em>et al.</em> 2000</td>
</tr>
<tr>
<td>Japan</td>
<td><em>C. parvum</em></td>
<td>37–100% of sites&lt;br&gt;1.4–2.4 oocysts/20 L</td>
<td>Rural sites, varying livestock populations (cattle, swine, poultry)</td>
<td>Ono <em>et al.</em> 2001</td>
</tr>
<tr>
<td>Swaziland</td>
<td><em>E. coli O157</em></td>
<td>12 of 81 (15%) of samples</td>
<td>River – Heavy rains, cattle faeces, outbreak from untreated drinking water.</td>
<td>Eflller <em>et al.</em> 2001</td>
</tr>
<tr>
<td>New Zealand</td>
<td><em>Campylobacter</em></td>
<td>(3 beaches) 85, 74, 52% of samples&lt;br&gt;Median: 0.84, 0.36, 0.12/100 mL</td>
<td>Predominantly agricultural catchment, levels higher during summer months.</td>
<td>Eyles <em>et al.</em> 2003</td>
</tr>
<tr>
<td>Malaysia</td>
<td><em>Giardia</em> spp.&lt;br&gt;<em>Cryptosporidium</em> spp.</td>
<td>4–23% of samples; 1.3–9.0 cysts/L&lt;br&gt;12–21% of samples; 0.7–240 oocysts/L</td>
<td>Rivers near cattle farms with potential bathing/swimming uses.</td>
<td>Farizawati <em>et al.</em> 2005</td>
</tr>
<tr>
<td>Canada</td>
<td><em>Campylobacter</em></td>
<td>50% samples;&lt;br&gt;Med: 63 /100 mL (1.2–1.2 × 10^6)</td>
<td>River watershed – Site with high livestock density. Weak correlations between pathogens and faecal indicators reported.</td>
<td>Dorner <em>et al.</em> 2007</td>
</tr>
<tr>
<td></td>
<td><em>E. coli O157:H7</em></td>
<td>6.7% samples;&lt;br&gt;Med: 100/100 mL (100 to 110)</td>
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<td></td>
<td><em>Giardia</em></td>
<td>35% samples;&lt;br&gt;Med: 22/100 L (2–1.0 × 10^4)</td>
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<tr>
<td></td>
<td><em>Cryptosporidium</em> spp.</td>
<td>37.9% samples</td>
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<thead>
<tr>
<th>Location</th>
<th>Organism</th>
<th>Results</th>
<th>Comments</th>
<th>Reference</th>
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<tbody>
<tr>
<td>USA</td>
<td>Cryptosporidium spp.</td>
<td>Median: 70 oocysts/10 L</td>
<td>Lake with significant agricultural communities; cattle grazing.</td>
<td>Keeley &amp; Faulkner 2008</td>
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<tr>
<td></td>
<td>Giardia spp.</td>
<td>Median: 5 cysts/10 L</td>
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<td>New Zealand</td>
<td>Campylobacter spp.</td>
<td>58% of samples</td>
<td>Dairy cattle predominant impact at five freshwater recreational water sites.</td>
<td>Till et al. 2008</td>
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<td></td>
<td>Salmonella spp.</td>
<td>7% of samples</td>
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<tr>
<td></td>
<td>Giardia spp.</td>
<td>8% of samples</td>
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<tr>
<td></td>
<td>Cryptosporidium spp.</td>
<td>5% of samples</td>
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<tr>
<td>New Zealand</td>
<td>Campylobacter spp.</td>
<td>66% of samples</td>
<td>Sheep/pastoral predominant impact at six freshwater recreational sites.</td>
<td>Till et al. 2008</td>
</tr>
<tr>
<td></td>
<td>Salmonella spp.</td>
<td>21% of samples</td>
<td>Poor correlations reported between E. coli and all pathogens except Campylobacter.</td>
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<tr>
<td></td>
<td>Giardia spp.</td>
<td>6% of samples</td>
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<td></td>
<td>Cryptosporidium spp.</td>
<td>2% of samples</td>
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<tr>
<td>Kenya</td>
<td>C. andersonii</td>
<td>25% of sites</td>
<td>River site surrounding pasture used for herded animals</td>
<td>Muchiri et al. 2009</td>
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<tr>
<td></td>
<td>C. parvum, C. hominis</td>
<td>0% of sites</td>
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<tr>
<td>Spain</td>
<td>Cryptosporidium spp.</td>
<td>93% of sites; 2–1350 oocysts/L</td>
<td>River basin – dairy farming; drinking, recreational water uses.</td>
<td>Castro-Hermida et al. 2009</td>
</tr>
<tr>
<td></td>
<td>Giardia duodenalis</td>
<td>100% of sites; 2–722 cysts/L</td>
<td>C. hominis most frequent at rec. areas; C. parvum and C. andersonii in river samples</td>
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<td>Location</td>
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<tr>
<td>Hong Kong</td>
<td><em>E. coli</em></td>
