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Review

Climate Change and Water-Related Infectious Diseases

Gordon Nichols [1,2,3,*], Iain Lake [3] and Clare Heaviside [1,4,5]

1 Centre for Radiation Chemicals and Environmental Hazards, Public Health England, Chilton, Oxon OX11 0RQ, UK; clare.heaviside@gmail.com
2 European Centre for Environment and Human Health, University of Exeter Medical School, C/O Knowledge Spa RCHT, Truro, Cornwall TR1 3HD, UK
3 School of Environmental Sciences, UEA, Norwich NR4 7TJ, UK; i.lake@uea.ac.uk
4 School of Geography, Earth and Environmental Sciences, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK
5 Department of Social and Environmental Health Research, London School of Hygiene and Tropical Medicine, 15-17 Tavistock Place, London WC1H 9SH, UK
* Correspondence: Gordon.nichols@me.com

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Abstract: Background: Water-related, including waterborne, diseases remain important sources of morbidity and mortality worldwide, but particularly in developing countries. The potential for changes in disease associated with predicted anthropogenic climate changes make water-related diseases a target for prevention. **Methods**: We provide an overview of evidence on potential future changes in water-related disease associated with climate change. **Results**: A number of pathogens are likely to present risks to public health, including cholera, typhoid, dysentery, leptospirosis, diarrhoeal diseases and harmful algal blooms (HABS). The risks are greatest where the climate effects drive population movements, conflict and disruption, and where drinking water supply infrastructure is poor. The quality of evidence for water-related disease has been documented. **Conclusions**: We highlight the need to maintain and develop timely surveillance and rapid epidemiological responses to outbreaks and emergence of new waterborne pathogens in all countries. While the main burden of waterborne diseases is in developing countries, there needs to be both technical and financial mechanisms to ensure adequate quantities of good quality water, sewage disposal and hygiene for all. This will be essential in preventing excess morbidity and mortality in areas that will suffer from substantial changes in climate in the future.

Keywords: climate change; waterborne disease; natural environment; risks; public health; cryptosporidiosis; cholera; leptospirosis; Legionnaires' disease

1. Introduction

The effect of human activity on observed changes to the climate system over recent decades is widely acknowledged and is a global cause for concern. Anthropogenic (man-made) climate change has led to a rise in annual global mean temperatures since pre-industrial times, with more rapid increases since the mid-1900s [1]. As well as changing weather patterns, increasing average temperatures and, potentially of more concern, is the increase in the frequency of extreme weather events which can have enormous human cost [2]. Climate change is seen as an example of a tragedy of the Commons [3], whereby it is in the interests of individuals to benefit from human activity but the overall impact on all people collectively will be negative unless there is an agreed intervention. It is generally the case that the largest impacts on health are realised in developing regions of the world such as the tropics, whereas the greatest contributors to greenhouse gas emissions are often developed countries which do not suffer the consequences of extreme events to the same extent [4]. Due to the lifetime of greenhouse gases such as carbon dioxide in the atmosphere, and the timescales associated with ocean warming, even if global CO_2 emissions were curtailed immediately, the effects on the earth's climate, including increasing temperatures and sea level rise would continue for a number of decades before starting to plateau [2]. However, this should be seen as a general call to action to reduce emissions as soon as possible, given that the impacts are likely to extend beyond current conditions and there are indications that economic investment now will be likely to reduce costs later [5]. There is also a need to develop adaptations to cope with changes in climate. Recent research highlighting the health benefits of limiting future temperature rises to the more ambitious target of 1.5 °C rather than 2 °C, in line with the Paris agreement of 2016, further emphasises the need to limit emissions [6].

Climate change affects health in a number of ways, and the impacts vary both geographically and between different populations. A growing and ageing population in much of the world means that the proportion of the population who are vulnerable to the effects of climate change will increase in the future [7]. The most direct impacts from climate change are from the effects of high temperatures, and from acute impacts relating to extreme events such as storms, floods and heatwaves. These physical or meteorological stressors can produce direct health effects, such as physical injury, illness, or mental health impacts due to the consequences of the aftermath. In places where infrastructure or adaptation measures are poor, the impacts will be more severe [2]. In addition to these types of impact on health, climate change is likely to modify or mediate existing health effects and exacerbate inequalities through a number of indirect pathways. These more indirect effects on health occur through climate interactions with ecosystems, water, biodiversity and land use changes. Climate change can lead to environmental degradation; can affect food and water availability and quality; and increase risks to health from pathogens, vectors and infectious diseases [8]. Civil conflict or mass movement of people may be partly driven by environmental degradation and can further increase risks to health. There is evidence to suggest that climate change can be a driver for civil war [9,10].

Waterborne and water-related diseases are sensitive to environmental conditions, some or all of which are likely to be affected by climate change. For example, climate change is likely to lead to changes in the frequency of heavy rainfall events, storms and drought periods [2], melting of polar ice and glaciers, warming and thermal expansion of the oceans causing sea level rise [11], and melting of permafrost, which may contribute to further warming [12]. Changes in interactions between the water cycle and the climate system will modify the risk from waterborne diseases from these physical impacts, as well as from the resulting risk of famine, water shortages, decreased water quality, increasing habitat for mosquitoes, alterations to seasonality of diseases and contaminated recreational waters. However, health impacts of waterborne disease over the longer term may be secondary to other health effects associated with other water issues (e.g., shortage, flooding, famine, the economy, sea level rise and war).

Tackling the climate change problem has focussed on mitigating the effects of greenhouse gas emissions through the Intergovernmental Panel on Climate Change (IPCC), through cross government international agreements on reducing carbon emissions and by providing reliable scientific evidence and reports. While the approach has generally been to reduce worldwide greenhouse gas emissions, the reductions are likely to be slow and work on adaptation strategies to deal with the climate change associated with overall increases in temperature is also being undertaken.

2. Climate Change and the Water Cycle

Even cursory examination of the evidence shows the importance of water in relation to climate change. The impact of water in the decline of civilisations has been examined and reviewed [13]. Climate change is likely to affect the water cycle across the globe [14] with potential influences on surface and groundwater quality; it will lead to changes in atmospheric water vapour content, changes in cloud types and cover, and changes in the frequency of severe storms. Over time, it is likely that there will be increased melting of glaciers and icecaps [15] and ocean warming (and associated thermal expansion) that will cause sea levels to rise [16]. It remains possible that the release of permafrost methane may contribute to further warming [12,17]. These changes in atmospheric conditions and moisture content are expected to result in an increase in floods, famine, hurricanes and tropical storms, drought [18], wild fires, chronic water shortages, decreased water quality, periods with increased mosquito vectors, alterations to the seasonality of diseases, contaminated recreational waters and rising sea levels. Most assessments of the risks to health from climate change are conducted over time periods ranging from the present to 80 years. However, there are potentially much larger risks over longer timescales, particularly if there is a substantial sea level rise, and prolonged periods with much-increased average and peak temperatures [19].

Although scientific understanding of how climate may affect weather patterns has increased enormously over the past few years, especially in relation to extreme weather, the consequences for, and influences on, water quality (e.g., microbiological quality) are far less studied [20]. Changes in water arise from interactions with the weather, affecting ecosystems, changing the flow of nutrients and pathogens in catchments, and influencing water quality. Climate change may influence the microbiological quality of river water, which may present risks to bathers [21]. A modelling approach involving Quantitative Microbial Risk Assessment found that although climate change increased the fluxes of a number of pathogens, the overall change in risk was limited. Part of this was due to the dilution effect of increasing rainfall. As risks are likely to be location specific, wider generalisations are difficult. The approach used in such studies could be transferred to other locations. In summary the IPCC states that in overall terms, climate change is projected to reduce the quality of raw waters [22].

3. Climate Change and Drinking Water-Related Infectious Diseases

The history of water-related disease dates back to the classical period when Empedocles is reported to have introduced drainage of a swamp (a public health intervention) to reduce disease [23]. The ability of waterborne diseases to cause large outbreaks that, in the case of typhoid and cholera, have a high morbidity and mortality, makes them important historically. A classification of water-related infections was drawn up by Bradley (Bradley's classification [24]) and has been adapted by others [25–27]. A modified-version groups diseases into waterborne; water access related; water based; water-related insect vectors; and engineered water systems, although this revision still excludes some water-related diseases (Table 1).

Drinking water is the most important waterborne disease risk because the contamination of large mains supplies can cause large outbreaks [28–32], and because small rural supplies are commonly contaminated [33,34] which, in developing countries, can lead to substantial infant mortality. Bottled water is usually safe, particularly natural mineral waters that are derived from deep wells or other secure sources, but outbreaks may occasionally occur. The water supplies on ships, trains and aircraft can be subject to contamination where the supply chain breaks down [35]. There are always potential risks when people drink untreated natural waters. The supply of clean water can become critical in areas of war, disaster, famine, drought, water shortage and flooding, and refugee supplies often need to be established rapidly to prevent outbreaks [36–41].

While climate change may affect the microbiological quality of water and water-related diseases, the arguments indicate notable uncertainty over what the specific impacts will be, and when and where they will be most acute. However, to assess the likely impacts upon the health of humans, there is a need to examine the resilience of society to changing water quality. Developing an understanding of these capabilities and adaptation potentials is key to assessing the likely influence of climate change.

Table 1. Criteria for water-related diseases [24–26,42].

