Review

Climate change, flooding, urbanisation and leptospirosis: fuelling the fire?

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ABSTRACT

Flooding and heavy rainfall have been associated with numerous outbreaks of leptospirosis around the world. With global climate change, extreme weather events such as cyclones and floods are expected to occur with increasing frequency and greater intensity and may potentially result in an upsurge in the disease incidence as well as the magnitude of leptospirosis outbreaks. In this paper, we examine mechanisms by which climate change can affect various ecological factors that are likely to drive an increase in the overall incidence as well as the frequency of outbreaks of leptospirosis. We will discuss the geographical areas that are most likely to be at risk of an increase in leptospirosis disease burden owing to the coexistence of climate change hazard risk, environmental drivers of leptospirosis outbreaks, local socioeconomic circumstances, and social and demographic trends. To reduce this disease burden, enhanced surveillance and further research is required to understand the environmental drivers of infection, to build capacity in emergency response and to promote community adaptation to a changing climate.

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1. Introduction

Leptospirosis is the most common bacterial zoonosis worldwide, caused by spirochetes of the genus *Leptospira*. There are 20 species of leptospires, consisting of over 200 serovars, circulating in a wide range of animal reservoir hosts including rats, other rodents, livestock and domestic pets.[1] Many of these serovars are known to be pathogenic to humans, who can acquire infection through direct contact with animals or through an environment contaminated by animal urine. Infection might occur through ingestion of contaminated food or water, through mucosal surfaces or through skin contact, particularly if there are breaks in the skin. Risk factors for infection therefore include occupational exposure (farming, slaughtering), recreational activities (swimming, canoeing), cultural factors (bathing in rivers, animal rearing, pets) and socioeconomic circumstances (sanitation, poverty).[2]

After an incubation period of 2–30 days, leptospirosis produces a biphasic illness with an acute or leptospiraemic phase lasting approximately 7–10 days followed by an immune phase in which immunoglobulins are produced to eliminate the organism from the host.[2,3] Leptospirosis can produce a wide range of clinical syndromes, including non-specific febrile illnesses, renal failure, liver failure, pulmonary haemorrhage and meningoencephalitis. It causes severe disease in at least hundreds of thousands of people each year, with fatality rates of up to 30% in

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some areas.[3] Treatment options include antibiotics such as doxycycline,[4] penicillin G,[5] ceftriaxone[6] and cefotaxime,[7] and patients with severe illness might require respiratory, renal or haemodynamic support.

Owing to its variable presentation, leptospirosis is often unrecognised or misdiagnosed and the true incidence is likely to be underestimated and underreported. The WHO has identified leptospirosis as a neglected tropical disease of global importance, requiring further research to understand its epidemiology, ecology and the disease burden that it causes around the world.[3]

2. Ecology of leptospirosis

The ecology of leptospirosis involves the complex interaction between humans, animal reservoirs, leptospires and the environment in which they coexist. These interactions are illustrated in Figure 1.

Not surprisingly, therefore, there are distinct epidemiological patterns of leptospirosis depending on the ecological setting. In rural areas, transmission is usually associated with farming and livestock, with increased risk during the warm and rainy months. In urban areas, infection is associated with overcrowding, poor hygiene standards, inadequate sanitation and poverty, all of which typically occur in urban slums in developing countries.[8] In developed countries, infection is now increasingly being associated with outdoor recreational exposure and international travel.[9]

3. Environmental drivers of leptospirosis

Although leptospirosis is common and widespread, there remain significant gaps in our understanding of its transmission dynamics and of the trigger factors for disease outbreaks. However, epidemiological studies have identified various environmental risk factors for infection or outbreaks that differ between ecological settings. A number of these factors are likely to be influenced by climate change and urbanisation and will be discussed below.

Figure 1. The ecology of leptospirosis. Leptospires are maintained in nature by a wide variety of mammalian reservoir hosts. Humans can acquire leptospirosis through direct contact with infected animals or by indirect contact with an environment that has been contaminated by animal urine. The cycle of transmission of leptospirosis is in turn driven by environmental forces, including sociodemographic factors, climate and land use.

