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Climate change and recreational waterrelated infectious diseases

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Abstract

Climate change and recreational water-related infectious diseases

Since micro-organisms and therefore also human pathogens in recreational waters are highly influenced by climate and environmental conditions, any climate *change* may alter the infectious disease burden from exposure to pathogens transmitted through recreational water. This is due to die-off or inactivation of the pathogens or, alternatively, their survival and growth.

Known recreational waterborne pathogens were systematically reviewed with respect to their specific climate dependencies, water type preferences (i.e. fresh, marine or swimming pool water) and their significance to public health. Some indigenous species of bacteria, amoebas and algae are able to grow in aquatic environments, whereas enteric bacteria, viruses and parasites that are derived from human or animal faeces are not. The growth of waterborne pathogens in aquatic environments depends on environmental conditions (including climate), and on pathogen characteristics. Major climate *factors* that determine the number, type, virulence and infectivity of pathogens in recreational waters, and thus may have an impact on diseases transmitted through recreational water, include temperature, UV radiation, precipitation patterns and water availability. For example, increased water temperature can influence growth and die-off or inactivation of waterborne pathogens. For those pathogens that can grow in natural and artificial recreational water environments, such as *Vibrio* spp. in sea water, *Pseudomonas aeruginosa* in freshwater and *Legionella* in swimming pool systems, an increase in exposure and possibly disease incidence can be expected. Increased UV radiation may result in increased inactivation of enteric pathogens, or alternatively growth, whereas increased precipitation intensity will lead to peak concentrations of these pathogens due to e.g. sewage overflow and runoff. Disease that is specifically related to indoor pools is unlikely to be affected by climate factors due to the controlled environment in these facilities.

With respect to the impact of climate *change*, there is a need to identify emerging waterborne infectious diseases and prioritise both emerging and known waterborne infectious diseases in general and recreational waterborne infectious diseases in particular. Because of the direct influence of climate on recreational water quality and the direct exposure of humans to recreational water, quantification of the impact of climate change on the disease burden through exposure to recreational water is required. Climate *factors* not only affect pathogen behaviour, but also influence human behaviour, thus stressing the need to study both the complexity of pathogen behaviour in recreational waters and social behaviour with respect to expected climate *changes*.

Key words:

recreational water, climate change, water quality, infectious diseases

Rapport in het kort

Klimaatveranderingen en recreatiewater overdraagbare infectieziekten

Het RIVM heeft in kaart gebracht welke micro-organismen mensen via recreatiewater ziek kunnen maken en in welke mate *klimaatverandering* daar invloed op heeft. De fysiologie van deze ziekteverwekkers wordt namelijk beïnvloed door *klimaatfactoren*, zoals temperatuur UV-straling en neerslag. Zodoende kunnen ziekteverwekkers door *klimaatverandering* sterven, overleven of juist in aantal toenemen. Deze veranderingen beïnvloeden de mate waarin zij via recreatiewater ziekte kunnen veroorzaken. In het overzicht is ook aangegeven welk watertype de micro-organismen prefereren (zoet-, zout-, of zwembadwater) en welke ziekteverschijnselen ze kunnen veroorzaken.

Naar verwachting leidt een hogere watertemperatuur ertoe dat ziekteverwekkers die zich in recreatiewater kunnen vermeerderen, in hogere aantallen in recreatiewater aanwezig zijn. Daardoor treden mogelijk meer ziektegevallen op. Bacteriën die van nature in recreatiewater voorkomen en zich daar kunnen vermeerderen zijn *Vibrio* (veroorzaakt oorontsteking en wondinfecties) en *Pseudomonas aeruginosa* (oorontsteking). Toenemende UV-straling kan ertoe leiden dat ziekteverwekkers vanwege de warmte in aantal toenemen of juist sterven, doordat genetisch materiaal beschadigd raakt. Door hevige regenval kunnen tijdelijk en plaatselijk zeer hoge aantallen micro-organismen uit feces in recreatiewater terechtkomen doordat het riool de hoeveelheid water niet meer aankan en overloopt of doordat mest van het land afspoelt in het water. In binnenzwembaden wordt het binnenmilieu constant gehouden, waardoor ziekteverwekkers die hierin voorkomen waarschijnlijk niet door *klimaatfactoren* worden beïnvloed.

Om de invloed van *klimaatverandering* vast te stellen op nieuwe (*emerging*) en bekende infectieziekten die via recreatiewater worden overgedragen, is nader onderzoek nodig. Het gaat daarbij om de invloed van *klimaatfactoren* op zowel de verwekkers van deze infectieziekten als op de manier waarop mensen omgaan met zwemmen in recreatiewater

Trefwoorden:

recreatiewater, klimaatveranderingen, waterkwaliteit, infectieziekten

Contents

Summary		7
1	Introduction	11
1.1	Water-transmitted infectious diseases	11
1.2	Pathogens in recreational waters	12
1.3	Global change	14
1.4	Aim of the report	14
2	Water-transmitted pathogens	15
2.1	Acanthamoeba	15
2.2	Adenovirus	15
2.3	Aeromonas	16
2.4	Cryptosporidium	16
2.5	Cyanobacteria	16
2.6	E. coli O157	17
2.7	Enterovirus	17
2.8	Giardia	18
2.9	Hepatitis A virus	18
2.10	Legionella	19
2.11	Leptospira	19
2.12	Molluscipoxvirus	19
2.13	Mycobacterium	20
2.14	Naegleria fowleri	20
2.15	Norovirus	20
2.16	Papillomavirus	21
2.17	Pseudomonas aeruginosa	21
2.18	Rotavirus	22
2.19	Shigella	22
2.20	Staphylococcus aureus	22
2.21	Trichobilharzia	23
2.22	Trichophyton	23
2.23	Vibrio	23
3	Recreational water types	25
3.1	Bathing sites in surface water	25
3.2	Natural or green pools	25
3.3	Paddling pools	25
3.4	Interactive water features and decorative fountains	26
3.5	Indoor pools	26
4	Impact of climate change on recreational waterborne pathogens	27
4.1	Temperature increase	27
4.1.1	Water temperature increase	27
4.1.2	Seasonality	30
4.2	Rainfall intensity and frequency	30
4.2.1	Run-off, sewage overflows and flooding	30
4.2.2	Resuspension of river sediments	31

4.3	Water availability	31
5	Discussion	33
6	Conclusions and recommendations	37
	References	39
	Acknowledgement	45

Summary

Since micro-organisms and therefore also human pathogens in recreational waters are highly influenced by climate and environmental conditions, any climate *change* may alter the resultant infectious disease burden from exposure to recreational water transmitted pathogens due to die-off or inactivation or, alternatively, survival and growth of the pathogens. Due to the complexity of pathogen behaviour in recreational waters, it is yet unclear to which extent climate *change* will affect recreational waterborne diseases in the Netherlands. Moreover, disease burden will also be influenced by other factors that are outside the scope of this report, such as environmental, demographic and economic changes, and technical development. Here, we list each of the pathogens that may be transmitted via various types of recreational waters (i.e. fresh, marine or swimming pool) with their public health significance and relevant characteristics with respect to climate *change*.

Major climate *factors* that determine the fate and behaviour of pathogens in recreational waters, and thus may impact on recreational water transmitted diseases, include temperature, UV radiation, precipitation patterns and water availability. Water temperatures have a significant impact on the concentrations of waterborne pathogens in surface waters through their influence on growth patterns of pathogens. Some waterborne pathogens, such as species of non-faecally derived bacteria (e.g. *Pseudomonas aeruginosa* and *Vibrio* spp.) and amoebas (e.g. *Naegleria fowleri*), can grow in aquatic environments and their numbers are likely to increase with increasing water temperature, although some (e.g. *Trichobilharzia*) are parasites that require a host for replication. Cyanobacteria generally grow better at higher surface water temperatures and both in fresh and marine waters blooms of toxic algae are expected to occur more often at elevated water temperatures. Increase of global atmospheric temperature may result in prolonged warming of land and water enabling these indigenous pathogens to proliferate for longer periods thus extending the time frame with increased concentrations of these waterborne pathogens in recreational waters which may result in increased exposure of bathers to these pathogens.