Class	Sub-Class	Examples
Waterborne infection	Infectious through drinking water	*Cryptosporidium* spp., *Giardia* spp., *Vibrio cholerae*, *Dracunculus medinensis*
	Infectious through recreational water	*Cryptosporidium*, Adenovirus, *Leptospira* spp., *Naegleria fowleri*
	Infectious through inhalation (engineered systems)	*Legionella pneumophila*
	Infectious through contact	*Pseudomonas aeruginosa*
	Infectious through contamination of wounds	*Mycobacterium marinum*, *Vibrio vulnificus*, *Aeromonas hydrophila*
	Infectious through growth in equipment and water systems	*Mycobacterium avium* complex
	Infectious through growth in soil or water	*Acanthamoeba* spp., *Burkholderia pseudomallei*
	Infectious through growth in coastal waters	*Vibrio* spp.
	Infectious from food contamination with water/soil	*Clostridium botulinum*
	Infectious through water contamination of food	*Cyclospora cayetanensis*, *Cryptosporidium* spp., *Salmonella* Typhi
	Infections through near-drowning	*Aeromonas hydrophila*
	Infectious through injection of non-sterile water	*Clostridium botulinum*, *Clostridium novyi*
Waterborne chemical or toxin	Potent toxins through inhalation	*Ostreopsis* spp. (HABS)
	Potent toxins through seafood	Dinoflagellate and diatom fish and shellfish poisoning (HABS)
	Potent toxins through drinking	Cyanobacterial blooms (HABS)
	Potent toxins through dialysis	Cyanobacterial blooms (HABS)
	Potent toxins through recreational exposure	Cyanobacterial blooms (HABS)
Water washed (poor access)	Hygiene related	*Shigella* spp., *Chlamydia trachomatis*, scabies, pneumonia
	Infections related to drought	*Coccidioides immitis*
	Infections related to flooding	*Leptospira* spp.
Water based	Parasite lifecycle requiring water and transmitted by water	*Schistosoma* spp., *Dracunculus medinensis*
	Parasite lifecycle requiring water and transmitted by food	*Fasciola* spp., *Opisthorchis sinensis*, *Heterophyes heterophyes*
	Parasite lifecycle transmitted by waterborne route	*Dracunculus medinensis*, *Spirometra* spp., *Echinococcus* spp., *Sarcocystis* spp., *Toxoplasma gondii*
Water-related insect vectors	Vector breeding in water	Dengue virus, *Onchocerca* spp., *Trypanosoma* spp.
Waste water related	Parasites maturing in waste water	*Ascaris lumbricoides*, *Cyclospora cayetanensis*
Diseases related to damp	Toxicosis related to food stored damp	Mycotoxins (aflatoxin, patulin, ochratoxin)
	Disease related to living in damp conditions	Mycotoxins

One of the major pathways through which contaminated water affects individuals is though drinking water. In terms of management, these supplies range from unimproved sources where the individual is effectively consuming raw water, to large, managed supplies where multiple barriers exist to prevent microbiological contamination of water supplies. Climate change has a number of potential influences upon water treatment, and higher temperatures are known to enhance biological methods of water treatment [43]. However, countering this effect are a number of other factors linked to more extreme weather, such as increased rainfall and water turbidity [44,45] which may increase risks to microbiological water quality in some locations. A review of the impacts of climate change on surface water contamination concluded that it was likely to increase the risk associated with drinking water supplied mainly during extreme climatic events [46]. Pathogen risk was argued to rise mainly due to elevated temperatures and extreme rainfall, especially in temperate countries.

Ensuring appropriate water infrastructure, regular monitoring and appropriate management techniques, such as Water Safety Plans, are likely to be increasingly important to address changing risks. In the future rapid testing (e.g., PCR based) [47] and new treatment technologies (e.g., nanomaterials) [48] may play an increasing role in addressing climate change challenges. The ability to respond to changing risks will vary according to the resources available. In terms of supplies less able to adapt to a changing water quality, we highlight small water supplies, private water supplies as well as supplies in lower income areas as potentially being at greatest risk.

4. Settings Other Than Drinking Water, and the Range of Water-Related Diseases

Drinking water is not the only route through which potentially contaminated water may affect individuals; bathing water is another important pathway. As argued above, modelling is challenging, and this is especially the case given the multiple number of potential exposure points. Water quality modelling is currently possible, and could be extended to include climate change. Warning the public about water risks in relation to bathing water is one way to address changing risks associated with climate change [49].

Infections can be related to exposure to natural and man-made recreational waters. These include thermal waters (amoebae, *Legionella*) [50], inland recreational fresh waters, ponds and lakes (cyanobacteria, *Pseudomonas aeruginosa* [51], enteric pathogens, *Leptospira* spp., *Trichobilharzia* spp. [52], *Schistosoma* spp. [53], *Vibrio* spp.) [54], wild swimming (enteric pathogens), coastal waters including sea sports, sea water pools, bathing beaches (dinoflagellates and diatoms, jelly-fish larvae, toxic seaweed, enteric pathogens) and the beach environment, including run-off from fields and sewers, beach sand, and so forth. Recreational exposure to man-made fresh water pools includes treated swimming pools (*Cryptosporidium*), natural pools (enteric pathogens), spa baths (*P. aeruginosa* [55], *Legionella* spp.), water parks (*Cryptosporidium* spp.), foot wash and foot spas (*Mycobacterium* spp. [56] and *P. aeruginosa* [57]) and inflatables (*P. aeruginosa*, *Aeromonas hydrophila* [58]).

Infections from working in water can include *Schistosoma* spp., *Burkholderia pseudomallei* [59] and wound infections from water (*Vibrio vulnificus* [60], *Mycobacterium* spp., [61] *B. pseudomallei* [62]). Water transmission in man-made systems and equipment includes hospital/medical uses of water, water for dialysis and hydration (cyanobacteria), water for washing and decontamination, hospital water systems, water transmission in intensive care (*P. aeruginosa*) [63–66], contaminated equipment including endoscope washers (*Mycobacterium* spp.) [67], humidifiers, taps and wash basins, showers (*Legionella* spp.) and water births [68–71]. A variety of industrial waters can contribute to respiratory infection, including cooling towers and thermally polluted waters (*Legionella* spp.).

The disposal of waste can contribute to water contamination, particularly chemical contamination, but also pathogens. Sewage disposal is the main source of human faecal contamination in developed countries and sewage treatment is designed to reduce this to a minimum. However, animal waste probably represents a larger input to the natural environment as a result of defecation on fields and run-off. In developing countries, human faeces are commonly deposited in the natural environment at defaecation sites or middens where the ‘night soil’ matures over time and some pathogens require this to become infectious (*Ascaris lumbricoides* [72], *Cyclospora cayetanensis*). There are also potential risks associated with water passing through waste burial sites, particularly mass graves associated with plague, smallpox or anthrax, and from water running from leather processing sites (*Bacillus anthracis*).

Water is important in agriculture and food production, and irrigation may be conducted with water that is not of potable quality. Where this is done for salad items and soft fruit that are eaten without further treatment, then outbreaks can occur [73,74]. Contaminated water used for washing and food processing can also cause outbreaks. Food retailers require water on the premises in order for staff to wash their hands. Water-related foodborne disease (water-based) includes helminths and other macro-parasites, ciguatera, shellfish dinoflagellate toxins and similar toxins [75]. As shellfish filter large volumes of water, there are common outbreaks associated with faecal pathogens (especially norovirus and *Vibrio cholerae* [76], *Vibrio parahaemolyticus* [76] and *Vibrio vulnificus* [76]). Many processed drinks and foods contain water, and infections are prevented by source water protection, filtration, heat treatment or preservative treatment and a matrix that prevents pathogenic organisms from multiplying.

Where water is in short supply, water washed diseases may occur [14]. This can be in desert areas where lack of water and chronic water shortages, together with flies resulting from poor waste disposal, can allow the transmission of enteric (shigellosis) and eye infections (*Chlamydia trachomatis*).

Vector borne diseases (mosquito-borne, tick-borne, fly-borne, triatomid bug) can be strongly influenced by weather and geographic parameters, are likely to change in distribution as a result of climate change and are difficult to predict accurately [77], but are not examined further in this paper.

5. Methods and Reviews Related to Water Quality and Health

Systematic review (SR) and meta-analysis (MA) are methods which have been used extensively to elucidate the relationships between microbiological contamination and ill health. As climate change will impact water contamination, an examination of systematic reviews relating to water quality has been undertaken. A SR of the effectiveness of interventions to reduce the health impact of climate change around the world, found a weak evidence base and gaps in dealing with extreme weather events [78]. This follows a previous SR [79]. The seasonal differences in faecal contamination of source waters used for supplying drinking water have been examined in a SR [80]. They found increased contamination in the wet season. A general review of wider evidence for pathogens being waterborne and the impacts of climate are included in the review of pathogens (Table A1, Appendix A).

6. Flooding

Flooding causes local or widespread disruption of normal life and makes waste disposal difficult. A SR of waterborne infections and climate change found evidence of outbreaks and increased sporadic disease following flooding [37], and included cholera and other diarrhoeal diseases. Other reviews have found similar results [36] and the health impacts of flooding showed that monitoring, mitigation and communication had the potential to reduce loss of life [81]. Tsunami related flooding can have a disproportionate impact on women, children and the elderly [82]. The impact of flooding is generally greater in developing rural countries with poor infrastructure compared to developed countries where people in flooded properties can be readily moved to non-flooded areas for a temporary period and provided with potable water. This is particularly true of coastal areas [83]. After Hurricane Katrina, there was an outbreak of norovirus deriving from populations being held in a stadium [84] and an increase in *Vibrio* infections resulting from coastal waters [85]. An increase in flood related disease might be expected under climate change with altered weather patterns and more severe weather events. Early warning systems with effective disease surveillance, prevention and response are important in preventing infectious diseases following flooding [86].

7. Drought

Drought can be a hidden risk with the potential to cause a public health disaster [87]. A SR of the health effects of drought found the main categories included: Nutrition-related effects; water-related disease (including *Escherichia coli*, cholera and algal bloom); airborne and dust-related disease (including coccidioidomycosis); vector borne disease (including malaria, dengue and West Nile Virus); mental health effects; and other health effects [88]. A review in Canada found that drought can affect respiratory and mental health, with illnesses related to exposure to toxins, food, water and vector-borne diseases [89]. Drought-related health impacts vary widely and depend upon drought severity, population vulnerability, health and sanitation infrastructure, and available resources with which to mitigate impacts as they occur. Population resilience is affected by socio-economic environment. A SR has examined the likely impacts of climate change on water quality and disease in the Mekong delta basin [90].

8. Disasters

The water needs for disaster recovery identified relations between the amount of water provided and the diarrhoea and mortality rates, but emphasised the inadequacy of the data [91]. As responses to climate related emergencies influence subsequent morbidity and mortality, it is important to understand the impact of water, sanitation and hygiene (WASH) interventions on health outcomes in humanitarian crises. The current evidence base is limited, and is unsuitable for determining associative or causal relationships [92]. People living with HIV have a higher morbidity where there is contaminated water, poor hygiene and sanitation. Programs to improve these also improved morbidity [93].