<td>Geo. mean: 978 cfu/100 mL</td>
<td>Two beaches impacted by livestock wastes (mainly swine)</td>
<td>Cheung <em>et al.</em> 1990</td>
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<td></td>
<td>Enterococci</td>
<td>Geo. mean: 144 cfu/100 mL</td>
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<td>USA</td>
<td>Faecal coliforms</td>
<td>Day 2 (leading edge): &gt;1 × 10^6 cfu/100 mL</td>
<td>River – Accidental swine waste spill</td>
<td>Burkholder <em>et al.</em> 1997</td>
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<td>Day 14: 100–1000 cfu/100 mL</td>
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<tr>
<td>UK</td>
<td><em>E. coli</em></td>
<td>River 1: 56–8300 cfu/100 mL</td>
<td>Two rivers: Livestock predominate in catchments; outflows near bathing beaches. High flow samples statistically higher than low flow samples.</td>
<td>Crowther <em>et al.</em> 2003</td>
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<td></td>
<td>Enterococci</td>
<td>River 1: 9.5–810 cfu/100 mL</td>
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<td></td>
<td><em>E. coli</em></td>
<td>River 2: 120–19000 cfu/100 mL</td>
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<tr>
<td></td>
<td>Enterococci</td>
<td>River 2: 17–3300 cfu/100 mL</td>
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<tr>
<td>USA</td>
<td>Faecal coliforms</td>
<td>Monthly samples: 50–17,400 cfu/100 mL</td>
<td>Watershed – Pasture 60% of land use; cattle have free access to stream at many locations.</td>
<td>Graves <em>et al.</em> 2007</td>
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<td>Spring high flow: 30–3480 cfu/100 mL</td>
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<td>Autumn low flow: 30–4480 cfu/100 mL</td>
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<td>Canada</td>
<td><em>E. coli</em></td>
<td>Daily geo. mean: 14–2189 cfu/100 mL</td>
<td>Bathing beach – located at mouth of river draining mainly agricultural area. 1999–2008 seasonal data.</td>
<td>Huron County Health Unit 2008</td>
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<td></td>
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<td>Seasonal geo. mean: 32–186 cfu/100 mL</td>
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<td>Location</td>
<td>Organism</td>
<td>Results</td>
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<tr>
<td>USA</td>
<td>Enterococci</td>
<td>Site 1: Geo. mean 2600 cfu/100 mL (95% C.I. 1011–6685) Site 2: Geo. mean 1423 cfu/100 mL (95% C.I. 795–2547)</td>
<td>Stream – Two sites where cattle have free access.</td>
<td>Lee et al. 2008</td>
</tr>
<tr>
<td>UK</td>
<td>Faecal coliforms, Enterococci</td>
<td>D: Geo. mean: $1.9 \times 10^3$ cfu/100 mL D: Geo. mean: $2.2 \times 10^2$ cfu/100 mL</td>
<td>15 Rivers – 11-year monitoring period during summer bathing season. D: Dairy land use areas, P: Pasture land use areas (cattle, sheep)</td>
<td>Kay et al. 2008</td>
</tr>
<tr>
<td></td>
<td>Faecal streptococci</td>
<td>P: Geo. mean: $3.6 \times 10^2$ cfu/100 mL P: Geo. mean: 4.7 cfu/100 mL</td>
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<td>SEPA 2009</td>
</tr>
<tr>
<td>Scotland</td>
<td>Faecal coliforms, Faecal streptococci</td>
<td>Mean 95th %ile: 1804 cfu/100 mL (500–3400) Mean 95th %ile: 1083 cfu/100 mL (171–4498)</td>
<td>Coastal bathing beach impacted by grazing livestock. 2000–2008 seasonal data.</td>
<td></td>
</tr>
<tr>
<td>India</td>
<td>Enterococci</td>
<td>Median 32 cfu/100 mL (23–44)</td>
<td>River Site 1 – Rural area with agricultural farms; drinking water, hygienic uses.</td>
<td>Lata et al. 2009</td>
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</table>
water than zoonotic pathogens; some zoonotic pathogens do not always occur in livestock wastes, but exhibit a seasonal presence, and some tend to survive much longer than FIOs in the aquatic environment. This data scarcity highlights significant gaps in our understanding of the occurrence of zoonotic pathogens in different water types impacted by livestock wastes. Additional empirical data could also help better characterize their relationships to FIOs and to validate transport models described in Chapter 5. Nevertheless, zoonotic pathogens are responsible for human illness and although the risks from waterborne exposures are not well known, measures to control their presence in water and reduce human exposures should be taken.