Other, merely faecally derived waterborne pathogens cannot grow in aquatic environments, rather at increased water temperatures they will lose their ability to infect human cells and to replicate. Especially host-dependent pathogens are highly sensitive to high environmental temperatures. These pathogens include enteric bacteria (e.g. *Escherichia coli* O157:H7 and *Shigella* spp.) and viruses (e.g. noroviruses and enteroviruses), but also pathogenic species of *Leptospira* that are shed in urine of chronically infected hosts. Inactivation by increased water temperatures may be of lesser relevance for parasites such as *Cryptosporidium* and *Giardia* that create environmentally robust survival structures. Heavy rainfall events are expected to occur more often during summers and with rainfall pathogenic micro-organisms of human and animal faecal origin may enter surface waters by discharges of raw and treated wastewater, and runoff from the land of faecal matter from wildlife, domestic animals or manure. It may be assumed that runoff and sewage overflow, affecting both fresh and marine waters, increase proportionally with increases in extreme precipitation, but these may be controlled with sewage treatment, increased storage capacity for rainwater, and appropriate effectuation of bathing water profiles in the current European Bathing Water Directive.

Surface waters, natural or green pools, paddling pools and interactive water features are recreational water types most likely affected by temperature increase, whereas changes in precipitation patterns affect both fresh and marine surface waters. Climate factors are unlikely to affect pathogens specifically related to indoor pools due to the controlled environment in these facilities.

With respect to the impact of climate change, there is a need to prioritise and quantify waterborne infectious diseases in general and recreational water infectious diseases in particular. Therefore, a close watch should be kept on emerging and zoonotic threats in relation to climate opportunities. Ongoing recreational water surveillance and investigation of outbreaks in relation to climate factors will identify causative agents and their behaviour related to climate factors.

1 Introduction

1.1 Water-transmitted infectious diseases

Public health may be affected by exposure to pathogens in recreational waters. A public health threat occurs when:

1. either or not imported water-transmitted pathogens are present in recreational waters;
2. water-transmitted pathogens can sustain themselves;
3. hosts are exposed to pathogens in the recreational waters;
4. hosts are susceptible to infection and disease.

Infections with waterborne pathogens are generally mild, but may also be asymptomatic, or result in serious illness (WHO, 2003). Water-transmitted pathogens may be bacteria, viruses, parasites, amoebas or algae. The way they are transmitted via water differs (Table 1). Pathogens that are water-transmitted may follow various routes, ranging from water ingestion to transmission via insect vectors, and are classified into four different categories according to Bradley (1977). Waterborne pathogens are passively carried in water bodies. Waterborne diseases are caused by the ingestion of water contaminated by human or animal faeces or urine containing pathogenic bacteria, viruses or parasites (e.g. gastroenteritis). Water-washed diseases are the result of contact with contaminated water (e.g. conjunctivitis). Water-based diseases are caused by parasitic worm infections in which waterborne intermediate organisms support an essential part of the life cycle of the infecting agent (e.g. schistosomiasis). Insect vectors breeding in water or insect vectors only biting near water cause water-related infectious diseases (e.g. malaria).

Table 1 Water-transmitted infectious diseases divided into four categories according to their transmission route. Adapted from Bradley (1977)

Category	Transmission	Examples
Waterborne	Ingestion of water contaminated by human or animal faeces or urine containing pathogenic bacteria, viruses or parasites	Gastroenteritis, enteric hepatitis, amoebic and bacillary dysentery, cholera, leptospirosis, poliomyelitis, typhoid/paratyphoid fever
Water-washed	Skin, ear or eye contact with contaminated water and poor personal hygiene	Conjunctivitis, trachoma, intestinal helminth infections, leprosy, scabies
Water-based	Parasitical worm infections, the parasites are found in intermediate organisms living in water	Dracunculiasis, schistosomiasis, (tricho)bilharziasis
Water-related	Insect vectors breeding in water or biting near water	Dengue, lymphatic filariasis, malaria, onchocerciasis, trypanosomiasis, yellow fever

In this report, we focus on waterborne, water-washed and water-based infectious diseases most relevant for recreational waters in high-income, temperate climate regions such as Western Europe, with an assignment-driven emphasis on the Netherlands. Most reports and publications on climate change and infectious diseases have so far focused on water-related or vector-borne disease (Semenza and Menne,

2009). However, discussion about water-related disease should not ignore the complex interplay of the multitude of factors that are generally dominant in the dynamics of their transmission. Particularly the complexity of the ecology and behaviour of the host and that of the vector should be taken into account for assessing the significance of climate for the prevalence and incidence of these diseases. For water-related infectious diseases one is therefore referred to Reiter (2008).

1.2 Pathogens in recreational waters

Some water-transmitted pathogens, such as species of non-faecally derived bacteria, amoebas and algae, can grow in aquatic environments, other so-called enteric bacteria, viruses and parasites that are faecally derived cannot (Figure 1). Growth of water-transmitted pathogens in aquatic environments depends on environmental conditions including climate, and on the pathogen characteristics.

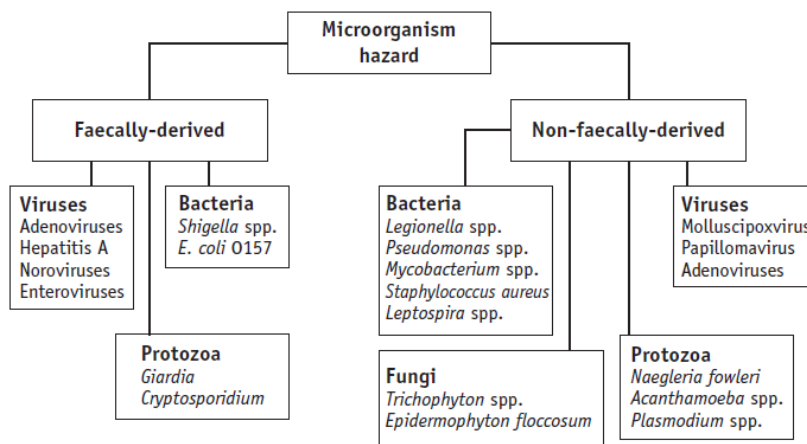


Figure 1 Recreational water-associated (non)-faecally-derived pathogens. From WHO (2006)

Enteric pathogens may be bacteria such as *Escherichia coli* O157:H7 and *Campylobacter*, viruses such as noroviruses and enteroviruses, and protozoan parasites such as *Cryptosporidium* and *Giardia*. Other waterborne pathogens are adenoviruses, hepatitis viruses, *Shigella* spp. and *Salmonella* spp. The causative agent of leptospirosis, pathogenic species of *Leptospira*, however, is shed in urine of chronically infected hosts such as rats, cows and dogs, but not in faeces.

So-called indigenous, water-washed and/or waterborne pathogens have evolved within an original ecosystem and exist there. Good examples are *Pseudomonas aeruginosa* in freshwater, which causes otitis externa upon exposure, and *Vibrio* spp. in marine or brackish water, that are capable of causing ear conditions, wound infections and gastro-enteritis. *Trichobilharzia* also belongs to this category of waterborne infectious diseases causing the well-known symptoms of swimmers' itch, although it is a parasite that requires a host organism for its replication.

Faecal matter in water may originate from animals or humans that serve as the sources for enteric pathogens. Table 2 displays possible sources of example micro-organisms. Some animal derived pathogens cause disease in humans; they are the so-called *zoonotic* pathogens. Well-known examples of zoonotic pathogens are *Campylobacter* spp. and *Cryptosporidium* spp. from birds and husbandry animals and *Vibrio* spp. from fish.

Water-transmitted pathogens may also be introduced from other natural or manmade environments, e.g. *Legionella* spp. can occupy artificial aquatic environments originating from natural habitats (Borella et al., 2005).

Besides known pathogens, new pathogens may be introduced into the human population causing a new infectious disease, the so-called *emerging* pathogens. Emerging pathogens also include those pathogens that have changed by acquiring novel features, such as antibiotic resistance by bacteria like MRSA, or by acquiring a higher virulence trait like *Escherichia coli* O157:H7, or by mutation or recombination of the virus genome like SARS (Blaak et al., 2010a).

This report does not address *Clostridium botulinum*, the bacterium that produces toxins that cause botulism. Botulism is mainly a food borne intoxication, although waterborne botulism could theoretically also result from exposure to preformed toxin. The botulism types that cause illness in waterfowl (C, D and E) do not cause human illness. Human illness is associated with botulism types A, B, E and rarely F (WHO, 2002).