9. Climate Impacts on Water, Sanitation and Hygiene (WASH)

Understanding the climate change impacts on water-related diseases requires an understanding of water, sanitation and hygiene. Much of the burden of waterborne disease appears to result from small and rural supplies, although there may be under-ascertainment of outbreaks in urban areas with mains supplies due to limited disease surveillance. This is important in an examination of the burden of waterborne disease and future changes as a result of altered weather patterns. Waterborne disease burden methodologies used in developed countries to attribute acute gastrointestinal infection (AGI) to drinking water, include simple point estimates, quantitative microbial risk assessment, Monte Carlo simulations based on assumptions and epidemiological data from the literature [94]. In developing countries, inadequate water and sanitation are associated with risk of diarrhoeal disease [95], particularly in young children, and raised maternal mortality occurs in households with poor sanitation and a poor water environment [96]. The microbiological quality of household water correlates with health outcomes (diarrhoea and trachoma) [97], although improved sources do not always provide water that is completely free of faecal contamination. Point of use devices can be effective [98], however, contamination of water between source and point of use remains a continuing problem [99]. An examination of interventions to reduce diarrhoea in less developed countries found, that while interventions were generally effective, the heterogeneity between studies made the exact conditions causing disease reductions difficult to assess [100], and others found a dearth of methodologically sound studies [101]. There were also inadequacies in behavioural models and frameworks for intervening in WASH specific interventions [102]. The impacts of WASH on child diarrhoeal morbidity has been examined in a number of studies [103] and there was a general lack of good quality studies of diarrhoea morbidity in children in India [104]. While water treatment (e.g., chlorine water treatment at point of use) can be effective, most studies are short term [105]. An examination of water distribution system deficiencies demonstrated that study blinding can be important [106]. Expecting to obtain good information on the risks from water-related infections under climate change, in the absence of reliable, experimental evidence for effectiveness of interventions, seems naïve.

Of 293 outbreaks linked to water supplies in Canada and the US, failure of existing treatment and lack of water treatment were the leading causes [107]. Temporary water outages and chronic outages in intermittently operated systems can be associated with gastrointestinal infection [106]. The Walkerton outbreak of *E. coli* O157 and *Campylobacter* in Canada highlighted the role that heavy rainfall can play in outbreaks [108,109]. However, this was also linked to poor management. There are many studies that have examined the role of rainfall before an outbreak. It is generally seen that heavy rain is more common before many outbreaks, suggesting the source water is compromised [32,36,110–112]. The association between waterborne outbreaks with a period of prolonged low rainfall in the four weeks before an outbreak may also indicate a vulnerability to weather [32], although this was not seen in other studies. There is a strong need for water utilities to build water safety plans that factor in likely changes in climate over future scenarios, while retaining an understanding of historical weather events. Behaviour change interventions for water and sanitation in developing countries have looked at risk factors, attitudinal factors, normative factors, ability factors, and self-regulation factors [113]. Social marketing for water and sanitation products showed this improves health threat awareness and provides a solution to reducing disease burden [114].

Good water sourcing, treatment, distribution, storage and clean point of use remain the key to community health. Water and sanitation in schools is an important area where improvements can facilitate improved educational achievement [115].

There is a need for robust epidemiological studies that quantify the health risks associated with both small, private water systems, and large community supplies. More information is needed on pathogen quantification, susceptibility of vulnerable sub-populations, the influence of extreme weather events, the proportions of the population served by different water sources and the treatment level, source water quality and condition of the distribution system infrastructure. The exposure to faecal contamination in potable water has been estimated, suggesting that there may be a substantial under-estimate of disease burden [116].

10. Which Water-Related Pathogens Are Important?

A wide range of pathogens are known to be transmitted through water (Table A1, Appendix A). Historically, some diseases, such as cholera, dysentery and typhoid have been very important from a public health perspective, causing extensive morbidity and mortality. Many of the diseases are a problem where there is limited infrastructure, as in developing countries or rural regions of developed countries and can be sensitive to social disruption and infrastructure damage. It is important to understand the future health impacts of climate change and to understand where the most important disease burdens will be. Waterborne diseases can be sensitive to emergence, but this is generally related to the discovery of new infectious agents or identification methods (e.g., cryptosporidiosis, microsporidiosis, legionellosis, hepatitis E) rather than newly emergent diseases. However, some classical waterborne pathogens may emerge in new areas with climate change (e.g., cholera), and Legionnaires' disease, which is predominately derived from contaminated water systems in the built environment, may increase as a result of raised temperatures.

An examination of 24 analytical studies assessing the association between extreme precipitation or temperature and drinking water-related waterborne infections, found that most studies showed a positive association with increased precipitation or temperature. A few studies showed an association with decreased precipitation and several in which there was no association [117]. Infections included cholera, typhoid, paratyphoid, campylobacter, shigella, hepatitis A, cryptosporidiosis, giardiasis and waterborne outbreaks.

10.1. Schistosomiasis

Schistosoma are transmitted as a result of cercaria burrowing through the skin of people working or bathing in contaminated waters. The cercaria develop in infected snails. Although temperature, precipitation and humidity are known to influence the development of schistosome parasites, as well as their intermediate snail hosts (*Biomphalaria* spp.; *Oncomelania* spp.) [118–121] and their internal defence system [122], modelling climate change impacts on disease can have mixed results [123,124]. Some scenarios show predicted increases and decreases [125], with degrees of uncertainty [126,127]. Increases in parasite growth related to temperature can be offset by increased snail mortality at higher temperatures [127]. Schistosoma eradication campaigns may be impacted by changes in snail distribution, migrant workers and weather [128]. The impact of water and sanitation on schistosomiasis has shown that access to safe water and adequate sanitation is important in reducing schistosomiasis [129,130].

10.2. Guinea Worm

Dracunculus medinensis is transmitted by drinking water contaminated with copepods that contain the parasite larvae, and infections are easily controlled with simple measures. This disease is moving rapidly towards eradication under the supervision of the Carter Centre, with the World Health Organisation, UNICEF and CDC [131,132]. Although climate is likely to influence disease, the biggest problems in elimination have been organising surveillance in conflict areas [133], and the recent demonstration of a transmission cycle in dogs, particularly in Chad [134].

10.3. Nematodes

Ascaris, *Trichuris* and hookworms are soil transmitted nematodes, and transmission is related to inadequate methods for faecal/wastewater disposal. Risk of *Necator* infections were linked to rainfall in East Timor [135]. For *Ascaris lumbricoides*, higher temperatures in the coolest quarter of the year resulted in reduced risk. There is little evidence to suggest that changes in climate might greatly increase disease transmission and evidence that helminth control measures, if effectively undertaken, might cause substantial reductions in disease. A SR of spatial and temporal distribution of soil transmitted helminths was used to determine changing disease burden and predict treatment needs for eradication [136]. Another soil helminth SR and MA identified reductions in disease associated with WASH activities, but emphasised the limited nature of the studies, which were mostly observational [137].

10.4. Protozoa

Waterborne cryptosporidiosis is common, even in developed countries because the parasite's oocysts are resistant to chlorine, which is the main chemical treatment used for disinfecting both drinking water and indoor recreational waters, including swimming pools [138]. The oocysts are common in natural waters and can be present in source waters. A SR and MA of the impacts of weather on surface waters indicated that contamination with *Cryptosporidium* and *Giardia* was 2.61 and 2.87 higher during and after heavy rainfall [139]. A SR was used to examine the risks of endemic cryptosporidiosis, and found increased risk associated with the unsafe use of water [140]. This makes the need for risk assessment necessary. Cryptosporidiosis outbreaks may well increase if there are more frequent incidents of severe weather. In many countries, surveillance involving the laboratory identification of isolates is absent or suboptimal. Without good surveillance, outbreaks will be missed, and the prevention of these not dealt with. A SR of *Toxoplasma* outbreaks showed longer incubation following exposure to contaminated water compared to meat related exposures [141]. A SR of intestinal protozoal infections found significantly lower odds of infection in people with treated water [142]. *Giardia* transmission is not as well understood as *Cryptosporidium*, mostly because typing approaches have been suboptimal and routine surveillance in developed countries has focussed on the link to travel, rather than indigenous sources of infection [143]. Hygiene linked to water is important and occurrence in developing countries shows no relationship to rainfall [144]. However, the infection is common, and determining any change due to climate may be difficult. Both *Giardia* and *Cryptosporidium* are common in developing countries, and include a variety of species and types, and it has been suggested that climate change will increase malnutrition and contamination of water sources [145].

Naegleria fowleri infections are commonly associated with thermally polluted waters and cases might increase with raised temperatures. However, many of the reported infections are associated with geothermal waters that will not be greatly impacted by climate change.

10.5. Cholera and Other Diarrhoeal Diseases

Cholera remains one of the major diarrhoeal disease concerns with climate change. There has been a long history of associations between seasonality and weather as contributing factors in outbreaks. Cholera is also readily inserted into disaster situations and can contribute to morbidity and mortality. Examination of the weather relationship in El Niño years to the occurrence of cholera suggests that weather might be able to be used for predicting outbreaks in East Africa [146]. However, the assumptions in models are not necessarily always proven in practice [147–149]. As pandemics of cholera have occurred in the past, there is a strong need to reduce the risks of another pandemic arising out of a disaster situation. Changes in seawater temperature may contribute to changes in disease incidence [150]. The impact of water, sanitation and hygiene interventions are important in the control of cholera [151]. Home water treatment and storage interventions can reduce diarrhoea and cholera [152]. This study demonstrated the dearth of good evidence. A SR looked at the environmental determinants of cholera in inland Africa [147]. They found that spread was linked to displaced populations and the poor water and sanitation associated with these settings. A similar review of coastal cholera by the same authors found that cholera seasonality is driven by rainfall-induced contamination of unprotected water sources [148].

The impact of a changing climate is most important when it comes to the quality of drinking water and diarrhoeal diseases, particularly in developing countries [37]. There are relationships between many of the bacterial infections and temperature, and evidence of links to heavy rainfall and flooding [32,110,117]. The sources of exposure may be agricultural [153] or from sewage, and the different sources contain different pathogens, with human viruses rarely being detected in animal waste [154]. Engagement with the water sector is important in reducing risks.

10.6. Legionella

Legionnaires' disease is commonly associated with thermally polluted waters [155]. Due to the relationship between temperature and the occurrence of *Legionella* spp. in water, one might expect an increase in cases or outbreaks associated with climate change. Studies indicate that temperature and humidity [156,157], or vapour pressure [158], may play a role in the occurrence of sporadic disease. Due to concerns about the multiplication of *Legionella* spp. at the consumer endpoint (taps and showers) the European Drinking Water Directive has been modified to include a risk assessment for this pathogen. A SR on cooling towers related to Legionnaires' disease provided quite detailed advice on risks and their mitigation [159]. As climate changes becomes more apparent, there may be improvements in our understanding of previously unrecognised transmission routes from the natural environment.

10.7. Leptospira spp.

Leptospirosis outbreaks are commonly linked to flooding in rural developing countries. This relates to the dislocation of small mammal populations [160–162]. It is expected that an increase in flooding will contribute to more leptospirosis cases. Floods are one of the most important drivers of leptospirosis on islands and in Asia [163].