3.1. Rainfall and flooding

Heavy rainfall and flooding increase the risk of leptospirosis by bringing bacteria and their animal hosts into closer contact with humans. Numerous outbreaks of leptospirosis have been reported following extreme weather events around the world, in geographically diverse areas including India,[10,11] Laos,[12] Indonesia,[13] Italy,[14] Brazil,[15]

Table 1
Examples of leptospirosis outbreaks associated with heavy rainfall and flooding

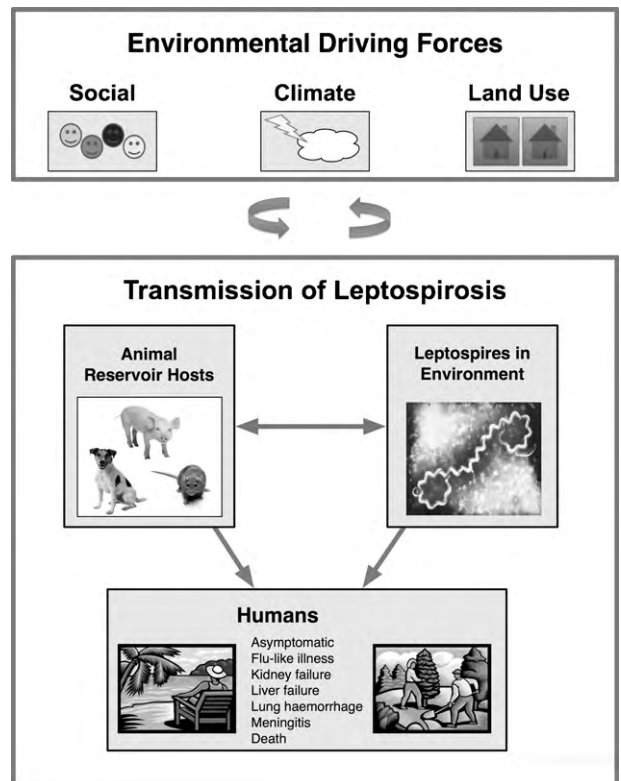| Country/region	Year	Flooding event
Mumbai, India[10]	2005	944 mm of rain in 24 h resulted in an eight-fold rise in the number of cases compared with the previous 4 years
Kerala, India[11]	2002	Peaks in leptospirosis incidence seen 7–10 days after peaks of heavy rainfall
Orissa, India[22]	1999	19.2% of study subjects in flooded villages after a cyclone were found to have serological evidence of symptomatic leptospiral infection
Laos[12]	2006	Flooding in home property associated with seropositivity for leptospirosis (odds ratio 2.12)
Indonesia[13]	2002	Outbreak followed massive flooding in Jakarta in January 2002
Italy[14]	2002	Devastating flooding in suburban area resulted in 6.8% seroconversion rate for leptospirosis
Guyana[16]	2008	Epidemic followed severe flooding, with 30% of Guyana's inhabitants displaced from their homes
Nicaragua[17]	1995	Epidemic of leptospirosis followed severe rainfall and flooding in 2005. Over 5000 mm of rain compared with annual average of 1300 mm
Puerto Rico[18]	1996	Leptospirosis diagnosed in 6% of non-dengue febrile illnesses pre-hurricane versus 24% of non-dengue febrile illnesses post-hurricane
New Caledonia[20]	2008	High rainfall and flooding associated with La Niña in early 2008. Epidemic of leptospirosis in 135 people. Incidence of 500/100 000 population in Bourail region

Guyana,[16] Nicaragua,[17] Puerto Rico,[18] the USA,[19] New Caledonia[20] and Australia.[21] Details of some of these outbreaks are given in Table 1.

In Argentina, flooding has emerged as the major risk factor for leptospirosis, ahead of occupational exposure.[23] In Mumbai, India, an eight-fold increase in disease incidence was noted after severe flooding in 2005.[10] In Manila, Philippines, a large outbreak of leptospirosis was reported after tropical storms and severe flooding in October 2009. The number of leptospirosis-related hospital admissions soared from 140 to 1027 in just 3 days, with a case–fatality rate of 8.6%.[24] A higher seroprevalence of infection has also been associated with heavy rainfall and flooding in China, France, Brazil, Trinidad and Tobago, and French Polynesia.[25–29] These reports demonstrate that leptospirosis outbreaks can affect both developing and industrialised nations alike and occur in a wide variety of settings including large urban centres, rural areas and small island states.