Table 2 Sources for waterborne pathogens

pathogen	source		
	human	animal	environmental
<i>Acanthamoeba</i>	-	-	+
<i>Adenovirus</i>	+	+	-
<i>Aeromonas</i>	+	+	+
<i>Cryptosporidium</i>	+	+	-
Cyanobacteria	-	-	+
<i>E. coli</i> O157	+	+	-
Enterovirus	+	+	-
<i>Trichophyton mentagrophytes</i> var. <i>interdigitale</i>	+	-	-
<i>Trichophyton rubrum</i>	+	-	-
<i>Giardia</i>	+	+	-
Hepatitis A virus	+	-	-
<i>Legionella</i>	-	-	+
<i>Leptospira</i>	-	+	-
<i>Molluscipoxvirus</i>	+	-	-
<i>Mycobacterium</i> (nontuberculous mycobacteria)	-	-	+
<i>Naegleria fowleri</i>	-	-	+
Norovirus	+	-	-
Papillomavirus	+	-	-
<i>Pseudomonas aeruginosa</i>	-	-	+
Rotavirus	+	-	-
<i>Shigella</i>	+	+	-
<i>Staphylococcus aureus</i>	+	-	-
<i>Trichobilharzia</i>	-	+	-
<i>Vibrio</i>	+	+	+

1.3 Global change

Amongst other factors such as migration and industrial development, climate factors will affect the aquatic environment and thus the numbers and behaviour of waterborne pathogens, but also human behaviour (Semenza and Menne, 2009). Climate change is likely to have a wide-ranging and adverse impact on human health which may be direct or indirect. Direct effects include extreme weather conditions, such as floods as a result of heavy rainfall, and sea level rise, e.g. leading to an increased risk of drowning, and temperature related effects, such as heat waves and smog. An increased frequency or severity of heat waves would cause an increase in mortality and illness (McMichael, 2001). Indirect effects may include the introduction of invasive species that may lead to exposure to new or emerging pathogens. Waterborne disease incidences may also be influenced by climate change; e.g. air temperature will affect water temperature and increased temperature can influence growth and die-off or inactivation of waterborne pathogens. Under the influence of sunlight and water temperature, growth of specific species of bacteria, amoebas and algae in water may occur. However, high water temperatures and intense sunlight irradiation largely inactivate or kill enteric micro-organisms that cannot replicate in water but depend on their human or animal host for replication. Other factors such as nutrient levels and dissolved organic carbon also influence the life and death of waterborne pathogens (Porcal et al., 2009).

1.4 Aim of the report

Due to the complexity of pathogen behaviour in recreational waters, it is yet unclear to which extent climate change will affect recreational waterborne diseases in the Netherlands. In addition, other factors such as environmental, demographic and economic changes and technical development will occur, influencing the disease burden (Gezondheidsraad, 2009), but these factors are outside the scope of this report. This report describes each of the pathogens that may be transmitted via recreational waters with their public health significance and relevant characteristics with respect to climate in chapter 2. Recreational water types are described in chapter 3. In chapter 4 the possible effects of climate change on recreational waterborne pathogens and infectious disease will be explained. Results are discussed in chapter 5 and conclusions and recommendations are listed in chapter 6.

2 Water-transmitted pathogens

Many species of bacteria, viruses, parasites, algae, and amoebas may be water-transmitted. These water-transmitted pathogens are micro-organisms that can infect and cause illness in humans and animals. In this chapter, epidemiology and microbiology for each of the recreational water-transmitted pathogens listed in Table 2 are described in detail. The micro-organisms are presented in alphabetical order. The possible effects of climate change on these pathogens are discussed in chapter 4 and presented in Table 3.

2.1 Acanthamoeba

Acanthamoeba species are free-living amoebas that can be found in all aquatic environments. *Acanthamoeba* are feeding and replicating trophozoites (25-40 µm long) with needle-like acanthopodia from the body, which form dormant cysts of 15-28 µm in diameter under adverse conditions. *Acanthamoeba* cysts are very resistant to extreme temperatures (-20 °C to 56 °C), disinfection and desiccation. The human pathogenic species *A. castellani*, *A. culbertsoni* and *A. polyphaga* have an optimal growth temperature of 30 °C, but will also grow at 36-37 °C. *Acanthamoeba* numbers in freshwater vary according to the water temperature and the availability of bacteria as a food source. Although *Acanthamoeba* species are common in the environment, human infections are rare worldwide. Infections are usually chronic and very persistent. Human pathogenic *Acanthamoeba* cause granulomatous amoebic encephalitis (GAE), an extremely rare disease of the immunocompromised that is invariably fatal. In the Netherlands, cases of GAE have not been identified to date (Gezondheidsraad, 2001). In healthy people, *Acanthamoeba* causes keratitis, a severe inflammation of the cornea that may lead to blindness. The wearing of contact lenses while swimming (mainly in swimming pools) is a risk factor, even so is trauma to the eye during contact with contaminated water (WHO, 2003a; WHO, 2006). Microbial keratitis in wearers of contact lenses caused by *Acanthamoeba* does occur in the Netherlands, but the number of cases is low (Gezondheidsraad, 2001). Data on the occurrence of *Acanthamoeba* in surface waters in the Netherlands are lacking (Gezondheidsraad, 2001).

2.2 Adenovirus

Adenoviruses are medium-sized (90–100 nm), non-enveloped (naked) icosahedral viruses composed of a nucleocapsid and a double-stranded linear DNA genome. Adenoviruses survive longer in water than enteroviruses and hepatitis A virus which may be due to their double-stranded DNA (Mena and Gerba, 2009a). Viruses of the family *Adenoviridae* infect various species of vertebrates, including humans. There are 51 described serotypes in humans of which one third are associated with human disease, while other infections are asymptomatic (Mena and Gerba, 2008). Adenoviruses are responsible for 5–10 % of the upper respiratory infections in children, and many infections in adults as well. Children and the immunocompromised are more severely impacted by adenovirus infections than healthy adults (Schilham et al., 2002). Adenoviruses have been responsible for many recreational water-related outbreaks, more than any other waterborne virus, including a great number of swimming pool related outbreaks (Mena and Gerba, 2008). Of the many types of adenoviruses, some (type 40 and 41) are associated with waterborne gastrointestinal illness, whereas other types are associated with respiratory and ocular symptoms. In the Netherlands, adenoviruses come fourth on the list of viruses with more than 1200 diagnosed cases each year, most likely a large under representation of actual cases (RIVM CIb, 2010). Adenoviruses were frequently detected in Dutch surface waters (Rutjes and De Roda

Husman, 2007); they are capable of robust survival in water, are of equal or greater sensitivity to oxidizing disinfectants compared with other waterborne viruses and are the most resistant pathogens to UV (Mena and Gerba, 2008).

2.3 Aeromonas

Aeromonas spp. are Gram-negative rod-shaped cells of 0.3-1.0 x 1.0-3.5 µm in size, that are facultative anaerobes. *Aeromonas* are autochthonous inhabitants of aquatic environments. They are ubiquitous in fresh and marine waters and their numbers relate to the water temperature and the trophic state of freshwater; in marine water their presence is supported by organic matter coming from land.

Aeromonas spp. tolerate a wide range of water temperatures (4-45 °C), but optimal growth occurs at 35 °C. *Aeromonas* can cause human illnesses, including gastroenteritis and wound infections.

Aeromonas mostly affects children under five years of age and immunocompromised adults. In association with recreational water use, infections of open wounds and cases of pneumonia after aspiration of contaminated water have been reported (WHO, 2003a; Rund and Theegarten, 2008).

Aeromonas was reported in Dutch surface waters and sediments (Blaak et al., 2010b).

2.4 Cryptosporidium

Human infections with the intestinal parasite *Cryptosporidium* are commonly caused by *C. hominis* and *C. parvum*. *Cryptosporidium* oocysts are shed by infected persons or animals and enter surface water through direct faecal input, discharge of treated and untreated sewage, and runoff from agricultural lands; oocysts are ubiquitous in surface water used for recreation or drinking water production.

Cryptosporidium oocysts are spherical and about 4-6 µm in diameter. Oocysts are extremely resistant to chlorination at the concentrations commonly used for drinking water and swimming pool water disinfection.

Cryptosporidium causes gastroenteritis in humans; the most obvious symptom is profuse watery diarrhoea. Infected persons shed about 10⁶-10⁷ oocysts per gram faeces, for about 1-2 weeks.

In otherwise healthy individuals, symptoms of *Cryptosporidium* infections generally persist for 1-2 weeks, but in immunocompromised persons infections can be chronic with diarrhoea being severe and life threatening. At present, no consistently effective, approved therapeutic agent with anticryptosporidial activity is available. Transmission occurs through the faecal-oral route, either from person-to-person or from animal-to-man, but may also be waterborne. Waterborne transmission of *Cryptosporidium* oocysts is associated with consumption of contaminated drinking water and recreation in contaminated surface water or swimming pools. Many water-related outbreaks of cryptosporidiosis have been reported over the past years (Fayer et al., 2000; Fayer, 2004). The presence of *Cryptosporidium* oocysts has been demonstrated in Dutch surface waters (Schets et al., 2008a) and swimming pools (Schets et al., 2004), but cases of waterborne cryptosporidiosis have not been observed in the Netherlands to date.