10.8. Pseudomonas aeruginosa

The ability of *Pseudomonas* to grow in water is dependent on being able to extract nutrients from the surfaces it is growing on, and to bloom within the body of the water. This includes outbreaks of folliculitis associated with spa pools and is dependent on temperature. One must therefore expect some increase associated with increased temperatures. A SR of *Pseudomonas aeruginosa* in hospitals found evidence that the water systems can be the source of this organism, and that contamination mostly occurs at the distal end [164]. Water resource management is important in control of this [165]. *P. aeruginosa* infections are common, and numbers related to water use may increase with a changing climate.

10.9. Harmful Algal Blooms (HABs)

Harmful algal blooms have the potential to increase with changes in climate [75]. The neurotoxin producing dinoflagellate and diatom plankton mainly cause disease through shellfish poisoning and Ciguatera poisoning in fish, but can also be responsible for the mass deaths of fish. Monitoring of shellfish waters can facilitate shellfish bed closures as a means of controlling exposure through food, while ciguatera is mostly controlled by not eating carnivorous reef fish. Blooms can cause respiratory symptoms in people on affected bathing beaches. Freshwater cyanobacteria are a potential risk through untreated potable water, and the toxic products can cause liver disease. In developed countries, these problems should be dealt with by water utilities.

10.10. Shiga-Toxin Producing E. coli (STEC)

As water is commonly contaminated with the faeces of agricultural animals, ways of reducing *E. coli* O157 excretion by cattle have been examined [166]. Further work on preventing haemolytic uremic syndrome found that vaccine use on animals reduced carriage, but the study emphasised the importance of public health measures [167]. Patients were consistently found to have exposure to rodents, behavioural and sanitation related risk factors.

10.11. Norovirus

An examination of norovirus transmission routes showed higher attack rates in foodborne than waterborne transmission, and higher rates in surface derived than groundwater derived waters [168]. Given the very common occurrence of this pathogen, any change will possibly depend more on progress in vaccinations rather than an impact from climate change. However, outbreaks may occur when large populations are kept in confined areas during an emergency [84].

10.12. Trachoma

Chlamydia trachomatis is the cause of trachoma, a disease of the eyes related to water shortage. Water can be important in reducing trachoma, where the F and E of the SAFE strategy (surgery, antibiotics, facial cleanliness and environmental improvement) were strongly linked to disease reduction [169]. Another trachoma SR found the studies too limited to demonstrate the impact of F and E [170]. The SAFE interventions are dramatically reducing disease but could be disrupted in chaotic situations associated with climate change.

11. Preparing for Climate Change

The principal reason for drinking water infections is the absence of reliable infrastructure. For rural communities worldwide, this includes the source waters used for drinking, the methods used to transport it from source to household, safe storage within the household, any treatment used and hygiene and sewage disposal changes. The principal underlying factor is poverty. Improving water treatment needs to be accompanied by improvements in sewage disposal and hygiene training. Climate change will not alter these underlying principles. What could change is the frequency of water shortages, population movements, conflict, refugee camps and so on, and a deterioration in the hygienic quality of water that people receive. Good planning associated with disasters can reduce the risks of waterborne diseases [41]. Any increase in disease associated with disasters in developing countries can have knock-on effects in developed ones.

With climate change, it is important to build knowledge of the mechanisms by which changes in weather can influence individual pathogens, and how these may subsequently affect human health. Not all problems associated with diarrhoeal diseases are as a result of outbreaks and it is important to understand the drivers for sporadic disease, and the disease burdens associated with the range of common pathogens. Good surveillance is necessary in order to detect clusters and outbreaks at an early stage, so that they can be investigated and controlled in a timely way, and so that future outbreaks can be prevented.

Most enteric pathogens are very seasonal, with bacterial pathogens (e.g., *Salmonella* spp., *Campylobacter* spp., STEC) predominating in the summer months, while viral gastroenteritis predominantly peaks in the winter (e.g., norovirus, rotavirus) [171]. The analytical examination of weather drivers has relied on time series approaches, that have limitations due to the collinearity between, for example temperature and seasonality, making it difficult to get definitive evidence of the causal mechanisms and to predict the impact of changes in climate. A review of mathematical approaches to demonstrating weather influences on waterborne infections has been undertaken [172]. The studies grouped into two clusters: Process-based models (PBM) and time series and spatial epidemiology (TS-SE). A review of analytical epidemiology studies looked at the quality of evidence for associations with rainfall, temperature, and so on, and waterborne disease identified the difficulties with developing optimum approaches [117]. A more systematic examination of the seasonality of a full range of pathogens [171] may widen our understanding of those that are linked to climate fluctuations. There are also a range of less analytical approaches that can contribute to a better understanding of waterborne pathogens and future risks (Table A1, Appendix A). Further development of tools to separate the effects of weather from other influences on seasonality needs to be undertaken, utilising surveillance data from a wider geographic area and linking local cases to local weather.

12. Conclusions

There have been a number of previous reviews and publications highlighting potential impacts of climate change and water-related illness in water-related or waterborne disease [37,38,117,172–182]. Some approaches examine the technological means to best represent the data [42,175,177,178,183], some examine outbreaks [28,32] and others focus on effects of the hydrological cycle in particular regions [28,110,174,179], while others have adopted a systematic review approach [37]. This paper has examined a full range of water-related pathogens, providing an evidence base for regarding them as water-related and indicating which studies have provided evidence. In addition to a changing climate, the world will continue to experience an increasing human population, with ever greater inter-connectivity through travel and information technology. Animal infections will continue to contribute to zoonotic disease and we should expect new pathogens to continue to arise. With climate change we need to watch for the rise in cholera worldwide. Although this is predominantly a disease of the poor and is not generally a problem in developed countries that have safe drinking water, it still has the potential to cause pandemic disease if there is general chaos, as can be found in disaster situations. The growth of *Vibrio cholera* in coastal waters means there can be changes in exposure with alterations in rainfall and temperature [150]. There remains a strong need for timely surveillance and rapid epidemiological response to outbreaks and new waterborne pathogens. The needs of developing countries in relation to waterborne diseases are both technical and financial, and ensuring adequate quantities of good quality water will be essential in preventing excess morbidity and mortality in areas that will suffer from substantial changes in climate in the future.

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Abbreviations

CA	Cost analysis
CEO	Circumstantial evidence only
CSS	Cross sectional survey
EACI	Ecological association between climate and infections
EACO	Ecological association between climate and outbreaks
EACWQ	Ecological association between climate and water quality
FTA	Fault Tree Analysis
GAMTS	Generalised additive model time series
GDSE	Gastrointestinal and dermatological symptoms and exposure
GLM	Generalised linear model
HSM	Hindsight suitability model
LR	Literature review

MLM	Multi-level modelling
MM	Mathematical modelling
MMF	Microbiological monitoring of flooding
MMO	Microbiological monitoring of outbreaks
MMST	Microbiological monitoring with salinity and temperature
NBM	Negative binomial model
MSRA	Multiple stepwise regression analysis
NE	No published evidence
OI	Outbreak investigation
PMCC	pairwise-matched case-control study
POCS	Prospective observational cohort study
PORA	Post outbreak rainfall analysis
POTA	Post outbreak temperature analysis
POWE	Post outbreak water examination
PRA	Poisson regression analysis
RAI	Review of animal infections
RCS	Retrospective cohort study
RCCS	Retrospective case-crossover study
RILO	Rodent investigation linked to outbreak
ROS	Retrospective outbreak surveillance
RRM	Rainfall runoff model
RSA	Rainy season association
RSE	Recreational swimming exposure
SA	Spatial analysis
SCS	Sporadic case series
SFA	Seasonal factor analysis
TSAT	Time series analysis of temperature
QMRA	Quantitative microbial risk assessment
WMCS	Water microbiology and case series
WMR	Water microbiology and rainfall

Appendix A

Table A1. Evidence of water related, waterborne, water-based, water contamination of equipment, water washed, water-based food contamination, water toxicosis, respiratory aerosol transmitted organisms, those that might be subject to climate change and the types of evidence.

Pathogen	How Climate Might Affect Disease Occurrence	Strength of Evidence for Water Related Infections	Human Waterborne Outbreaks or Infections	Type of Infection Route	Study Linking Weather/Climate and Infection
Acanthamoeba	*A. polyphaga* linked to contact lens washing and hygiene important. Infections linked to flooding (presumed contamination of potable water). Water contamination links.	Strong	[183–194]	Waterborne	PMCC [195]; LR [196]
Adenovirus	Subgroups A–E cause upper respiratory infections, conjunctivitis, febrile illness, sore throat and swollen glands. The enteric subgroup F adenoviruses Ad40 and Ad41 cause gastroenteritis in children. Contamination of groundwater used as a drinking water source and from faecal or respiratory contamination of untreated recreational waters. Swimming pool outbreaks.	Moderate	[184,197–201]	Waterborne	POWE [202]; OI [203]
Aeromonas spp.	Can cause wound infections and are thought to be a cause of diarrhoea. Point source diarrhoea outbreaks do not occur and evidence of their role in diarrhoeal disease is equivocal. They are commonly found in raw foods, sewage and source waters, and can bloom in drinking water distribution systems. Seasonality similar to *Salmonella*.	Weak	No waterborne outbreaks [204].	Waterborne	NE
Arcobacter spp.	*A. butzleri* is a Campylobacter-like bacteria that is associated with watery diarrhoea. *A. skirrowii* can cause persistent diarrhoea. *A. cryaerophilus* is a third species found in human infections. *Arcobacter* spp. can be isolated from animals, birds, food, water and the environment. Arcobacter infections are uncommon and there is no evidence of the impact of weather on infections. Three waterborne outbreaks but no evidence Arcobacter was the cause.	Weak	[202,205]	Waterborne	NE
Ascaris	*A. lumbricoides* ova in 'night soil' need to mature at ambient temperatures before they are infectious. Rain can wash infectious oocysts into water sources used for irrigating salad vegetables. Transmission through irrigation of salad vegetables.	Weak	[206–208]	Water based	NE
Astrovirus	Astroviruses cause diarrhoea in children under five years old. Viruses are excreted in faeces, and they will be present in sewage. Contact with contaminated recreational waters may be a risk factor. Outbreaks often mixed. Outbreak linked to flood water contamination of shellfish with several viruses.	Weak	[31,209–212]	Waterborne	POWE [213]