Flooding and other natural disasters can also increase the risk of infectious diseases such as leptospirosis by disrupting public health services and infrastructure, damaging water and sanitation networks, displacing populations, damaging homes and increasing environmental exposure to pathogens.[30]

3.2. Temperature

Leptospires are able to survive for longer periods of time in higher temperatures and humid environments,[8] and seasonal variation in the incidence of leptospirosis is well documented.[13] Surveillance in Argentina from 1999 to 2005 showed that 76% of cases occurred during the warmer and wetter months.[23] In Guadeloupe, record numbers of cases were reported from 2003 to 2005 following very hot and wet seasons associated with two El Niño events.[31]

Higher temperatures can also reduce surface water availability by evaporation and at the same time encourage water-based activities for humans and animals (e.g. swimming, bathing, drinking), thereby promoting contact between humans, livestock, pets and wildlife through more intense sharing of shrinking surface water sources.[32]

3.3. Exposure to animals

As can be expected from its mode of transmission, leptospirosis has been shown to be associated with exposure to animals, particularly to rats, rodents, domestic pets and livestock.[8] The animals implicated in disease transmission vary between serovars and geographic locations, and the risk of exposure depends on sanitation, living conditions, agricultural practices and local fauna as well as cultural factors.

Contact with rats has been shown to be a significant risk factor for infection in many diverse environmental settings including large urban communities in India,[33] Brazil[34] and Tokyo,[35] small island states including New Caledonia[36] and the Seychelles,[37] and strawberry fields in Germany.[38]

3.4. Poor sanitation and inadequate waste disposal

Sanitation and waste management are major problems in developing countries and contribute significantly to the incidence of many infectious diseases and other adverse health outcomes. The presence of garbage, waste and sewage encourage the proliferation of rodents and can therefore increase the risk of leptospirosis. Garbage can also block drainage systems and exacerbate flooding risk. Many studies around the world have confirmed that close contact with garbage and sewage are significant risk factors in leptospirosis transmission, particularly in urban slums.[15,33,34,37]

4. Climate change and effects on the environmental drivers of leptospirosis

4.1. Flooding

Flooding results from the interaction between rainfall, surface run-off, sea level, catchment size and local topography. These factors can in turn be modified by land use, urbanisation, deforestation, agricultural practices, irrigation, dams and water management.[39] As a result of global climate change, additional factors that will contribute to the risk of flooding include rising sea levels, rising sea and land surface temperatures, increasing frequency of extreme weather events, more intense tropical cyclones and larger storm surges.[40]

Flooding is the most common natural disaster both in developed and developing countries and is expected to occur with increasing frequency.[41] From 2004 to 2008, flooding and tropical cyclones were responsible for 40% of natural disasters around the world, and approximately 120 million people are currently exposed to tropical cyclones each year.[40] Seventy percent of these disasters occurred in Asia, the Pacific Islands, Africa and the Middle East where the majority of the world's most vulnerable populations live.[42]

In 2007, heavy rains and flash floods displaced approximately 16 million people in south Asia, affecting 11 million in India, 4.5 million in Bangladesh and 250 000 in Nepal.[43] In India, where leptospirosis outbreaks are common after flooding, summer monsoon rainfall is projected to rise by 20%. In addition, glacial retreat in the Himalayas is expected to increase the volume of water flow into major river systems, further contributing to the flooding risk.[44,45]

Although rainfall is expected to decrease in some areas of the world as a result of climate change, increasing rainfall, cyclone intensity and flooding risk are expected to occur in the tropics, where most of the areas currently known to have a high incidence of leptospirosis are found.[40]

4.2. Rising temperatures

Global temperatures are predicted to rise by 1.4–5.8 °C by the year 2100.[39] As discussed above, higher temperatures are associated with an increased incidence of leptospirosis. Global warming can therefore lengthen the

seasons and expand the geographical areas for optimal survival and transmission of leptospires.

4.3. Animal reservoirs

Rainfall, flooding and natural disasters can influence animal population density and behaviour in different ways. On the one hand, rodents and other animals might proliferate due to the scattering of garbage, debris and food, the disruption of sewage and waste management systems and the stimulation of vegetation growth resulting in an increase in food availability.[30] On the other hand, flooding can destroy animal habitats and reduce their population size, but it can also transiently increase contact between animals and humans while the animals have been driven out of their usual domain and people have been displaced from their homes.[46]

As mentioned above, decreased rainfall can also increase contact between humans and animals by reducing surface water supply. In addition, decreased rainfall can eliminate food sources and force rodents into human habitats to scavenge for food, thereby increasing their contact with people.[46]

The way in which climate change will modulate existing animal behaviour (e.g. feeding, migration and reproduction) is complex and dynamic and will depend on multiple environmental and ecological factors as well as the animal species involved.