2.5 Cyanobacteria

Cyanobacteria have some characteristics of bacteria and some of algae. They have the same size as algae, contain blue-green and green pigments and can perform photosynthesis. Due to eutrophication of many water bodies, as a result of human activities, excessive proliferation of cyanobacteria occurs, resulting in extremely high cell densities which may cause considerable nuisance during water recreation due to transparency loss, discoloured water and scum formation. The effects of

cyanobacteria on human health are associated with algal toxins. Toxic cyanobacteria are found worldwide in inland and coastal waters (Chorus et al., 2000.)

Marine algal toxins are primarily a problem because they concentrate in shellfish and fish that are eaten by man. However, human exposure may also occur through dermal contact causing 'seaweed dermatitis', water ingestion or inhalation of water droplets. Symptoms related to these exposure routes have primarily been observed in Japan, Australia, New Zealand and the south-eastern states of the USA; cyanobacteria species involved appear not to cause problems in European recreational waters (WHO, 2006). In freshwater, the most widespread cyanobacterial toxins are microcystins and neurotoxins. Blooming of *Microcystis*, and more recently *Planktothrix* and *Anabaena* is frequently observed in the Netherlands (DG Water, 2010). Internationally, there are numerous reports of lethal poisoning of animals that drank from water with cyanobacteria; and human cases of illness or death through exposure to cyanobacterial toxins have been reported related to renal dialysis and drinking water consumption (Chorus et al., 2000). However, illness reports related to recreational water exposure to freshwater are usually anecdotal and there are no papers on large outbreaks in international literature. Moreover, epidemiological studies did not find significant differences between people exposed and non-exposed to cyanobacteria in recreational waters, or only noted a trend of more mild health complaints in the exposed compared to the non-exposed at longer duration of water contact and higher cyanobacterial cell counts (Stewart et al., 2006). There may, however, be long term effects such as liver damage and development of tumours but solid data that demonstrate these effects lack to date (Funari and Testai, 2008).

2.6 *E. coli* O157

E. coli O157 are small (0.5 x 2.0 µm), non-motile, Gram-negative, facultative anaerobic rods. Unlike most *E. coli*, *E. coli* O157 does not grow well at 44.5 °C, which requires modified detection.

E. coli O157 causes non-bloody diarrhoea that may progress to bloody diarrhoea and haemolytic uremic syndrome (HUS) with acute renal failure. Infected persons shed about 10⁸ bacteria per gram faeces; the duration of shedding is 7-13 days (Coia, 1998). The infective dose for *E. coli* O157 is not known, but may be similar to that of *Shigella* (ID₅₀ < 5 x 10²). *E. coli* O157 has been associated with outbreaks of illness in children that played in paddling pools with inadequate water treatment and insufficient disinfection. Accidental faecal releases were thought to be the source of the contamination of the water (WHO, 2006). In the Netherlands, *E. coli* O157 has been detected in drinking water from private water supplies (Schets et al., 2005) and surface water (Heijnen and Medema, 2006).

2.7 Enterovirus

Enteroviruses belong to the family of *Picornaviridae* which consists of eight genera and over 200 serotypes. *Picornaviridae* are small positive single sense strand RNA viruses with a diameter of 27-30 nm, without envelope and surrounded by a capsid. Naked picornavirus RNA, if protected from nucleases, is virulent, although less virulent than if contained within the viral particle. Transmission of enterovirus mainly occurs through the faecal-oral route, but can also take place via the respiratory route, through contact with secretions from dermal lesions and via aerosols or water.

Human infections may be asymptomatic; clinical symptoms are mild respiratory illness (common cold), gastrointestinal disease, and hand, foot and mouth disease (HFMD). Serious complications such as aseptic meningitis may also occur. In regions with a temperate climate enterovirus illness most frequently occurs in the warmer months, whilst in the tropics there is no apparent seasonal occurrence.

Infected persons shed large numbers of enteroviruses with their faeces. Surface water may become contaminated through direct faecal input, discharge of treated and untreated sewage, and runoff from agricultural lands. Enteroviruses can survive in the environment for long periods; they are resistant to low pH and fluctuations in temperature. For direct detection of enteroviruses in water, cell culture methods are available that may be used in combination with molecular techniques such as RT-PCR. In swimming pools or similar environments, humans are the source of contamination which may occur when faeces or vomit are shed in the water, but in these environments transmission is often via unhygienic toilets. The number of swimming pool related outbreaks caused by enteric viruses is limited, although outbreaks have been recorded related to swimming pools with inadequate or malfunctioning water treatment (WHO, 2006).

2.8 Giardia

Giardia is a protozoan parasite. *Giardia intestinalis* (or *lamblia* or *duodenalis*) is the species found in mammals including man. *Giardia* cysts are 12-15 x 6-8 µm in size and resistant to various disinfectants (Thompson, 2004). Cysts may enter surface water through direct faecal input, discharge of treated and untreated sewage, and runoff from agricultural lands; cysts are ubiquitous in surface water used for recreation or drinking water production. *Giardia* infections result in gastroenteritis that lasts for about 7-10 days; the infection is usually self-limiting, but chronic infections do occur. Infected persons or animals shed about $3 \cdot 10^6$ robust cysts per gram faeces; shedding may last for up to six months (Thompson, 2004). Giardiasis can be well treated. Transmission occurs through the faecal-oral route, either from person-to-person or from animal-to-man, but may also be waterborne. Outbreaks of *Giardia* infections have been reported throughout the world and are often associated with the consumption of untreated surface water, contaminated groundwater or drinking water with limited or malfunctioning treatment. Outbreaks related to swimming pools are often due to accidental faecal releases and insufficient water treatment (Fayer et al., 2004; Thompson, 2004). The presence of *Giardia* cysts has been demonstrated in Dutch surface waters (Schets et al., 2008a) and swimming pools (Schets et al., 2004), but cases of waterborne giardiasis have not been observed in the Netherlands to date.

2.9 Hepatitis A virus

The Hepatitis A virus (HAV) is a small, non-enveloped Picornavirus with a diameter of 27-30 nm. HAV causes an acute infectious disease of the liver, so-called hepatitis A. HAV is shed in large numbers by infected persons with their faeces (Brundage and Fitzpatrick, 2006). Hepatitis A virus infection confers lifelong immunity and causes symptoms in approximately 10 % of infected children. The disease is of no special significance to the population in endemic areas. However, in Europe, the United States and other industrialized countries, the infection is contracted primarily by susceptible young adults, most of whom are infected with the virus during trips to countries with a high incidence of the disease. In the Netherlands, annually 600-1200 hepatitis A cases are reported (estimated reporting of 30 % of clinical cases) with over 60 % of patients younger than 20 years of age. Transmission of hepatitis A virus mainly occurs through the faecal-oral route, but can also take place via aerosols or water. The presence of HAV in the Meuse River was determined in 2004/2005 (unpublished results). HAV was shown to survive in experimentally contaminated fresh-, sea-, and wastewater for long periods (Sobsey et al., 1988). In addition, the virus shows a minor sensitivity to chemical or physical inactivation similar to that of poliovirus (Siegl et al., 1984).

2.10 Legionella

Legionella are Gram-negative, non-spore-forming, motile, aerobic rods of 0.5-1.0 x 1.0-3.0 µm in size. The genus comprises over 50 species of which pathogenicity is not always clear; it appears that many pathogenicity factors are involved. *Legionella* species are ubiquitous in natural and artificial water environments worldwide. *Legionella* are heterotrophic bacteria that may be free-living, or living within amoebas or biofilms. *Legionella* proliferate at water temperatures over 25 °C; they may be present in high numbers in natural spas using thermal spring water, in poorly maintained hot tubs and whirlpools. In the swimming pool environment, a risk of infection may arise from using showers. *Legionella* infections occur through inhalation of contaminated aerosols; there is no evidence of person-to-person transmission. *Legionella pneumophila* is the most frequent isolated species that may cause either *Legionella*-pneumonia or Pontiac-fever, a mild fly-like condition. There are no typical symptoms of *Legionella*-pneumonia; symptoms are divers and some infected persons do not develop symptoms (WHO, 2006; WHO, 2007). *Legionella* bacteria are frequently detected in tap water distribution systems in the Netherlands (Versteegh et al., 2007).