Factors affecting the ability of livestock faecal pathogens to reach areas within a watershed where the potential for human exposure through water contact activities can occur have been discussed. If an adequate number of pathogens survive the stresses existing in the aquatic environment, they may be present in sufficient numbers to cause infection and illness. The independent action, or single-organism premise is a generally accepted hypothesis that suggests that a single infectious organism is sufficient to cause infection (Haas et al. 1999). However, it is further believed that the likelihood of a single organism surviving the entire battery of defences encountered within a host is small, and that in general, a number of organisms are required for infection (Haas et al. 1999). Epidemiologically-derived estimates of the number of cells required to be ingested to lead to infection have ranged from as many as $10^3$–$10^4$ cells for less infective species and strains of enteric bacteria and protozoa to as low as 10–100 cells for more highly infective species and strains (Percival et al. 2004, Pond 2005).

The biological properties exhibited by the individual pathogen types themselves are also important to survival. It is well recognized that Giardia cysts and Cryptosporidium oocysts are extremely resistant to environmental stresses and can survive for long periods in the environment, whereas vegetative bacterial cells are more sensitive and die off more quickly.

Specific virulence mechanisms possessed by the faecal pathogens of relevance have been discussed in Chapter 2. In general, these are products or mechanisms which facilitate a pathogen’s ability to cause disease through invasion and colonization of the host, the impact on host cell functions and the evasion of the host’s immune defences. These take on different forms for different pathogens, but have the similarity that they must be expressed in order to be capable of causing illness. Also, as addressed in Chapter 2, particular species and strains of these pathogens can vary in their virulence potential. Different genotypes of Cryptosporidium parvum, and assemblages of Giardia duodenalis (lamblia) are known to have unique virulence capabilities (Fayer
2004, Nichols 2008). Strains and serotypes of a range of virulence levels have also been demonstrated for the waterborne bacterial pathogens: *Campylobacter*, pathogenic *E. coli*, *Salmonella* and *Yersinia* (Lightfoot 2004, Molbak & Scheutz 2004, Percival et al. 2004).

7.3.3 Host

Aspects that influence the susceptibility of the host include the type (degree) of water exposure, the duration of the contact period and the strength of the defences or immunity exhibited. The nature of water activity also impacts the means through which pathogens may gain entry into the human host. Three main routes exist for the uptake or entry of pathogens during water-related activities: inhalation, direct body contact and oral ingestion.

7.3.3.1 Inhalation

Airborne pathogens in droplet form can enter the human respiratory tract as a result of direct inhalation through the mouth or nasal passages. A number of natural and human-based actions can result in the production of aerosols containing microbes (Haas et al. 1999). These include waves, white-water spray and spray from engine-driven water activities. In these contexts, inhalation can be a conceivable route of entry for any primary or secondary-contact activity.