5. Where can we expect an increase in leptospirosis disease burden?

Areas at highest risk are those where multiple risk factors for leptospirosis are likely to coexist, such as the combination of increasing flooding risk, rising temperatures, overcrowding, poor sanitation, poor health care, poverty, and an abundance of rats and other animal reservoirs. These conditions are most likely to occur concurrently in urban slums, low-lying coastal areas and small island states. Many of the areas known to have a high incidence of leptospirosis belong to one of these ecological settings (see Table 2), and their disease burden from leptospirosis is likely to increase as a result of climate change, population growth and urbanisation. Infection can also potentially lead to secondary long-term effects such as chronic disease, economic loss and psychosocial problems, with the most severe impact likely to be seen in areas with already high vulnerability and poor coping mechanisms.[30,40,57]

Table 2
Selected regions with reports on leptospirosis incidence

Country/region	Incidence (100 000/year)
Seychelles[47]	101
New Caledonia[13]	2.1–30
Andaman Islands[48]	50
Vanuatu[49]	40
Antilles/Guyana[50]	23
Réunion and Mayotte[26]	12
Kerala, India[51]	11.4
American Samoa[52]	10.4
China[13]	7.1
Thailand[13]	0.3–23.7
Sri Lanka[13]	14
Cambodia[13]	7.7
Costa Rica[53]	6.7
New Zealand[54]	4.4
Hawaii, USA[55]	3.3
Cuba[53]	2.5
Queensland, Australia[53]	2.1
Brazil[53]	1.3
Argentina[53]	1.0
Australia[56]	0.52

Table 3
Predicted population by 2025 in selected megacities[59] and their risk of flooding[60]

Rank	City	Population by 2025 (millions)	Risk of:		
			Flood	Storm surge	Tropical storm
1	Tokyo, Japan	36.4	+	++	++
2	Mumbai, India	26.4	++	++	+
3	Delhi, India	22.5	++		
4	Dhaka, Bangladesh	22.0	+++	+	+++
5	São Paulo, Brazil	21.4	+		
6	Mexico City, Mexico	21.0	+		
7	New York–Newark, USA	20.6	+	++	++
8	Kolkata, India	20.6	+++	++	+++
9	Shanghai, China	19.4	++	+++	++
10	Karachi, Pakistan	19.1	++	++	+
12	Lagos, Nigeria	15.8	+		
13	Cairo, Egypt	15.6	++		
14	Manila, Philippines	14.8	++	+	+++
16	Buenos Aires, Argentina	13.8	++	++	
17	Los Angeles, CA, USA	13.7	++		
18	Rio de Janeiro, Brazil	13.4	++		
19	Jakarta, Indonesia	12.4	++	+	
20	Istanbul, Turkey	12.1	++	+	
22	Osaka-Kobe, Japan	11.4	++	++	++
23	Moscow, Russia	10.5	+		
27	Paris, France	10.0	++		

+: low risk; ++: medium risk; +++: high risk.

5.1. Megacities and urban slums

Urbanisation can potentially magnify flooding intensity by ten-fold.[58] Large cities are particularly prone to flooding owing to the combination of large paved, compacted or roofed areas that are more impermeable than vegetated land and generate more run-off. Furthermore, large urban areas can also create their own microclimate and cause intensification of rain, hail and thunderstorms.[34] For cultural and economic reasons, many large cities are situated near the coast or large rivers, thus compounding their risk of flooding. The risk of flooding in some of the world's largest cities is shown in Table 3.

The world's population is expected to increase from 6.7 billion in 2007 to 9.2 billion in 2050. The number of urban dwellers is expected to almost double from 3.3 billion to 6.4 billion during this time, with most of the increase occurring in less developed countries.[59] By 2025 it is estimated that there will be 27 megacities around the world, with 22 of these in less developed countries.[59] One in three urban dwellers, or one billion of the world's population, currently live in slums. Owing to population growth and increasing urbanisation, UN-HABITAT estimates that by 2020 there will be 1.4 billion slum dwellers in the world, accounting for 20% of the world's population.[61]

Africa is the world's most rapidly urbanising region and also has the highest slum growth rates, with environmental refugees migrating from rural to urban areas as a result of droughts and floods.[61] Over 70% of inhabitants in African cities (accounting for at least 100 million people) currently live in slums that are prone to flooding.[42] The average number of people in Africa impacted by flooding could increase from 1 million per year in 1990 to 70 million in 2080.[62]

One-half of the urban population in developing countries currently lack piped water, waste collection, paved roads, sewers and stormwater drains.[42] The above predictions in human demographics will therefore have significant implications for the future epidemiology of infectious diseases, including leptospirosis.