2.11 Leptospira

Leptospire are motile spirochaete bacteria, 0.1-0.3 µm wide and 6-20 µm long. The genus consists of two species, but there is a lot of serological variation within the species and therefore leptospire are classified as serovars. Free-living, non-pathogenic, *L. biflexa* are ubiquitous in the environment, whereas pathogenic *L. interrogans* live in the kidneys of animal hosts (rats, cows, pigs) and are excreted in the urine, which can contaminate surface water. The infection is transmitted via direct contact with infected urine or indirectly via contact with contaminated surface water. *L. interrogans* is the causative agent of leptospirosis which may vary from a mild flu-like illness to severe disease with liver and kidney failure and hemorrhages (Weil's syndrome). Leptospire have a relative low resistance to adverse environmental conditions, such as low pH, desiccation, exposure to direct sunlight and disinfectants. Outbreaks of waterborne leptospirosis are generally related to contact with freshwater, but two outbreaks associated with non-chlorinated swimming pools have also been reported (WHO, 2003b; WHO, 2006). Annually, approximately 30 cases of leptospirosis are diagnosed in the Netherlands; on average 2-7 cases are related to recreational contact with surface water. The other cases are related to occupational exposure to surface water in the Netherlands, or result from infections abroad (Hartskeerl and Goris, 2008).

2.12 Molluscipoxvirus

Molluscipoxvirus is a double-stranded DNA virus that causes molluscum contagiosum, an innocuous cutaneous disease. Virus particles are brick-shaped and about 320 x 250 x 200 nm in size. The infection appears as small round papules or lesion, about 3-5 mm in diameter, which spontaneously resolve in 0.5-2 years. In swimming pools and similar environments, infected bathers are the only source and the infection is spread via contaminated surfaces or swimming aids (WHO, 2006).

2.13 Mycobacterium

Mycobacteria are rod-shaped bacteria (0.2-0.6 µm x 1.0-10 µm) that differ from other bacteria because of their cell wall with high lipid content, and their low growth rate; these characteristics make them resistant to disinfectants and antibiotics. The genus *Mycobacterium* is divided into the strictly pathogenic species, such as *M. tuberculosis*, and the atypical mycobacteria. The strictly pathogenic species exclusively have human and animal reservoirs, but the atypical mycobacteria are ubiquitous in the environment. These atypical mycobacteria or nontuberculous mycobacteria are important environmental opportunistic pathogens that generally affect persons with reduced immune competence. *M. marinum* and *M. avium* are relevant in the swimming pool environment. *M. marinum* causes skin and soft tissue infections. Infections frequently occur on elbows and knees resulting in localized lesions (swimming pool granuloma). Respiratory infections are caused by *M. avium* through inhaling contaminated aerosols, and are generally related to use of hot tubs (with high frequency and long duration) with inadequate disinfection and cleaning. Symptoms are flu-like and include cough, fever, chills, malaise and headaches; the condition is referred to as 'hot tub lung'. Both species infect otherwise healthy individuals. Mycobacteria are more resistant to disinfectants than most other bacteria and therefore maintenance of disinfection at appropriate levels is required, supplemented by thorough cleaning of surfaces (WHO, 2006; Falkinham III, 2009). A study that was performed in the 1980s demonstrated the presence of atypical mycobacteria in semi-public swimming pools and whirlpools in the Netherlands. Mycobacterial densities showed a negative association with the concentration of hypochlorous acid in the bathing water (Havelaar et al., 1985).

2.14 Naegleria fowleri

Naegleria fowleri is a thermophilic free-living amoeba that is found in thermal freshwater worldwide. The lifecycle includes environmentally robust spherical cysts with a diameter of 8-12 µm. The cysts have a smooth wall with one or two mucus-plugged pores, through which the trophozoites emerge at infection. The organism can successfully reproduce in water of up to 46 °C. *N. fowleri* has been isolated from both natural and artificial thermally enriched habitats, such as natural hot springs, freshwater lakes, domestic water supplies, chlorinated swimming pools, water cooling towers and effluent from industrial processes. In man, *N. fowleri* causes primary amoebic meningoencephalitis (PAM), a rare but usually fatal condition. Infection occurs when the organism is enabled to enter the body during forceful contact of the water with the olfactory epithelium, e.g. during diving, jumping or underwater swimming. Subsequently, the organism migrates to the brain and the nervous system. Infections are usually acquired in ponds, natural spas and artificial lakes (WHO, 2003a; WHO, 2006). Cases of PAM have not been diagnosed in the Netherlands, however four cases that occurred after exposure to non-chlorinated swimming pools and one case related to exposure to thermally contaminated surface water have been reported from Belgium (Gezondheidsraad, 2001). There is one report of the detection of *N. fowleri* in cooling water from power stations in the Netherlands (Gezondheidsraad, 2001).

2.15 Norovirus

Noroviruses belong to the family of the *Caliciviridae*, are 28 – 35 nm of size, are non-enveloped viruses and contain a positive sense, single-stranded RNA genome of approximately 7.6 kb (Green et al., 2002). The norovirus genus is divided into five genogroups (genogroup GGI to GGV). The diversity of norovirus variants increases continually due to the generation of new variants, with two

groups of strains predominating in the past five years (Höhne and Schreier, 2004; Lindell et al., 2005; Lopman et al., 2004; Maunula and Von Bonsdorff, 2005; Reuter et al., 2005). Most human pathogenic noroviruses cluster within genogroup I (GGI) and genogroup II (GGII). No zoonotic potential could be demonstrated for these two genogroups, therefore they are considered to be solely human.

Norovirus infections cause acute gastroenteritis in humans. Symptoms include projectile vomiting, watery non-bloody diarrhoea with abdominal cramps and nausea within 24 to 48 hours after exposure (McCarthy et al., 2000). Infected persons shed large numbers of viral particles to the environment. Transmission occurs through the faecal-oral route. Noroviruses are the primary cause of viral diarrhoea in adults. Outbreaks originating from contaminated drinking water as well as from recreational water have been described (Boccia et al., 2002; Häfliger et al., 2000; Hoebe et al., 2004; Nygard et al., 2004). Because no robust cell culture system for the detection of infectious human noroviruses is available (Duizer et al., 2004), information on the persistence of infectious virus particles in the environment is limited. Due to the non-enveloped structure of noroviruses, they are presumed to be as resistant to environmental degradation and chemical inactivation as other culturable human enteric viruses, such as poliovirus.

2.16 Papillomavirus

Papillomavirus is a double-stranded DNA virus that causes benign cutaneous tumours; an infection on the sole of the foot is referred to as plantar wart. Virus particles are spherical and approximately 55 nm in diameter. Papillomaviruses are very resistant to desiccation and can remain infectious for many years. In swimming pools, infected bathers are the primary source of papillomavirus; infections are usually acquired through contact with contaminated floors (WHO, 2006).

2.17 Pseudomonas aeruginosa

Pseudomonas aeruginosa are aerobic, non-spore-forming, motile, Gram-negative rods with an optimum growth temperature of 37 °C, but they may also grow at 42 °C. The rods are approximately 0.5-1 x 1.5-4 µm in size. *P. aeruginosa* is ubiquitous in water, vegetation and soil. *P. aeruginosa* is capable of using various organic compounds in low concentrations for growth, and can therefore proliferate in aquatic environments. *P. aeruginosa* is an opportunistic pathogen that does not infect healthy individuals, but becomes infectious when the immune system is weakened, e.g. after surgery, during immunosuppressant therapy and antibiotic use. *P. aeruginosa* is resistant to many commonly used antibiotics and is, as such, a feared cause of nosocomial infections. Infections are generally local, affecting wounds, the urinary tract, the respiratory tract, ears, eyes, the intestines and the skin. *P. aeruginosa* multiplies in surface waters when the water temperature exceeds 18-20 °C. In swimming pools, the bacterium may proliferate on humid surfaces, but also in places where pool hydraulics are suboptimal. Swimming pool related infections due to *P. aeruginosa* are most often otitis externa and folliculitis; otitis externa is frequently observed after exposure to contaminated surface water. Swimming pool related infections are often associated with insufficient disinfection and cleaning (WHO, 2006; Mena and Gerba, 2009). During the summer season, ear complaints associated with *P. aeruginosa* infections as a result of exposure to contaminated surface waters are common in the Netherlands (Schets et al., 2006a).