7.3.3.2 Direct body contact

For direct body contact, small cuts or abraded skin, as well as prominent access points like the eyes or ears are potential entryways for microbial pathogens. These routes would be considered of relevance for all primary-contact activities. Skin contact is the most frequent type of exposure during contact with near-shore sands, soils or sediments. For secondary-contact recreational pursuits, exposed arms and legs constitute the most frequent points of contact; but it is also important to consider that splashing can lead to additional exposure scenarios, and spills or falls can result in whole-body immersion. Schistosomes, whose infectious larvae are water-based, actively penetrate the skin of suitable hosts in contact with contaminated water.

7.3.3.3 Oral ingestion

Faecal microorganisms that are transmitted via the faecal-oral route and which infect the gastrointestinal tract are referred to as enteric pathogens (Haas et al.
1999). As suggested by the exposure definitions, swallowing water constitutes a significant route for potential pathogen entry during primary-contact activities. This would encompass swimming and bathing as well as any drinking uses of untreated or inadequately treated water. Recent reports indicate that playing in beach sand may expose children to pathogenic microorganisms through ingestion (Whitman et al. 2009). This route would be of particular importance for children during beach sand play. Water ingestion is regarded to be less likely during secondary contact exposures. Still, as with direct body exposures, inadvertent immersion can lead to whole body contact, and brings with it the potential for water ingestion.

Based on the discussions in Chapter 2, the routes of human entry for the livestock faecal pathogens of concern are illustrated in the following table (Table 7.3).

### Table 7.3  Primary faecal pathogens of livestock origin and their routes of entry for infecting a human host.

<table>
<thead>
<tr>
<th>Pathogen name</th>
<th>Route(s) of entry</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bacteria</strong></td>
<td></td>
</tr>
<tr>
<td>Campylobacter spp.</td>
<td>Oral ingestion</td>
</tr>
<tr>
<td>Pathogenic E. coli</td>
<td>Oral ingestion</td>
</tr>
<tr>
<td>Salmonella spp.</td>
<td>Oral ingestion</td>
</tr>
<tr>
<td><strong>Protozoa</strong></td>
<td></td>
</tr>
<tr>
<td>Cryptosporidium (parvum, hominis)</td>
<td>Oral ingestion</td>
</tr>
<tr>
<td>Giardia duodenalis (lamblia)</td>
<td>Oral ingestion</td>
</tr>
</tbody>
</table>

According to the principles of risk assessment (Haas 1999), the development of an exposure estimate requires knowledge of the concentration of organisms in the medium and the amount of medium that the individual may come in to contact with. For the primary livestock zoonotic pathogens, it is apparent that oral ingestion is the exposure route of most significance. The probability of human infection and illness occurring through other exposure routes can be considered insignificant. Consequently, the amount of water potentially ingested represents the critical contact factor when assessing exposure for these pathogens. Estimates of the quantities of water ingested during water activities are difficult to obtain, and as a consequence, research in this area has been limited. Approximations have largely focused on swimming-type exposures of the kind seen in freshwater environments. Values proposed for the amount of water that may accidentally be swallowed by an adult or a child during a swimming episode have ranged from 250 mL (WHO 2003), to 100 mL (Haas 1983, Mena...
et al. 2003) to 50 mL or less (Evans et al. 2006). These values may not hold for other types of water exposure, however, as different assumptions may be necessary for different activities and water types.

For all waterborne pathogens, the potential for exposure is also influenced by the frequency and duration of water contact activities. The probability of coming in contact with pathogenic microorganisms increases with repeated water visits or prolonged exposures (Pond 2005). In addressing livestock zoonotic pathogens specifically, certain behavioural, demographic, socioeconomic and climate factors can have affects on this component. With recreational water activities, children are likely to have more frequent exposures and spend more time in the water than adults. In countries in warmer climates, individuals may see more opportunities for recreation due to higher water temperatures and longer seasons. It has also been put forward that equipment advances, for example, wetsuits can extend the length of a contact season or session (Pond 2005). In developing countries, exposures are likely to be out of basic necessity for sanitary purposes or occupational requirements, as opposed to leisure pursuits. Gender factors may also play a comparatively larger role in these countries. An example may be communities where women shoulder the burden for chores involving water contact such as laundering and bathing of children.