Burkholderia pseudomallei	Waterborne outbreaks in Australia with circumstantial & epidemiological evidence for water as the source. Infections and outbreaks linked to tropical storms, rainfall and drought.	Strong	[214–224]	Waterborne	POWE [216,222]
Burkholderia cepacia	Contamination of indoor water systems, predominantly in hospitals; contaminated sterile solutions, [225–229] disinfectant solution and taps can occur. Clinical circumstantial & epidemiological evidence but no link to weather parameters.	Strong	[225,227,230–245]	Waterborne	NE
Balamuthia mandrillaris	Occurs in soil and causes amoebic meningoencephalitis. Limited evidence of occurrence in thermal water sources and hot water systems [246–248].	Weak	[185,246,249]	Waterborne	NE
Balantidium coli	A ciliated protozoan organism found in wild and domestic pigs. It causes dysentery in man and other primates. The routes of transmission are not clear. Rare infection thought to be drinking water-borne but little supporting evidence.	Weak	[187,250–252]	Waterborne	NE
Blastocystis hominis	An amoeba that can be detected in patients with diarrhoea. Limited evidence of family outbreak [253] but no waterborne outbreaks. Its significance as a human pathogen is unclear [254–256]. Transmission is probably by contaminated food and water. Little evidence of waterborne transmission. No weather links.	Weak	[187,190,257–259]	Waterborne	NE
Bocavirus	Human bocavirus (HBoV) is comparatively newly discovered and is thought to be spread from person to person by the respiratory and faecal-oral routes. The virus has been detected in respiratory samples, faeces and blood. It has been commonly detected in children with upper or lower respiratory infections. Infection has been seen worldwide. No evidence of waterborne infection or infections linked to water, although it has been detected in sewage [260].	None	None	Unknown	NE
Campylobacter spp.	The commonest bacterial cause of diarrhoea. Most infections are sporadic, but waterborne outbreaks linked to camp sites, travelling abroad, hospitals and large communities. Infection is commonly derived from contaminated poultry and water for the chicken flocks may be one source of contamination. *Campylobacter* spp. are spiral/curved organisms when isolated from patients, and change to a more resistant coccal stage when present in water. Most human infections are caused by *C. jejuni*, *C. coli* and *C. lari*. *Campylobacter fetus* subsp. *fetus*, can cause human infections, with septicaemia and gall bladder infection being more common than with the other species. *C. upsaliensis*, *C. hyointestinalis* subsp. *lawsonii* and *C. hyointestinalis* subsp. *hyointestinalis* are occasionally isolated from diarrhoeal patients. Infection through contaminated drinking water—heavy rainfall	Strong, outbreaks represent a small percentage of cases	[261–268]	Waterborne	PORA [109,269]; EACI [270]

Chilomastix mesnili	A flagellated protozoan that is thought to have limited pathogenicity. Parasite present in wastewater. It is probably transmitted by contaminated food and water, and can be found in patients with diarrhoea. Weak circumstantial evidence of water transmission [271–274]. No link to climate.	Weak	NE	Unknown	NE
Chlamydia trachomatis	Trachoma, caused by *C. trachomatis,* is associated with a lack of water. Transmission by flies is reduced by face washing.	Strong	NE	Water washed	NE
Chryseobacterium/ Elizabethkingia/ Flavobacterium	*E. meningoseptica,* (syn. *C. meningoseptica, F. meningoseptica*). Contamination of washed wounds. Water aerator colonisation and ICU infection—no identified climate association.	Weak, circumstantial	[275–277]	Waterborne	NE
Coronavirus (SARS)	Has caused severe respiratory illness and can be excreted in faeces. Survives in sewage for 2 days at 20 °C and 14 days at 4 °C [278]. Possible contamination of bathing waters during outbreak. Possible aerosolisation in buildings.	Weak	NE	Unknown	NE
Cryptosporidium spp.	Cause diarrhoea in young mammals and in humans but cannot grow in the environment. Large waterborne outbreaks have been reported throughout the world. Oocysts are excreted in faeces and sewage. Many species (*C. hominis*, *C. parvum*, *C. meleagridis*, *C. cuniculus*, *C. ubiquitum*, *C. viatorum*, *C. canis*, *C. felis*, *C. suis*, *C. scrofarum*, *C. bovis*, and *C. muris*) and genotypes of *C. parvum*) can cause human disease. Rainfall can contribute to drinking water contamination from both human and animal faeces [279].	Strong	[28,138,187,190,271–274,280–285]	Waterborne	SA [286] SFA [287]; OI [288–292]; POWE [202]; FTA [293]; RSA [294]
Cyanobacteria	Grow as blooms or mats, mostly within fresh water bodies. There are a large variety of species, many producing potent toxins that can cause acute and chronic disease in mammals, including man. The toxins include microcystins, nodularins, anatoxins, Saxitoxins, aplysiatoxins, cylindrospremopsins, beta-methyl-amino-L-alanine (BMAA) and lipopolysaccharides. Algal blooms are more commonly found in eutrophic (eutrophic waters have a high concentration of nutrients) inland waters. Human health risks arise if the water is consumed untreated, if people bathe or participate in water contact sports in waters with a scum or heavy bloom and if contaminated water is used in renal dialysis. There have been some notable outbreaks associated with cyanobacterial toxins with a high mortality rate in dialysis patients. There are also associations between exposure to cyanobacterial toxins and long-term health risks including cancer. The risks from BMAA linked to neurological disease are unclear. Climate influence on algal blooms. Human recreational and drinking water exposures.	Strong for outbreaks linked to peritoneal dialysis.	[295,296]	Water toxicosis	CEO
Cyanobacteria—*Anabena* spp.	Found in eutrophic waters. Has caused liver damage and deaths in waterfowl, sheep, cattle and other agricultural animals. *Vibrio cholerae* has	Weak	NE	Potential water toxicosis	NE

	been found to survive for long periods inside *A. variabilis*. Toxin producing species include *A. flos-aquae*, *A. lemmermannii*, *A. circinalis*, *A. millerii and A. planctonica*.				
Cyanobacteria—*Aphanisomenon* spp.	Produce the toxins anatoxin-a, saxitoxins and cylindrospermopsin. Toxin producing species includes *A. ovalisporum*.	None	NE	Potential water toxicosis	NE
Cyanobacteria—*Anacystis* spp.	*A. nidulans* can produce lipopolysaccharide toxin.	None	NE	Potential water toxicosis	NE
Cyanobacteria—*Cylindrospermopsis raciborskii*	Found in eutrophic waters and produces anatoxin-a. Palm Island Mystery Disease in Queensland, Australia caused 140 children to be hospitalised with a variety of symptoms including malaise, anorexia, vomiting, headache, liver enlargement, bloody diarrhoea and kidney damage. Water from a dam contaminated with *C. raciborskii* was thought to have been responsible.	Strong	[297,298]	Water toxicosis	NE
Cyanobacteria—*Lyngbya majuscule*	A marine cyanobacteria that produces a variety of toxic metabolites including apratoxin A, Palau'amide, 15-norlyngbyapeptin A and lyngbyabellin D, a quinoline alkaloid, malyngamide T and the potent neurotoxins antillatoxin, antillatoxin B, and kalkitoxin. Debromoaplysiatoxin has been isolated from *Lyngbya gracilis* also has dermonecrotic activity and may be the dermatitis-producing substance in *L. majuscula*, the causative agent of "swimmers' itch" outbreaks in Hawaiian waters.	Moderate	[299]	Water toxicosis	NE
Cyanobacteria—*Microcystis* spp.	*M. aeruginosa* is a common cyanobacteria found in eutrophic waters. It can cause hepatic failure and diarrhoea in man and other animals. An association was found between drinking water from a reservoir contaminated with *M. aeruginosa* and raised liver enzymes in a population in New South Wales, Australia. Other toxic species include *M. viridis* and *M. botrys*.	Strong	[300–302]	Water toxicosis	GDSE [303]
Cyanobacteria—*Nodularia* spp.	*N. spumigena* can cause poisoning of cattle and sheep which drink contaminated water. The nodularin toxin is hepatotoxic.	Weak	NE	Potential water toxicosis	NE
Cyanobacteria—*Nostoc* spp.	Produce microcystins and the beta-methyl-amino-L-alanine (BMAA) that has been implicated as the cause of neurodegenerative disease among the Chamorro people of Guam (Guam disease). Evidence not conclusive.	Weak	NE	Potential water toxicosis	NE
Cyanobacteria—*Oscillatoria* spp.	Produce anatoxin-a which can cause neurotoxicity leading to respiratory failure. Consumption of water contaminated with the toxin has been associated with liver cancer in China and acute respiratory failure and death in dogs. Includes *O. agardhii*, *O. nitroviridis* and *O. limosa*.	Moderate	NE	Potential water toxicosis	NE

Cyanobacteria—Planktothrix spp.	Produces microcystins, anatoxin-a and homoanatoxin-a. The main toxin producing species are *P. agardhii*, *P. mougeotii* and *P. formosa*.	None	NE	Potential water toxicosis	NE
Cyanobacteria—*Phormidium* spp.	*P. favosum* is a cyanobacterium that produces anatoxin-a and has been associated with neurotoxicosis in dogs. Toxin producing species include *P. bijugatum*, *P. molle*, *P. papyraceum*, *P. uncinatum* and *P. autumnale*. Toxin producing strains have been found in water from reservoirs in Australia.	None	NE	Potential water toxicosis	NE
Cyanobacteria—*Raphidiopsis*	*R. mediterranea* can produce the toxins homoanatoxin-a, anatoxin-a, and non-toxic 4-hydroxyhomoanatoxin-a.	None	NE	Potential water toxicosis	NE
Cyanobacteria—*Trichodesmium*	*T. erythraeum* is a marine cyanobacteria that is reported to produce a neurotoxin. This organism contributes to some ciguatera toxin accumulation in fish.	Moderate	NE	Potential water toxicosis	NE
Cyanobacteria—*Umezakia natans*	Produces the toxin cylindrospermopsin.	None	NE	Potential water toxicosis	NE
Cyclospora cayetanensis	Contaminated water applied to salads and soft fruits through irrigation/spraying. Repeated outbreaks linked to Mexico.	Strong	[189,190,271–274,304,305]	Waterborne, Water contaminated food	NE
Dinoflagellates and diatoms	These are protozoan organisms that can produce a range of potent toxins. They occur predominantly in saltwater and, under the right conditions, can produce blooms that cause 'red tides' that can cause toxic effects in fish and other sea-life. The toxins can accumulate within shellfish, causing paralytic shellfish poisoning (PSP), diarrhoretic shellfish poisoning (DSP), neurotoxic shellfish poisoning (NSP), Amnesic Shellfish Poisoning (ASP). Some of the toxins can also accumulate through passing up the food chain to give carnivorous fish that are toxic (ciguatera toxin). Coastal blooms causing respiratory symptoms, ciguatera and shellfish poisoning. Blooms of dinoflagellates are linked to weather and nutrients.	Strong	[306–324]	Toxin contamination of marine foods	CEO [325]
Diatom—*Nitzschia* spp., *Pseudo-nitzschia* spp. & *Amphora* spp. Amnesic Shellfish Poisoning	*Pseudo-nitzschia* spp. And *Nitzschia navis-varingica* are diatoms that cause Amnesic Shellfish Poisoning through the production of domoic acids. Symptoms include dizziness, nausea, vomiting, cramps, diarrhoea, dizziness, headache, seizures, disorientation, short-term memory loss, respiratory difficulty and coma. The toxins are regularly detected in UK waters and shellfish. Blooms of *Pseudo-nitzschia australis* have been implicated in deaths of fish and sea lions. Other species include P. *calliantha, P. delicatissima, P. fraudulenta, P. galaxiae, P. multiseries, P. multistriata, P. pungens, P. seriata, P. turgidula*. *Amphora coffeaeformis* is a diatom that produces domoic acid, but its role in human disease is unclear.	Moderate	[326–329]	Toxin contamination of marine foods	NE