2.18 Rotavirus

Rotavirus particles are up to 76.5 nm in diameter and are not enveloped. Rotavirus is a genus of double-stranded RNA virus in the family *Reoviridae*. There are seven species of this virus, referred to as A, B, C, D, E, F and G. Rotavirus A, the most common, causes more than 90 % of infections in humans. The faeces of an infected person can contain more than 10 trillion infectious particles per gram; only 10–100 of these are required to transmit infection to another person. Rotavirus is transmitted by the faecal-oral route. It infects cells that line the small intestine and produces an enterotoxin, which induces gastroenteritis, leading to severe diarrhoea and sometimes death through dehydration. Worldwide, rotavirus infection is the leading single cause of severe diarrhoea among infants and young children. In the Netherlands, approximately 200,000 rotavirus cases occur annually, mostly in children under two years of age. By the age of five, nearly every child in the world has been infected with rotavirus at least once, promoting immunity. Infectious rotavirus was detected in 11 of 12 source water samples for drinking water production in the Netherlands (Rutjes et al., 2009). Reduction of infectivity of rotavirus is low in surface and groundwater even in the presence of chlorine, but higher at higher temperatures (Espinosa et al., 2008).

2.19 Shigella

Shigella species are small (0.5 x 2.0 µm), non-motile, Gram-negative, facultative anaerobic rods. Symptoms of shigellosis include diarrhoea, fever and nausea; they usually last for 4-7 days and are self-limiting. Infected persons shed about 10⁶ bacteria per gram faeces; shedding may last for up to 30 days. The infective dose for *Shigella* is between 10 and 100 organisms. *Shigella* has been associated with outbreaks of disease related to swimming facilities such as artificial ponds and other small water bodies with limited water movement and without disinfection. Contamination of the water generally occurs through accidental faecal releases (WHO, 2006). Outbreaks of shigellosis associated with exposure to recreational waters in the Netherlands have not been detected to date.

2.20 Staphylococcus aureus

Bacteria within the genus *Staphylococcus* are non-motile, non-spore-forming Gram-positive cocci (0.5-1.5 µm), that grow aerobically and anaerobically. In humans, *S. aureus* is clinically the most important species. Humans are the only known reservoir of *S. aureus* and many healthy people carry the bacterium as a commensal, either on the anterior nasal mucosa, on the skin or in the faeces. During all swimming activities, the bacterium is washed from the human body resulting in a constant contamination of the bathing water. Infections that result from exposure to contaminated water may not become apparent until 48 hours after exposure and are associated with high bather density. *S. aureus* can cause skin conditions, wound infection, urinary tract infections and ear and eye infections through contact with contaminated water (WHO, 2006). *S. aureus* strains have been isolated from Dutch surface waters; some of these isolates were resistant to antibiotics commonly used in clinical practise thus posing a potential risk of infections with antibiotic resistant bacteria (Blaak et al., 2010b).

2.21 Trichobilharzia

Swimmers' itch or cercarial dermatitis is the result of the penetration of the human skin by cercariae of bird pathogens of the genus *Trichobilharzia*. These bird schistosomes have a two-host life cycle with freshwater snails as their intermediate host and waterfowl as their final host. Eggs produced by the females embryonate within the host body; fully developed eggs are expelled via faeces or nasal secretions to the aquatic environment. In the water body, the free-swimming larvae infect a suitable snail host, in which the larvae transform to sporocysts that asexually produce cercariae. Cercariae leave the snails into the water and attempt to reach a new host. The free-swimming cercariae exhibit a high affinity for the human skin and try to penetrate the skin resulting in an allergic response. Short exposure and first contact will result in a weak reaction, characterized by development of maculae, or colored markings. Typical symptoms develop after repeated exposure. Shortly after cercarial penetration into the skin a primary itching (like fine prickling) occurs persistently for up to 1 hour and the infection manifests as an itchy maculopapular eruption. Papulae can be encompassed by an erythematous zone that can persist for three days. The itching accompanying the eruption of papulae can range from negligible to unbearable. After ten days, the papulae usually disappear and leave pigmented spots that can persist for weeks. Severe infections can be accompanied by fever, limb and lymph node swelling, nausea and diarrhea (Horák et al., 2002). Outbreaks of presumptive cercarial dermatitis in freshwater lakes are frequently reported, also in the Netherlands (Schets et al., 2008b; Schets et al., 2010).

2.22 Trichophyton

Tinea pedis or athletes' foot is an infection of the skin between the toes that is frequently associated with attending indoor swimming pools or modern fun baths. Although various fungi may cause this dermatomycose, the most commonly isolated species in Europe are *Trichophyton mentagrophytes* var. *interdigitale*, followed by *T. rubrum*. These species are anthropophilic and in swimming pools and similar environments, bathers are the sole source. Most patients with tinea pedis constantly disseminate dermatophytes into the environment, although the amount varies remarkably. Transmission may therefore take place through direct person-to-person contact or through contact with surfaces that are contaminated with desquamated skin from infected bathers (WHO, 2006; Seebacher et al., 2008).

2.23 Vibrio

Vibrio species are motile Gram-negative rods with a single polar flagellum that are common inhabitants of various aquatic environments. Depending on the species, they tolerate a range of salinities and are common in marine environments. They are capable of multiplication in marine water at elevated water temperatures (> 17-20 °C). When environmental conditions are unfavourable, *Vibrio* species enter a viable non-culturable state which enables them to survive such conditions. Many *Vibrio* species cause disease in aquatic animals such as fish, shellfish and marine mammals but also in humans. Human pathogenic *Vibrio* species have been associated with wound infections (*V. alginolyticus*, *V. vulnificus*) and ear infections (*V. alginolyticus*) after exposure to contaminated surface waters, and gastroenteritis (*V. parahaemolyticus*, *V. cholerae* non-O1/O139) after consumption of contaminated food. More serious complications such as septicaemia (*V. vulnificus*) have also been reported, although these are rare and mainly occur in people who are immunocompromised or have a chronic liver disease. *V. cholerae* O1/O139 can cause acute watery diarrhoea in humans, which can lead to death, if left

untreated (Oliver and Kaper, 1997; Morris, 2003). *Vibrio* infections as a result of exposure to recreational waters in the Netherlands have been observed (Schets et al., 2006b; Schets et al., 2008c) and recent monitoring of Dutch coastal recreational waters has demonstrated the presence of various *Vibrio* species, such as *V. alginolyticus*, *V. parahaemolyticus*, *V. cholerae* non O1/O139 and *V. fluvialis* (Schets et al., in preparation).

3 Recreational water types

3.1 Bathing sites in surface water

According to the revised European Bathing Water Directive 2006/7/EC (Anonymous, 2006) bathing sites in surface water are defined as any element of surface water where the competent authority expects a large number of people to bathe and has not imposed a permanent bathing prohibition, or issued permanent advice against bathing. These include sites that have officially been designated as bathing sites where water quality is checked on a regular basis for faecal indicator parameters *E. coli* and intestinal enterococci using methods specified in the Directive; results of these controls are reported to the European Commission. The European Bathing Water Directive also applies to bathing sites that have not been designated as official sites but are visited by large numbers of bathers; water quality is monitored and competent authorities often consider these sites as future official bathing sites. Finally, there are bathing sites in surface water that are (infrequently) visited by small groups of bathers. These are no official sites, they are not under consideration to become official sites and water quality is not checked. Moreover, recreational water activities different than swimming, such as biathlons and triathlons and surfing and diving, do not adhere to specific (bathing) seasons and are generally not restricted to monitored bathing areas.

3.2 Natural or green pools

Outdoor pools with a separate swimming and filtration zone that are either situated in natural ponds, or use a concrete construction (old conventional pool or newly constructed) or PVC foil to form a pool, are considered natural or green pools. The filtration zone is planted with aquatic vegetation specially chosen to reduce levels of nutrients; in this zone organic matter and micro-organisms are trapped. There are drains to collect the water from this zone before it is pumped to the swimming zone. At this point, sand filters and UV disinfection may be incorporated. The swimming zone is free of vegetation and from this zone the water flows into the filtration or regeneration zone. No disinfectants are used (PWTAG, 2009).

3.3 Paddling pools

Paddling pools are small pools with limited depth (0.2-0.6 m), commonly located outdoors in an urban environment and mainly used by children. These pools may become polluted very quickly because of the small water volume and the high bather load. Moreover, children may urinate or defecate in them and introduce pollution such as mud and grass from the surrounding area. Also, dogs and other animals may enter and pollute the pools. Ideally these pools are small enough to empty and clean every day. Safe water quality can be maintained by continuous circulation and simple filtration, with continuous chemical dosing (PWTAG, 2009).