**Box 7.1 Additional pathogens of interest: Leptospira spp., Schistosoma japonicum**

Two additional pathogens, *Leptospira* spp. and *Schistosoma japonicum* are worth mentioning in the context of this chapter. These organisms are not among those thought to be of primary significance from a global perspective. However, both are major public health concerns in developing countries and represent interesting examples of disease transmission stemming from human contact with livestock wastes.

*Leptospira* spp

Leptospirosis is most significant in developing countries located in tropical and subtropical climates. The disease is considered endemic to most countries of Southeast Asia, and outbreaks have been recently reported in Nicaragua, Brazil and India (Vijayachari et al. 2008). In waterborne transmission, humans become infected as a result of direct body contact with water contaminated with leptospires, with the organisms gaining entry through mucous membranes or broken skin. Cattle and swine are considered the primary livestock reservoirs for *Leptospira* (Vijayachari et al. 2008). Rodents and dogs are also recognized carriers, and these animals may have more relevance in urban exposure scenarios. In developing countries
leptospirosis is primarily regarded as an occupational disease. Rice or sugar cane farmers and military personnel are among the more significant groups affected through water contact. Additionally, a number of outbreaks have been linked to disaster events and persons exposed to wet environments created by flooding (Barcellos & Sabroza 2001; Gaynor et al. 2007). Incidence of leptospirosis as reported in developed countries have been most commonly linked to recreational water activities, including both domestic exposures and those occurring during travel to endemic countries (Pond 2005).

*Schistosoma japonicum*

Incidence of *S. japonicum* have largely been reported in China, the Philippines and certain areas of Indonesia. Human exposures occur primarily among rice farmers working in marshland areas. These marshlands serve as the natural habitat for water buffalo, the primary reservoir for this organism. Increasing use of these animals as work animals has also been reported in these countries (Gray et al. 2008).

Infection with *S. japonicum* is acquired through direct contact with contaminated waters. The organism is capable of gaining access to the human body by penetrating through intact or broken skin; it then travels to the bloodstream to develop and cause further illness. Data specific to rates of *S. japonicum* infection in affected countries has been limited. Globally, however, schistosomiasis (from all sources) is estimated to affect 207 million people, with an additional 779 million being considered at risk of infection (Steinmann et al. 2006).

A final element of consequence in the discussion of host uptake and susceptibility is the issue of strength of immunity. The status of a host’s immune system has a significant role in determining the susceptibility to infection and the severity of illness (Pond 2005). Groups recognized as having reduced immune functions include persons in different vulnerable life stages (pregnant women, children, the elderly), undernourished individuals, and persons with compromised or suppressed immune defences either as the result of disease (HIV/AIDS, cancer, liver disease) or medical interventions (chemotherapy, immunosuppressive medications). Tourists as a group may be comparatively more vulnerable than resident populations—a consequence of lacking prior exposure to the types of pathogens in new environment. Other considerations can have a positive effect on the host’s immune status. The overall gains to health from repeated physical activity may improve and individual’s ability to resist disease. As well, repeated exposures to, or past infections with certain waterborne pathogens may confer a degree of immunity to the user (Dangendorf 2004).
7.4 ADEQUACY OF TOOLS FOR ASSESSMENT AND MONITORING; REGULATORY CHALLENGES

Various voluntary programmes, guidelines, policies, standards and regulations based on sound science can be used in parallel at the source of contamination and at sites of human exposure, to proactively manage risks and limit exposures to zoonotic pathogens from livestock. The relevance of these tools as they pertain specifically to exposure assessment are addressed in the following Chapter, with their potential role as exposure interventions.

Monitoring activities specific to water exposures chiefly involve measurements of faecal indicator organism levels as an indication of the potential risk of exposure, and waterborne illness surveillance as an indication of the burden of illness potentially attributable to the hazards.