With the increasing risk of flooding and continuing population growth and urbanisation in developing countries, these areas are likely to experience an upsurge in the scale and severity of leptospirosis epidemics. Unfortunately, slum inhabitants are also some of the most vulnerable and impoverished people in the world and have a poor capacity to cope with extra health challenges. This poor resilience will further magnify their disease burden from leptospirosis.

Leptospirosis is more common in developing countries, but it is also reported in urban areas in more affluent cities such as Tokyo, Japan,[35] Baltimore, MD, and Detroit, MI, USA.[63] Although developed countries are generally better able to manage disease outbreaks, disease burden can still be significant due to the sheer number of people in megacities who will potentially be at risk.

5.2. Low-lying areas

Sea levels have risen by 10–20 cm since the late 1950s and are projected to reach 45 cm by 2100.[41] Areas particularly vulnerable to flooding from rising sea levels include deltas with very large populations (e.g. Ganges-Brahmaputra, Mekong, Chang Jiang, Nile and Mississippi Deltas), low-lying coastal cities and small island states.[57]

The world's coastal population could potentially grow to 5.2 billion people by 2080 and a rise in sea level of 1 m could potentially affect 18.6 million people in China, 13 million in Bangladesh, 5 million in the Mekong Delta, 4 million in the Red River Delta, 3.5 million in Egypt and 3.3 million in Indonesia.[40,41] Many of these areas are already known to have a high incidence of leptospirosis, and the additional pressures of population growth and flooding are likely to drive an upsurge in disease burden.

5.3. Small island states

Small islands are expected to experience greater increases in surface temperature than average global rates. Extreme climate events such as heatwaves, extreme rainfall and cyclones are also expected to occur with increasing frequency. Between small island states there is a wide diversity in size, elevation, soil types, drainage, natural resources, surface freshwater supply, agriculture practices, socioeconomic status, demography and health status.[64] Depending on these factors and their geographical location, climate change is likely to affect some islands more severely than others. For example, susceptibility to sea level rise and coastal flooding varies significantly even between different Pacific Islands.[57,65]

However, small island states share common characteristics that can increase their vulnerability to natural disasters—their small physical size, remoteness, limited natural resources, delicate ecosystems, high population density, poor infrastructure, dependency on neighbouring countries, and limited financial and human resources.[57]

6. Challenges in the diagnosis of infectious diseases following flooding

Leptospirosis is often poorly recognised and overlooked as a cause of fever or systemic illness. Misdiagnosis is common because of its variable symptoms and non-specific presentations that can mimic many other infectious diseases such as dengue, malaria, hepatitis, pneumonia and meningitis. Depending on geographic location, other infections that might be included in the differential diagnosis include haemorrhagic fevers, Q fever, scrub typhus, yellow fever and rickettsial infections.

Epidemics of infectious diseases are common following natural disasters, and concurrent outbreaks of multiple infections can lead to diagnostic challenges, particularly if laboratory facilities are inadequate. Misdiagnosis or delayed diagnosis has significant clinical implications because early treatment of some of these infections (e.g. leptospirosis, malaria and meningitis) is crucial to minimise morbidity and mortality. In addition, misdiagnosis can lead to critical delays in implementing disease-specific interventions, allowing epidemics to 'escape'.

Food- and water-borne infections are common after flooding and some of these can be difficult to differentiate clinically from leptospirosis. For example, hepatitis A and E are commonly seen in developing countries and can cause

an acute febrile illness and jaundice often seen in patients with leptospirosis.[9]

Epidemics of mosquito-borne diseases are also common during flooding because of the abundance of stagnant water available as larval breeding sites. A number of these infections, such as malaria, dengue and Chikungunya fever, are clinically difficult to distinguish from leptospirosis and studies have shown that leptospirosis is often misdiagnosed or underdiagnosed during dengue outbreaks.[9,18,55]

Co-infection with multiple pathogens might also occur and further complicate clinical diagnosis and management. A study of acute febrile illness in Egypt found that 12.4% of 1510 cases had more than one concurrent acute infection, with 83% of these having leptospirosis as one of their diagnoses.[9]

It is therefore important for clinicians to consider leptospirosis in the differential diagnosis of febrile illnesses after flooding. Early identification of cases and outbreaks will improve patient outcomes and facilitate timely public health interventions. The WHO's recommended case definitions for leptospirosis are shown in Box 1.