Dinoflagellate—*Alexandrium* spp., *Pyrodinium* spp. & *Gymnodinium* spp. Paralytic Shellfish Poisoning	Cause Paralytic Shellfish Poisoning (PSP) through toxin accumulation in bivalve molluscs. They can also cause mass fish kills. Species include *A. acatenella, A. andersonii, A. balechii, A. catenella, A. fundyense, A. hiranoi, A. minutum, A. monilatum, A. ostenfeldi* and *A. tamiyavanichii*. The toxins include saxitoxin and neosaxitoxin, spirolide, goniodomin A. Change in algal blooms with climate. Transmission through shellfish. *Gymnodinium catenatum* produces red tides and high mortality in fishes and can also cause Paralytic Shellfish Poisoning (PSP). *Pyrodinium bahamense* var. *compressa* can produce red tides has been implicated in PSP.	Strong	[189]	Toxin contamination of marine foods	NE
Dinoflagellate—*Dinophysis* spp. & *Procentrum* spp. Diarrhoretic Shellfish Poisoning	Cause Diarrhoretic Shellfish Poisoning (DSP) through accumulation of the toxins in bivalve molluscs. The toxins include okadaic acid, dinophysistoxin-1 (DTX1), dinophysistoxin-2 (DTX2) and pectenotoxin-2 (PTX2). The implicated species include *D. acuminata, D. acuta, D. caudata, D. fortii, D. miles, D. mitra, D. norvegica, D. rapa, D. rotundata, D. sacculus* and *D. tripos*. *Procentrum arenarium, P. belizeanum, P. cassubicum, P. faustiae, P. hoffmannianum, P. lima, P. maculosum* produce one or more toxins including okadaic acid, DTX1, DTX-2, prorocentrolide and fast acting toxins (FAT). Other species with less evidence of toxicity include *P. borbonicum, P. concavum, P. emarginatum, P. minimum, P. emarginatum, P. minimum, P. mexicanum, P. arabianum*.	Strong	[318,319,330,331]	Toxin contamination of marine foods	NE
Dinoflagellate—*Karenia* spp. Neurotoxic Shellfish Poisoning	The species *K. bicuneiformis, K. brevis, K. brevisulcata, K. concordia, K. cristata, K. mikimotoi, K. papilionacea, K. selliformis, K. umbella* produce red tides and can cause Neurotoxic Shellfish Poisoning (NSP). They also cause high mortality in fishes, invertebrates, marine animals and plants, and human respiratory distress, eye and skin irritations. Most species produce brevetoxin in culture. *K. brevis* is synonymous with *Gymnodinium brevis* and *Ptychodiscus brevis*.	Moderate	[309]	Toxin contamination of marine foods	NE
Dinoflagellate—*Protoperidinium* Azaspiracid Shellfish Poisoning	*P. crassipes* produces azaspiracid, which gives DSP-like symptoms of Azaspiracid Shellfish Poisoning in humans but a mixture of DSP-and neurotoxin-like effects in mice.	None	[332]	Toxin contamination of marine foods	NE
Dinoflagellate—*Gambierdiscus* spp. & *Gonyaulax tamarensis*. Ciguatera food poisoning	Produce ciguatoxin or maitotoxin that can pass up the food chain and accumulate in dangerous amounts in certain species of carnivorous fish and shellfish accumulate the toxins as they pass up the food chain. Ciguatera food poisoning produces gastrointestinal, neurological, and cardiovascular symptoms including diarrhoea, vomiting, abdominal pain, reversal of temperature sensation, muscular aches, dizziness, anxiety, sweating, and a	Strong	[333–344]	Toxin contamination of marine foods	NE

	numbness and tingling of the mouth and digits. Toxic species of *Gambierdiscus* include *G. pacificus*, *G. australes*, *G. yasumotoi* and *G. polynesiensis* and *Gonyaulax tamarensis*.				
Dinoflagellate—*Ostreopsis* spp.	*Ostreopsis lenticularis* is the presumed vector of ciguatera poisoning in the Caribbean. The toxin accumulates through the food chain and can be present in toxic amounts in carnivorous fish. *O. siamensis* produces ostreocin D, a palytoxin analogue and has been implicated in clupeotoxism, a fatal toxicosis through ingestion of clupeoid fish (sardines, anchovies and herring). *O. lenticularis* produces ostreotoxin-1 and -3, palytoxin analogues (polyethers), mascarenotoxin-A and -B. *O. mascarenensis* is possibly responsible for palytoxin poisoning, which in humans results in cramps, nausea, diarrhoea, etc, after eating of crabs and certain fish. *O. ovata* is also be a toxin producer and has been associated with toxic effects of bathing in a bloom of this organism (nausea, breathing difficulties, high fever, stomach cramps, irritation of the eyes, vomiting and diarrhea) in Italy.	Strong	[308,345]	Toxin contamination of marine foods; Potential water toxicosis	NE
Dinoflagellate—*Hematodinium* spp.	Cause Bitter Crab Disease and Pink Crab Disease in crabs, making them unpalatable. There is little evidence for a health risk associated with the consumption of infected crabs.	None	NE	Potential water/food toxicosis	NE
Dinoflagellate—*Heterocapsa* spp.	*H. circularisquama* forms red tides and can cause mass fish kills. Their role in human disease remains unclear.		NE	Potential water/food toxicosis	NE
Dinoflagellate—*Pfiesteria* spp.	*Pfiesteria piscicida* is a dinoflagellate that resides in estuarine waters and is responsible for mass fish kills. It has been associated with skin and neurological problems in humans exposed to the toxins, but this work has been challenged. *Pfiesteria shumwayae* causes mass fish kills in estuarine waters. No human illness has yet been associated with this organism.	Weak	NE	Unknown	NE
Dinoflagellate—*Protoceratium reticulatum*	*P. reticulatum* produces yessotoxin which may accumulate in bivalves and is toxic to mice. Its role in human disease is unclear.	None	NE	Unknown	NE
Dracunculus medinensis	*Dracunculus medinensis* life cycle involves the water flea Cyclops. It is the cause of dracontiasis. Human infection results from the consumption of water contaminated with infected water fleas. The adult worm emerges on the foot or leg, and rhabditoid larvae are released into the water where they re-infect water fleas. There is a WHO lead worldwide programme to eradicate Guinea Worm. Rainfall contamination of source waters. Infection associated with water scarcity and start of rainy season.	Strong	[346–351]	Waterborne	RSA [352,353]
Entamoeba histolytica	Causes invasive amoebic dysentery, with abscess formation in the liver and other body sites. Colonisation may occur through water contaminated with	Moderate	[187,189,190,258,271–274,354,355]	Waterborne	NE

	the cysts, often in developing countries where it is endemic. People infected with this organism have usually been travelling abroad recently. *E. histolytica* is visually similar but genetically distinct from *E. dispar*. A few waterborne outbreaks.				
Other *Entamoeba* spp.	*Entamoeba coli, E. dispar* and *E. moshnikovii* can colonise the human intestinal tract and is incapable of causing the invasive form of amoebic dysentery, and is not thought to be an enteric pathogen. *Endolimax nana*, *Enteromonas hominis*, *Retortomonas intestinalis*, *Iodamoeba butschlii*, *Pentatrichomonas hominis*, *Trichomonas hominis* are thought to be non-pathogenic. They are probably transmitted by contaminated food and water, and can be found in patients with diarrhoea. No evidence of rainfall impact.	Weak	NE	Unknown	NE
Echinococcus spp.	Main species *E. granulosus* and *E.multilocularis* and rarer species *E. vogeli* and *E.oligarthrus*. *E. granulosus* forms hydatids (fluid filled vacuoles) in wild ruminants, sheep, pigs, cattle and man, *E. g. equinus* in horses but not man, *E. g. canadensis* in caribou, reindeer and man and *E. g. borealis* cervids and man. *E. multilocularis* has subspecies including *E. m. multilocularis* in Europe and *E. m. sibiricencis* in North America. *E. vogeli* in South American Bush dogs with hydatids in rodents. *E. oligarthrus* in wild cats with hydatids in rodents. Infection results from consumption of *Echinococcus* ova and has been linked to the consumption of contaminated drinking water and direct contamination from dogs or foxes. Strong epidemiological association with drinking water contamination. Rainfall may contribute to contamination.	Strong	[356–363]	Waterborne	NE
Enterobius vermicularis	No waterborne outbreaks but sporadic infection related to drinking water quality. No weather associations.	Weak	[364–366]	Waterborne	NE
Enteroviruses including coxsackie, ECHO, polio	Gross contamination of drinking water leading to enterovirus outbreaks.	Moderate	[197,367–373]	Waterborne	OI [373], QMRA [374]
Enterovirus—Coxsackievirus A and B	Cause mycocarditis, pericarditis, skin rash, meningitis, respiratory infections and fever and are transmitted through the faecal-oral route. Coxsackie A can cause hand, foot and mouth disease, herpangina (fever, sore throat, pain on swallowing, anorexia and vomiting) and conjunctivitis. Coxsackie B can cause pleurodynia (chest pain) and severe infections in neonates. Outbreaks of Bornholm disease do not show evidence of being waterborne.	Weak	NE	Not waterborne	NE
Enterovirus—Echovirus	These enteric viruses usually manifest themselves as a maculopapular skin rash but can also cause meningitis. There are a number of serotypes.	Weak	[375–377]	Waterborne	NE