3.4 Interactive water features and decorative fountains

Interactive water features are arrangements of ground sprays or jets, usually outdoors, designed to be used by children mainly. The design of these interactive features is different from that of decorative water features such as municipal fountains that are not designed for interaction although they are sometimes played in. In interactive water features, the sprays are installed in a surround, like stone or rubber, and the water usually drains through the surround into a holding tank from which the water is pumped to the sprays. Micro-organisms may be introduced on feet. Disinfection and filtration of the water should be applied to maintain microbiologically safe water (PWTAG, 2009).

3.5 Indoor pools

Swimming pools include conventional pools (by tradition rectangular) which may be located indoors or outdoors, but also hot tubs, spa pools, hydrotherapy pools etc. The source water is tap water and some form of pool water treatment is in place in all pool types. Commonly a residual disinfectant is maintained in the pool water to safeguard microbiological quality. In several European countries legislation is in place that requires the regular examination of swimming pool water for various microbiological and chemical parameters for which guidelines or imperative values are specified in national legislation or standards (PWTAG, 2009).

4 Impact of climate change on recreational waterborne pathogens

In recreational waters, pathogen characteristics, such as number, type, virulence and infectivity, will be affected by climate conditions, resulting in die-off or inactivation or, alternatively, survival and growth of the pathogens. Major climate *factors* that determine the fate and behaviour of pathogens in recreational waters, and thus may impact on recreational water-transmitted diseases, include temperature, precipitation patterns, and water availability. Other important environmental conditions are the availability of nutrients and minerals, pH, ionic strength and ion composition, moisture content and UV/sunlight. Since micro-organisms and therefore also human pathogens are highly influenced by climate and environmental conditions, climate *change* may alter the resultant infectious disease burden from exposure to recreational water-transmitted pathogens.

The Intergovernmental Panel on Climate Change (IPCC) assesses the scientific, technical and socio-economic information relevant for the understanding of the risk of human-induced climate change. In the Netherlands, the Royal Netherlands Meteorological Institute (KNMI) is the national institute for weather, climate research and seismology that conducts research on climate change. Though atmospheric temperature and rainfall are recorded by IPCC and KNMI, both do not specifically record and project data on water temperature since changes in water temperature are seen as a secondary effect of climate change. However, for IPCC, Bates et al. (2008) observed and projected changes in climate as they relate to freshwater. Table 3 lists water cycle related climate changes that affect the environment, and the fate and behaviour of recreational water-transmitted pathogens, however to a variable extent, depending on the pathogen and the water type.

4.1 Temperature increase

Atmospheric temperature influences surface water temperatures and therefore, it may influence the recreational water-transmitted disease burden.

4.1.1 Water temperature increase

According to IPCC (2007), the global surface temperature rise in 2090-2099 may range from 1.1 to 6.4 °C relative to 1980-1999. The KNMI Climate Change Scenarios 2006 (Van den Hurk et al., 2006) suggest 0.9 to 2.8 °C global temperature increase in 2050 over 1990. Here, it is assumed that surface water temperature rise follows the increase of global atmospheric temperature. For shallow Dutch lakes, it could be concluded that there is a very tight coupling between air and water temperatures, irrespective of their size, resulting in highly similar patterns of lake temperature and a direct translation of climate warming into lake warming (Mooij et al., 2008). It should, however, be borne in mind that local differences may arise from e.g. different water depth, water flow and discharge of warm industrial waste water or water from cooling towers. With climate change, nights are expected to remain warmer as well, resulting in limited water temperature decrease during the night, thus contributing to either die-off of enteric pathogens or growth of environmental bacteria, amoebas and algae.

Water temperatures have a significant impact on the concentrations of waterborne pathogens in surface waters. Growth patterns of pathogens are highly dependent on water temperature amongst some of the other environmental conditions mentioned. Some bacteria, algae and amoebas can grow and proliferate in the aquatic environment independent of a host for replication. These species encompass *Acanthamoeba*, *Aeromonas*, cyanobacteria, mycobacteria, *Naegleria fowleri*, *Pseudomonas aeruginosa*

and *Vibrio*. Their numbers in the water body, either fresh or marine, increase with increasing water temperature.

Legionella species also do proliferate at elevated water temperatures, but need amoebas or other protozoa for their replication. Abundance of *Legionella* species is not expected to occur in surface water, due to overgrowth of other micro-organisms for which environmental growth conditions are more favourable, but *Legionella* does grow to high levels in drinking water distribution systems that also provide water for showers and whirlpools in swimming pools. Due to increased atmospheric temperature, drinking water used to fill paddling pools, and for interactive water features or fountains may warm in the features' plumbing system thus creating an environment for *Legionella* proliferation. High *Legionella* numbers in showers, whirlpools, interactive water features and fountains pose health risks through inhalation of aerosols. Increased surface water temperatures, as in outdoor recreational freshwaters, may have minor influence on the occurrence and proliferation of *Legionella* species; however, warm, humid and showery summer weather was found to be associated with a higher incidence of *Legionella* disease in the Netherlands (Karagiannis et al., 2009).

Rising temperatures favour cyanobacteria in several ways. Cyanobacteria generally grow better at higher surface water temperatures (often above 25 °C). Warming of fresh surface waters also strengthens the vertical stratification of lakes, reducing vertical mixing. Many cyanobacteria exploit these stratified conditions by forming intracellular gas vesicles, which make the cells buoyant. Buoyant cyanobacteria float upward when mixing is weak and accumulate in dense surface blooms. These surface blooms may even locally increase water temperatures through the intense absorption of light. The temperatures of surface blooms in the Baltic Sea and in Lake IJsselmeer, the Netherlands, can be at least 1.5 °C above those of ambient waters (Paerl and Huisman, 2008). Both in fresh (Roijackers and Lurling, 2007) and marine waters (Peperzak, 2005), blooms of toxic algae are expected to occur more often at elevated water temperatures. Moreover, as a result of global warming, water temperatures may be higher for prolonged periods, thus lengthening the period for explosive growth of cyanobacteria resulting in extended periods of nuisance blooms that affect recreational water quality.

Numerous water-transmitted pathogens cannot grow in aquatic environments, rather at increased water temperatures they will lose their ability to infect human cells and to replicate, e.g. enteroviruses (De Roda Husman et al., 2009). Especially host-dependent pathogens, though stable in warm-blooded animals at 37 °C, are highly sensitive to high environmental temperatures. These pathogens merely comprise of enteric bacteria and viruses, such as *E. coli* O157, *Shigella*, adenovirus, enterovirus, norovirus, rotavirus and hepatitis A virus, but also *Staphylococcus aureus* and pathogenic *Leptospira*. Inactivation by increased water temperatures may be less relevant for organisms that create environmentally robust survival structures, such as *Cryptosporidium* oocysts and *Giardia* cysts, because they are less temperature sensitive and also more persistent (Schijven et al., 2003).

In parasites such as *Trichobilharzia*, that depend on intermediate cold-blooded hosts, increased water temperatures accelerate development in freshwater snails and induce increased shedding of cercariae. Moreover, if elevated water temperatures result in more dense algal populations, snails will have excessive feeding opportunities thus resulting in higher numbers of intermediate hosts for *Trichobilharzia*. As a consequence of global warming, bird migration southward decreases and birds become sedentary, resulting in the presence of the parasite's final host for prolonged periods resulting in an extended replication season (Mas-Coma et al., 2009).

As for Papillomavirus, Molluscipoxvirus and *Trichopyton* species, these micro-organisms are of human origin and merely occur in indoor pools, where they spread through direct contact between humans or via contaminated floors or surfaces. Global warming is not likely to affect the growth of these pathogens in the swimming pool environment.