Laboratory diagnosis during the acute phase can be performed using methods such as ELISA for the detection of anti-*Leptospira* IgM,[67] lateral-flow enzyme immunosorbent assays,[68] or culture of blood, cerebrospinal fluid or urine in Ellinghausen–McCullough–Johnson–Harris (EMJH) medium.[69] Highly sensitive and specific diagnostic tests based on standard or real-time PCR have also been developed.[2,70] Immune-phase diagnostics remain reliant on the microscopic agglutination test,[71] which detects the presence of antibodies specific to leptospires using a panel of antigens representing the serogroups or serovars indigenous to the given geographical location.

7. Socioeconomic impact of leptospirosis

Apart from the effects of leptospirosis on the health of individuals, there are also potential financial and social impacts on the victims' families and their community. There are direct and indirect economic costs of the disease, including the cost of health care for the acute illness, management of long-term medical complications, loss of income as a result of the illness, and potential effects on long-term earning capacity. On a community level, thousands of people can potentially become infected in a short time during epidemics, and put enormous stress on healthcare facilities. Implementation of public health measures for prevention, control and surveillance will also put added stresses on the health system. Furthermore, leptospirosis can threaten livestock, thus compounding economic losses.

Many outbreaks of leptospirosis occur in urban slums where some of the world's most deprived and vulnerable people live, where socioeconomic resilience is invariably poor, where access to health care is usually already inadequate and where public health services are often limited. These circumstances combine to create an environment in which leptospirosis will have the greatest health and socioeconomic impacts on communities, and this situation

Box 1: WHO case definitions for human leptospirosis[66]

A. Clinical description

The usual presentation is an acute febrile illness with headache, myalgia (particularly calf muscle) and prostration associated with any of the following symptoms/signs:

- conjunctival suffusion;
- anuria or oliguria;
- jaundice;
- cough, haemoptysis and breathlessness;
- haemorrhages (from the intestines; lung bleeding is notorious in some areas);
- meningeal irritation;
- cardiac arrhythmia or failure; and
- skin rash.

Note. Other common symptoms include nausea, vomiting, abdominal pain, diarrhoea and arthralgia. The clinical diagnosis is difficult where diseases with symptoms similar to those of leptospirosis occur frequently.

B. Laboratory criteria

Presumptive diagnosis:

- A positive result of a rapid screening test such as IgM ELISA, latex agglutination test, lateral flow, dipstick etc.

Confirmatory diagnosis:

- Isolation from blood or other clinical materials through culture of pathogenic leptospires.
- A positive PCR result using a validated method (primarily for blood and serum in the early stages of infection).
- Four-fold or greater rise in titre or seroconversion in microscopic agglutination test (MAT) on paired samples obtained at least 2 weeks apart. A battery of *Leptospira* reference strains representative of local strains to be used as antigens in MAT.

C. Case classification (humans)

Suspected: A case that is compatible with the clinical description and a presumptive laboratory diagnosis.
Confirmed: A suspect case with a confirmatory laboratory diagnosis.

is likely to worsen with increasing urbanisation in developing countries.

8. Conclusions

The combination of climate change, flooding, population growth and urbanisation will almost certainly lead to an escalation in the global burden of disease from leptospirosis. Areas at particularly high risk include urban slums, low-lying areas and small island states.

The epidemiology of leptospirosis is complex and varies significantly in different environmental settings, and an ecological approach is therefore required to understand disease patterns at local, regional and global levels.[72] More enhanced surveillance and further research is required to understand better the transmission dynamics of leptospirosis and how these can be influenced by climate events, environmental factors, animal reservoirs, and

human demographic and social trends. Ongoing monitoring in the post-disaster phase is essential for assessing the long-term impacts of leptospirosis following flooding.[30]

Spatiotemporal modelling and disease mapping using Geographic Information Systems can potentially be useful for estimating current disease burden as well as predicting future disease burden as a result of environmental change. Valuable and dynamic information can be generated to pinpoint and project high-risk locations and hotspots for epidemics. Tools can also be developed to identify trigger factors for outbreaks, develop early warning systems, estimate and predict outbreak frequency and intensity, and identify areas most vulnerable to a high disease burden. If available, this information could be used by stakeholders in emergency and disaster response to manage risk factors at disaster sites, to improve the timeliness of emergency response, to assess the ability of response teams to cope with increasing future demands, to provide an evidence base for planning and allocating disaster management and public health resources, and to target interventions aimed at reducing infection risk and the overall burden of disease from leptospirosis. Understanding the environmental drivers of leptospirosis infection is also essential to effectively promote community awareness and hazard reduction and to build local capacity to prepare for the increasing risk of leptospirosis as a result of climate change.

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