Enterovirus—Parechovirus	Parechovirus type 1 (PeV1) and type 2 (PeV2) were previously known as echovirus 22 and echovirus 23, but there are six types. Infections can include meningoencephalitis, fever and myositis and may play a role in intra-uterine fetal deaths. Parechoviruses have been isolated from some patients with gastroenteritis. PeV1 has been associated with otitis media and cough.	Weak	NE	Unknown	NE
Enteroviruses—Poliovirus	There are three poliovirus types that have been eradicated from the UK. The WHO is organising the worldwide eradication of poliovirus. Wildtype WPV2 poliovirus was last observed in October 1999. Strategies for eradication include expanded use of type 1 monovalent oral poliovirus vaccine (mOPV1) to eliminate WPV1 transmission before WPV3 and targeted use of type 3 monovalent vaccine mOPV3 in selected areas.	Weak	NE	Unknown	NE
Escherichia coli	*Escherichia coli* contain both non-pathogenic organisms and strains that are an important cause of diarrhoeal disease (termed enterovirulent *E. coli*). Several classes have been defined based on the possession of distinct virulence factors. These are the enteropathogenic (EPEC), enterotoxigenic (ETEC), enteroinvasive (EIEC) and Vero cytotoxigenic (VTEC), enteroaggregative (EAggEC) and diffusely adherent (DAEC) strains of *E. coli*. In developing countries food and contaminated water are important vehicles for transmission of *E. coli*. These are less common in developed countries where there are higher standards of general hygiene.	Strong	[35,378–390]	Waterborne	NE
Escherichia coli—enteropathogenic (EPEC)	The classical enteropathogenic *E. coli* (EPEC) belong to a small number of serotypes and cause sporadic cases and outbreaks of diarrhoea in children, usually under the age of 2 years. A wider range of EPEC strains have caused sporadic cases and outbreaks affecting adults.	Weak	[378]	Waterborne	NE
Escherichia coli—enterotoxigenic (ETEC)	Common cause of traveller's diarrhoea that can be transmitted by water.	Strong	[35,379–383]	Waterborne	NE
Escherichia coli—enteroinvasive (EIEC)	Transmission through poor hygiene or contaminated food or water.	Moderate	[384]	Waterborne	NE
Escherichia coli—Shiga cytotoxigenic (STEC; VTEC; EHEC)	Infection through contaminated drinking water—heavy rainfall.	Strong	[385–390]	Waterborne	CA [391]; OI [109]
Escherichia coli—enteroaggregative (EAggEC)	Enteroaggregative *E. coli* (EAggEC) cause sporadic cases and outbreaks affecting all ages and like Enterotoxigenic *E. coli* (ETEC) are a major cause of travellers' diarrhoea.	Moderate	[392]	Waterborne	NE

Escherichia coli—diffusely adherent (DAEC)	Transmission poorly understood.	NE	NE	Unknown	NE
Fasciola gigantica	A liver fluke (helminth) that is common in cattle in the Middle East, Africa and Asia. The parasite requires a snail as an intermediate host, and man is infected through the consumption of aquatic plants contaminated with the metacercaria.	Moderate	[393]	Water based	NE
Fasciola hepatica	A liver fluke (helminth) that is common in herbivores that graze in wet pasture. The parasite requires a snail as an intermediate host, and man is occasionally infected through the consumption of aquatic plants, particularly watercress, contaminated with the metacercaria.	Strong	[394]	Water based	RAI [395–499]
Fasciolopsis buski	An intestinal fluke (helminth) that is common in areas of Indonesia and Northern Thailand and the Far East. The parasite requires a snail as an intermediate host, and man is infected through the consumption of aquatic plants, particularly water chestnuts and water caltrop, contaminated with the metacercaria.	Moderate	[400]	Water based	NE
Giardia spp.	Grows attached to the small intestinal lining and causes malabsorption in people. The parasite can be isolated from the faeces of wild and domestic animals, and waterborne outbreaks are usually associated with recreational water use. The parasite cyst, which is found in faeces, is moderately resistant to chlorine. The modes of transmission remain unclear. Giardia can be transmitted through recreational and drinking water, although hygiene is also important.	Strong	[28,143,271–274,281,283,401,402]	Waterborne	CSS [403]
Gongylonema pulchrum	Occurs commonly in domestic cattle and other vertebrates, but gongylonemiasis is very rare in humans. Only 48 cases have been described in the literature since 1864. An infection in Hungary was linked to ingestion of contaminated water from an open draw well.	Moderate	NE	Water based	NE
Helicobacter pylori	*H. pylori* is associated with gastritis, and with gastric and duodenal ulcers. The mode of transmission is not entirely understood. The reservoir of H. pylori is the digestive tracts of humans and some primates, and transmission is considered to be from person-to-person with the most common route being oral-oral. *H. pylori* is shed in the faeces after turnover of the gastric mucosa, and has been detected by PCR in sewage in Peru. Sewage pollution is therefore a possible though not proven route of transmission.	Moderate	[404–415]	Waterborne	NE
Helicobacter spp.	Is larger and more tightly helical than *H. pylori* and is associated with a small percentage of patients with gastritis. *Helicobacter bilis* is a Gram negative spiral bacterium that is regarded as an enteric helicobacter and has	None	NE	Unknown	NE

	been implicated in liver disease, particularly biliary tract cancer. Other enteric helicobacters that may be implicated in liver or intestinal disease include *H. hepaticus*, *H. rappani* and *H. pullorum*. *Helicobacter winghamensis* is a *Helicobacter* sp. that have been isolated from patients with gastroenteritis. It's role as a cause of diarrhoea has not been demonstrated. *H. pylori* can contaminate drinking water sources and infection is associated with drinking water source. No evidence of climate drivers.				
Hepatitis A	*Hepatitis A virus* causes hepatitis and can be acquired by person-to-person, through contaminated water, shellfish, and foods eaten raw or washed in contaminated water and waterborne routes. Infection resulting from sewage contamination of source waters and shellfish. Some rainfall associations.	Strong	[198,200,416–424]	Waterborne	PORA = [425]; SFA [426,427]
Hepatitis E	Hepatitis E virus has a genome of single stranded RNA. Epidemiological evidence suggests that the disease can be transmitted by drinking water contaminated with faeces or contact with an environment contaminated with faeces. Pigs may be an important reservoir of infection. Infections in the UK are associated with overseas travel. Large waterborne outbreaks	Strong	[198,209,428–436]	Waterborne	OI [428]
Isospora belli	A coccidian (protozoan) parasite related to *Cryptosporidium* and *Cyclospora*. Infection with *I. belli* may cause colicky pain, diarrhoea, malabsorption and fever. Transmission of *Isospora belli* to humans from contaminated water and infected animals is suspected but has not been clearly demonstrated. Close contact in barracks or institutions, the presence of other intestinal disease, and poor hygiene appear to favour transmission. Limited evidence of waterborne transmission	Weak	[187]	Unknown	NE
Laribacter hongkongensis	An aerobic, spiral shaped gram-negative bacteria isolated from a few people suffering from travel related diarrhoea. Cases were first identified in Hong Kong but have since occurred in other parts of the World. It has also been isolated from freshwater fish in China. The causative role of this organism in human gastroenteritis is still unproven.	None	NE	Unknown	NE
Legionella pneumophila	Legionellosis linked to climate (humidity/vapour pressure)	Strong	[275,437–443]	Aerosol transmission	PRA, RCCS [158,444,445]; POCS [446]; OI [447]
Leptospira spp.	Tightly coiled spiral bacteria that cause Weil's Disease (jaundice) in people. Infection is from rodents and agricultural and domestic animals, usually through exposure to contaminated water or urine. Drinking or exposing wounds or mucous membranes to contaminated water can result in infection. Infection through natural water contaminated by rodent urine and	Strong	[36,448–455]	Waterborne	[456]; OI [160–162,457–468]; RILO [469]; SA [470]; RCS [471]; NBM [472]; CSS [473]

	occasionally through unchlorinated drinking water. Outbreaks follow heavy rainfall and flooding and occasionally abnormally low rainfall.				
Microsporidia	*Enterocytozoon bieneusi* infection linked to transmission through food and water. *Encephalitozoon hellem* keratoconjunctivitis possibly related to water or mud. Link to rainy season in Singapore.	Weak	[187,189,474–481]	Waterborne	RSA [478]
Microsporidia—*Encephalitozoon* spp	*E. intestinalis* is a microsporidian (protozoan) parasite that is associated with diarrhoeal disease in immunodeficient patients, particularly AIDS. Its transmissibility by food and water is not known. *E. cuniculi* is associated with disseminated infection involving the kidneys, sinuses, lungs, brain and conjunctiva in immunodeficient patients, particularly AIDS. Its transmissibility by food and water is not known. *E. hellem* is associated with nasal and ocular disease in immunodeficient patients, particularly AIDS. Its transmissibility by food and water is not known.	Weak	NE	Unknown	NE
Microsporidia—*Enterocytozoon bieneusi*	A parasite associated with diarrhoeal disease in immunodeficient patients, particularly AIDS. Its transmissibility by food and water is not known. *E. bieneusi* is usually confined to the intestines and is not associated with disseminated infection. *E. bieneusi* has been detected in pigs, cats, dogs and a rhesus monkey. *E. bieneusi* is transmitted through the usual faecal-oral pathways including food and water. Outbreaks have been linked to water and food.	Weak	[189,474]	Waterborne	NE
Mycobacterium spp. (not TB)	Infections related to buildings and the built environment.	Strong	[275,482–492]	Waterborne	LR [493]
Mycobacterium avium	Contains three subspecies (*M. avium* subsp. *avium*, *M. avium* subsp. *sylvaticum* and *M. avium* subsp. *paratuberculosis*). Organisms belonging to the *Mycobacterium avium* complex (MAC) include *M. avium*, *M. intracellulare* and *M. scrofulacium*. They can cause intestinal infection, septicaemia and wasting in AIDS patients, up to 50% of whom may develop MAC bacteraemia. Where the isolates have been speciated they have been found to be predominantly *M. avium*. Isolates recovered from water are probably a source of human infection. Organisms of the MAC group are able to grow in both hot and cold-water systems.	Moderate	[275,494,495]	Waterborne	NE
Mycobacterium paratuberculosis	A slow-growing bacteria that causes Johne's disease in agricultural animals. It has been implicated in the causation of Crohn's disease in humans. *M. paratuberculosis* (or *M. avium* subsp. *paratuberculosis* (Map)) has been detected in water using PCR but has not to date been isolated from potable water supplies.	Weak	NE	Unknown	NE