In terms of the adequacy of faecal indicator monitoring practices it is clear that, worldwide, measurements have been restricted to bathing beach areas for the protection of recreational-type exposures. Efforts for other water types and user activity combinations have been comparatively limited. Additional challenges impacting the effectiveness of the current methods include:

- Significant spatial-temporal variability of faecal indicator concentrations in natural waters;
- Substantial delays between the time of testing and the acquisition of the information; and,
- Noted poor correlations between faecal indicators and individual pathogens.

A significant hindrance to establishing effective regulation and monitoring is that the issue of livestock contamination of natural waters traverses multiple subject areas (agriculture, environment, health), as well as jurisdictional and geographical boundaries. Regulation and monitoring at bathing beaches have been reasonably well established in most developed countries. Certain jurisdictions have defined specific regulatory requirements (US EPA, EU), while in others (Canada, Australia, New Zealand) enforcement falls under the broader scope of public health legislation. In contrast, regulatory coordination of monitoring relevant to other areas of potential human contact has not received much attention.

As for surveillance, all countries have mechanisms in place for infectious disease surveillance and reporting; however, reporting of data specific to waterborne illness has been limited. Fundamental reasons for this include lack of resources and technical capacity, preferential focus on diseases of epidemic or pandemic importance and absence of a rigorously coordinated reporting framework. Even in developed countries recognized for their robust surveillance mechanisms, it is widely believed that the rates and causes of waterborne illness
are severely underreported. As with monitoring, the chief obstacle interfering with regulation or improved management in this area is the challenge that the responsibilities for reporting, detection and communication cut across multiple sectors, jurisdictions and geographical boundaries. Examples of specific challenges to provide context to this problem:

- Responsibilities for disease reporting lie with the patient, the diagnosing physician, the medical laboratory and coordinating health agency, with the potential existing for information to go unreported or undetected at each level.
- In most countries, gastrointestinal illness is not a reportable illness in and of itself. At the most basic level, coordinated detection and identification steps are required in order to positively identify cases of waterborne infection and illness.
- Water exposures of relevance for these discussions (natural water exposures) often involve travel to other jurisdictions, which can increase the difficulty of case tracking and outbreak detection.

Advancements are being made that may permit some of these challenges to be overcome in the future. Gains in the area of monitoring include the development of rapid detection and predictive tools, as well as the gradual betterment of our understanding of pathogen-indicator relationships through continued research in this area. Challenges facing the improvement of surveillance mechanisms may be somewhat more daunting, but advances in information technology and electronic communications are expected to be of great benefit to this area. Considerable investments in terms of time, funding and cooperation between multi-jurisdictional stakeholders will be required to see these expectations fulfilled; however, the increasing global attention to the issue of waterborne zoonosis may serve as the catalyst for progress.

### 7.5 SUMMARY

The subject of human exposure to zoonotic waterborne pathogens from livestock wastes is of a considerable complexity. Environmental, biological, behavioural, geographical, political and cultural pressures all combine to form a complex web dictating the potential for human contact, infection and illness. In general, the risks that livestock pathogens present to humans during activities in relevant aquatic environments are insufficiently understood. Science has advanced our understanding of interrelationships between livestock waste contamination, water impairment, zoonotic pathogens and human infection and illness. However, echoing a conclusion of Chapter 5 – there are still many areas where
our basic knowledge is deficient. The lack of data pertaining to pathogen occurrence for numerous source and water environment combinations, and an evidence base for accurate measures of exposure for various water contact activities are but two examples.

Continued research is needed to advance our understanding in those areas where knowledge is lacking. One important challenge in developing tools to facilitate exposure assessments with a broad applicability is the role and relative importance of local factors in influencing the true nature of host-pathogen-environment interactions. Despite the advancement of the tools and knowledge, significant efforts will still be required to fit this information to the specific scenarios, contexts and circumstances. An additional challenge relates to the aforementioned mismatch between the strength of scientific resources and the burden of global illness seen in developed and developing countries. This raises the question how to identify opportunities or solutions for utilizing science to better comprehend the risks of livestock waterborne pathogen exposure with a more global focus.

REFERENCES