Naegleria fowleri	Colonises thermally polluted waters. Infections in Southern US are seasonal, with more in the summer. Infections in cattle are also seasonal. Infections may increase in some countries with warmer temperatures. Runoff from heavy rains introduces this organism into lakes, ponds, and surface waters [189,496].	Strong, links to water contamination	[187,189,497]	Waterborne	SCS [498]
Norovirus	Is mostly transmitted person-to-person. Transmission has also been indicated via contaminated ice, stored water on cruise ships, borehole water and contaminated recreational bathing waters. Municipal drinking water supplies have been implicated in outbreaks of gastroenteritis, usually following contamination by sewage. Strongly seasonal. Link to shellfish contaminated from infected faeces. Coastal water contamination linked to rainfall.	Strong	[416,499–508]	Waterborne	OI [509]
Plesiomonas shigelloides	*Plesiomonas shigelloides* is a bacterial pathogen that has been implicated as a cause of diarrhoeal disease. It is common in the natural waters in tropical countries. No well documented waterborne outbreaks (two reported in 1978). No associations with rainfall or temperature.	None	[51,296,497,510–513]	Waterborne	NE
Pseudomonas aeruginosa	Contamination of natural and man-made bathing waters. Most folliculitis infections are related to spa pools. Swimming in natural waters can cause otitis externa. No evidence of rain or temperature link.	Strong	[497,514]	Waterborne	NE
Rhinosporidium seeberi	Infections linked to lake, river and well water in India. Outbreak linked to bathing in stagnant water in Serbia.	Moderate	[515–518]	Waterborne	NE
Rotavirus	Rotavirus. Rotaviruses are part of the Reovirus family and have a double stranded RNA genome. Exposure is by contact with infected individuals or contaminated water or other materials. Group C rotaviruses have been identified throughout the world. Group B rotaviruses have caused large outbreaks of diarrhoeal illness in mainland China. The virus entered the population as a result of faecal contamination of water supplies drawn from rivers, and then spread through the population by person-to-person contact. Waterborne outbreaks in developing countries	Weak	[197,519–525]	Waterborne	[526]
Stenotrophomonas maltophilia	Hospital outbreaks linked to contaminated water systems.	Moderate	[527–531]	Waterborne	NE
Salmonella spp.	Are strongly associated with foodborne disease but can also be transmitted through waterborne and other routes. There is a particular problem with the occurrence of Salmonellas in agricultural animals and the transmission to people through poor slaughter hygiene and kitchen practices. This particularly results from their ability to grow within foods to numbers that can cause disease. Outbreaks and sporadic disease related to contaminated drinking water and recreational water. No clear links to rain.	Moderate	[518,532–545]	Waterborne	GAMTS [546]; GLM [546]; EACWQ [547]

Salmonella Paratyphi	Causes paratyphoid fever. Infections can be acquired from travel overseas, and food and waterborne infection can also occur.	Moderate	[548]	Waterborne	NE
Salmonella Typhi	Causes typhoid (fever and diarrhoea). The infectious dose is low, and large waterborne outbreaks were common in the first half of the 20th century. Waterborne infection can arise through sewage contamination of drinking water and through typhoid carriers who are water workers. There is no natural animal host of this pathogen. Most infections are in people returning from less developed countries.	Strong	[535,541,549]	Waterborne	RSA [550]
Sappinia diploidea	A rare cause of amoebic cerebral abscess.	None	[551,552]	Waterborne	NE
Sapovirus	A calicivirus, formerly called "Sapporo-like virus" (SLV), classic or typical calicivirus and are associated with relatively mild gastroenteritis in children. Outbreak linked to flood water contamination of shellfish with several viruses.	Weak	[183]		POWE [213]
Sarcocystis hominis	Sporocysts are infectious, causing muscle infections through drinking water.	Strong	[553,554]	Waterborne	NE
Schistosoma spp.	These are flukes (helminth) which are transmitted through the contamination of water with faeces containing the ova. Cases linked to flooding and land surface temperature.	Strong	[555]	Water based	OI [556]; SA [557–560]; RRM [561]; MM [562]; MLM [563]
Schistosoma intercalatum	The life cycle involves the ova hatching and infecting specific snail species, and the cercaria infect people occupationally or recreationally exposed to contaminated water through the skin.	Strong	[564]	Water based	NE
Schistosoma haematobium	The life cycle involves the ova hatching and infecting specific snail species, and the cercaria infect people occupationally or recreationally exposed to contaminated water through the skin. Infection is found in Africa and the Middle East.	Strong	[564,565]	Water based	NE
Schistosoma japonicum	Infection is found in Eastern Asia including Japan and Korea. Links to rainfall and temperature.	Strong	[566]	Water based	CSS [563]
Schistosoma mansoni	The life cycle involves the ova hatching and infecting specific snail species, and the cercaria infect people occupationally or recreationally exposed to contaminated water through the skin.	Strong	[564,567–570]	Water based	OI [556]; SA [560]
Schistosoma mekongi	The life cycle involves the ova hatching and infecting specific snail species, and the cercaria infect people occupationally or recreationally exposed to contaminated water (usually river water) through the skin. Infection is restricted to South East Asia, particularly the Mekong River basin in Kampuchea.	Strong	[571–574]	Water based	NE

Schistosoma spindale	A fluke (helminth) that commonly causes cercarial dermatitis of paddy field workers in Assam, India. It is unclear which species of animal the schistosomes derive from although ducks are likely.	Strong	[575]	Water based	NE
Spirometra spp.	These are tapeworms (helminth) and occur in amphibious animals including frogs. Ingestion of the first stage larvae which are present in the copepod *Cyclops* results in human sparganosis, with 'Sparganum' larvae forming in nodules. Infection is thought to derive from contaminated drinking water or the consumption of uncooked frogs or snakes. *S. mansonoides* (*S. erinacei-europaei*) is the organism most commonly diagnosed.	Weak	[576–579]	Waterborne	NE
Shigella spp.	Causes dysentery and can be readily passed between children and adults in unsanitary environments. They can occasionally be transmitted through contaminated food. Waterborne outbreaks of shigellosis have been common in the past, but are now uncommon and are usually the result of a combination of inadequate treatment, post treatment contamination and chlorination breakdown. *Shigella* spp. will not grow within water distribution systems. There are four species. *Shigella sonnei* is commonly transmitted between children and can be a problem in schools in the UK. *Shigella dysenteriae* is a more severe infection than *S. sonnei* and causes severe dysentery. Most *S. boydii, S. flexneri* and *S. dysenteriae* infections within England and Wales are usually acquired abroad. Lake water recreational outbreaks.	Strong	[355,580–584]	Waterborne	OI [284]
Torovirus	Toroviruses are enveloped viruses that have been linked to enteric infections in horses (Berne virus), cattle (Breda virus), pigs, and humans and transmission is thought to be via the faecal-oral route. In humans toroviruses have been found in infants with necrotising enterocolitis but their role in gastroenteritis remains unproved.	Weak	NE	Unknown	NE
Toxoplasma gondii	A protozoan parasite which occurs in a wide range of warm-blooded animals. The only definitive host in which the full sexual cycle has been observed is members of the cat family (Felidae), which excrete the oocysts which contaminate the environment and source waters. People can be infected from consuming food or water that is contaminated with oocysts or the consumption of undercooked meat which contains tissue cysts. Infection can be a particular problem for pregnant women and immunocompromised patients. Some evidence that heavy rainfall can precede outbreaks.	Strong	[187,190,585–589]	Waterborne	OI [590]; SA [591];
Trichobilharzia regent	A schistosome of birds and the cercaria can give rise to an itchy rash (known as cercarial dermatitis or swimmer's itch) in people who have had contact with the water. They are otherwise thought to be non-pathogenic to	Strong	[592–599]	Water based	NE

	humans. The parasites mature and lay eggs in the nasal cavities of waterfowl. The lifecycle involves snails.				
Vibrio cholerae	Causes cholera, a disease that is characterised by acute and life-threatening diarrhoea and dehydration usually in epidemic outbreaks. Cholera is transmitted through drinking water, shellfish and contaminated food. The disease is usually restricted to less developed countries where drinking water and waste disposal are poor, and to migrant populations associated with drought, flood, famine and war. Evidence of links to rainfall over the last century.	Strong	[600–602]	Waterborne	[603,604]; GAMTS [605]; [606]; EACO [607]; POWE [608]
Vibrio parahaemolyticus	Inhabits estuarine and marine environments. It can cause food-poisoning through the contamination of seafood. *V. parahaemolyticus* associated with raised water temperature.	Moderate	[609]	Foodborne through seafood	RSE [610]
Vibrio vulnificus	*Vibrio vulnificus* can cause severe, soft tissue infections, septicaemia, and deaths. Infection is through the consumption of contaminated seafood (particularly raw oysters). *V. vulnificus* infection increased following hurricane Katrina.	Strong	[609,611,612]	Waterborne; Foodborne through seafood	MMF [613]; HSM [614]; MMST [615]; OI [611]
Vibrio spp. (other than *V. cholerae*)	A variety of Vibrio spp. can cause human disease, including the halophilic *V. parahaemolyticus, V. fluvialis, V. hollisae* and the non-halophilic vibrios non-O1 *V. cholerae and V. mimicus*. Cholera is a classical waterborne disease, and the water route is still important in developing countries. There is no evidence that vibrios are able to cause human disease by growing within water distribution systems. *Vibrio* spp. are part of normal marine flora and can be found in marine, estuarine and river water. These organisms and proliferate during the summer months. People are infected through the consumption of raw or undercooked contaminated shellfish, other foods and faecally contaminated water. A large infective dose is required to initiate infection and person-to-person transmission does not occur. Infections in the United Kingdom tend to be in travellers returning from developing countries. Non-cholera *V. cholera* in warmer Baltic waters.	Strong	[36,609]	Waterborne	MMO = [616]; OI [617]; TSAT [611]; WMR [615]; POTA [617]
Yersinia spp.	*Yersinia* spp. are bacteria that can cause diarrhoea, arthritis and mesenteric lymphadenitis, and small waterborne outbreaks of infection can occur. Infection usually derives from an animal source, particularly pigs. Non-pathogenic types can be detected in people and are not thought to be involved as a cause of diarrhoea. *Y. pseudotuberculosis* causes fever, enlargement of the mesenteric lymph nodes, pseudo-appendicitis, septicaemia and diarrhoea. *Yersinia enterocolitica* can cause diarrhoea, arthritis and mesenteric lymphadenitis, and small waterborne outbreaks of infection can occur. *Y. fredriksenii* and *Y. kristensenii* have been isolated from	Moderate	[618–620]	Waterborne	NE

	the faecal samples of people with diarrhoea, but their pathogenic role is unclear.				
Mixed causes	Climate change and waterborne illness [180,181] Relationship between recreational water outbreaks and temperature [54]. Review of waterborne outbreaks [621]	NE	[187,190,257,258]	Mixed	ROS [36,622]; FTA [293]; RCCS [32,269]; QMRA [374,623]

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