Table 3 Effect of climate change on the environment and fate and behaviour of recreational water-transmitted pathogens

Climate change	Environmental effect	Recreational water-transmitted pathogen fate and behaviour	Recreational water-transmitted pathogens, examples	Recreational water types affected
Temperature increase	Water temperature increase	Growth of pathogens	<i>Acanthamoeba</i> , <i>Aeromonas</i> , Cyanobacteria, <i>Naegleria fowleri</i> , <i>Pseudomonas aeruginosa</i> , <i>Trichobilharzia</i> , <i>Vibrio</i>	Surface water (fresh and marine), natural or green pools, paddling pools, interactive water features
		Inactivation/die-off of pathogens	Adenovirus, <i>Cryptosporidium</i> , <i>E. coli</i> O157, enterovirus, <i>Giardia</i> , hepatitis A virus, <i>Leptospira</i> , norovirus, rotavirus, <i>Shigella</i> , <i>Staphylococcus aureus</i> ,	Surface water (fresh and marine), natural or green pools, paddling pools, interactive water features
	Elevated water temperature and water flow	Elevated concentrations of pathogens in surface water	Adenovirus, <i>Cryptosporidium</i> , <i>E. coli</i> O157, enterovirus, <i>Giardia</i> , hepatitis A virus, norovirus, rotavirus, <i>Shigella</i>	Surface water (fresh and marine)
Rainfall intensity and frequency	Run-off, sewage overflows and flooding	Intensity and frequency of peak concentrations of pathogens in surface water	Adenovirus, <i>Cryptosporidium</i> , <i>E. coli</i> O157, enterovirus, <i>Giardia</i> , hepatitis A virus, norovirus, rotavirus, <i>Shigella</i>	Surface water (fresh and marine)
	Resuspension of river sediments			
Water availability	Decrease in water volume	Pathogen concentrations	<i>Acanthamoeba</i> , <i>Aeromonas</i> , Adenovirus, <i>Cryptosporidium</i> , Cyanobacteria, <i>E. coli</i> O157, enterovirus, <i>Giardia</i> , hepatitis A virus, <i>Leptospira</i> , norovirus, rotavirus, <i>Shigella</i> , <i>Staphylococcus aureus</i> , <i>Trichobilharzia</i> , <i>Vibrio</i>	Surface water (fresh and marine), natural or green pools, paddling pools, interactive water features
	Decrease in availability of recreational water sites	Growth of pathogens	<i>Vibrio</i>	Surface water (fresh and marine), natural or green pools, paddling pools, interactive water features

4.1.2 Seasonality

The water temperature of the sea, rivers and lakes exhibits seasonal variation. However, water temperature changes occur at a slower pace than land temperature changes, with the land gradually warming the water in spring resulting in warm waters long after the end of summer.

Seasonality of waterborne pathogens has been well-reported. Commonly, concentrations of enteric waterborne pathogens in river waters are higher in winter and lower in summer, mainly due to effects of temperature and residence times (Schijven and De Roda Husman, 2005). In summer, temperatures are higher and residence times longer; therefore, enteric pathogens that cannot grow in water, die off or inactivate faster, whereas in winter, when water temperatures are lower, they survive longer.

For indigenous waterborne pathogens, such as *Vibrio* and *Pseudomonas aeruginosa*, the situation is opposite: concentrations are high during summer when water temperatures are higher, and during the colder winter months they survive in sediments, either or not through entering a viable but nonculturable state to survive adverse environmental conditions (Roszak and Colwell, 1987).

Increase of global atmospheric temperature may result in prolonged warming of land and water, enabling indigenous pathogens to proliferate for longer periods thus extending the time frame with increased concentrations of waterborne pathogens in recreational waters, which may result in increased exposure of bathers to these pathogens.

4.2 Rainfall intensity and frequency

4.2.1 Run-off, sewage overflows and flooding

The effect of increased inactivation due to higher water temperatures may be overshadowed by peak concentrations from runoff and sewer overflows, following heavy rainfall events that are expected to occur more often during summers (Schijven and De Roda Husman, 2005). With rainfall, pathogenic micro-organisms of human and animal faecal origin may enter surface waters by discharges of raw and treated wastewater, and runoff from the land of faecal matter from wildlife such as birds, waterfowl and deer, or domestic animals or manure. In this respect, the occurrence of peak concentrations of norovirus has been reported, but in general, peak events appear to be difficult to predict (Westrell et al., 2006). Since peak concentrations determine the risk of infection, this effect is likely to be of more importance than enhanced inactivation.

It may be assumed that runoff and sewage overflow, affecting both fresh and marine waters, increase proportionally with increases in extreme precipitation (Kok et al., 2001). Since more intense precipitation is expected to occur more in high latitudes (e.g. Northern Europe), this implies that peak concentrations of waterborne pathogens of faecal origin, such as *E. coli* O157, *Shigella*, *Cryptosporidium*, *Giardia*, norovirus, rotavirus, hepatitis A virus and enterovirus, in surface water as a consequence of precipitation are likely to occur increasingly more in these regions. In the subtropical and lower mid-latitude regions (e.g. Southern Europe), however, a beneficial effect is expected as a result of less precipitation and therefore longer residence times leading to increased inactivation.

Rain-generated floods as a result of heavy rainfall may pick up waterborne pathogens like *Cryptosporidium*, *Giardia* and *E. coli* O157 from animal manure spread onto the land and bring them to the recreational water. In this way, excreta from wild animals and waterfowl may also be flushed from the land surrounding recreational sites into the receiving waters.

More intense precipitation will increase surface and groundwater nutrient discharge into water bodies. In the short term, freshwater discharge may prevent cyanobacterial blooms by flushing. However, as the discharge subsides and water residence time increases as a result of drought, nutrient loads will be

captured, eventually promoting blooms. This scenario takes place when elevated winter-spring rainfall and flushing events are followed by protracted periods of summer drought (Paerl and Huisman, 2008).

4.2.2 Resuspension of river sediments

In the aquatic environment, the presence of pathogenic micro-organisms is much affected by the movements of the water itself. Such movements entail transport of micro-organisms from one water compartment to the other, for example runoff of manure from land to surface water, resuspension of pathogens from river sediments and dilution of water bodies.

In stagnant waters, particles, like *Cryptosporidium* oocysts and *Giardia* cysts, will slowly settle to the sediment. This may occur in natural environments in which the water flow is low, such as recreational lakes and slow-flowing streams and rivers in summer. Since (oo)cysts survive long, settling of (oo)cysts may result in accumulation in aquatic sediments (Medema et al., 1998). Viruses may also accumulate in river sediments, depending not only on water and soil characteristics but also on virus determinants (Skraber et al., 2009). Disturbance of these sediments, by for instance bathers, ships, or increased water flow due to heavy rainfall, may give rise to high concentration peaks in the water. If waterborne pathogens are resuspended from river sediments, this may lead to peak concentrations, which may strongly affect associated health risks, if coinciding with exposure (Schijven and De Roda Husman, 2005). Therefore, shifts in amplitude and timing of concentrations of waterborne enteric pathogens may occur, these shifts may comprise enteric waterborne pathogens that have survived in surface water sediments, such as enteroviruses, *Cryptosporidium* and *Giardia*, but also indigenous waterborne pathogens like *Aeromonas*, *Vibrio* and *Pseudomonas aeruginosa* that either proliferate or survive in sediments.

4.3 Water availability

With the expected changes in precipitation patterns, water availability may vary. Water availability may directly or indirectly be associated with the microbiological quality of the water. Scarcity or loss of water sources may lead to the use of source water of lesser quality, e.g. to fill paddling pools and in interactive water features or fountains, with increased risks and higher demand on treatment. There may also be less water or water of lesser quality for cleaning of the pools or sanitary facilities, which may result in poor hygiene situations.

Reduced water availability may result in decreased water volume in recreational lakes thus resulting in increased concentrations of the pathogens present. However, reduced water levels may result in increased water temperatures and increased sunlight radiation which has an inactivating effect on most pathogens, but to a different extent. A reduced volume of water in lakes or rivers may also change the physiochemical composition of the water, e.g. the availability of nutrients may decrease or increase and salinity may rise. The latter may e.g. cause a shift towards proliferation of micro-organisms that endure high salt concentrations, such as various human pathogenic *Vibrio* species.

5 Discussion

Climate changes will affect the introduction, spread and growth of human pathogenic micro-organisms in water, and therefore possibly also the number of infections, diseases and deaths by water-transmitted pathogens in the population (Hunter, 2003; McMichael et al., 2001), including those transmitted through exposure to recreational waters. Climate change scenarios, though uncertain, already show clear effects on public health. Research in warmer summers, with temperatures that can be expected more and more in the near future due to climate change, have shown enhanced levels of for instance ear complaints, wound infections and legionellosis (Schets et al., 2006a; Schets et al., 2006b; Karagiannis et al., 2009). Figures 2 and 3 illustrate the relation between the number of waterborne disease outbreaks related to recreational water reported in the Netherlands and climate factors such as temperature, hours of sunshine and rainfall.

Since climatic conditions largely determine pathogen fate and behaviour in the environment, in this case recreational waters, climate changes will most certainly influence the recreational water transmitted disease burden. However, the disease burden of many common waterborne diseases is currently unknown and a first task would be to describe the baseline relations between climate factors and health outcomes for a selection of pathogens. This will reveal the extent and form of the sensitivity of each specified health outcome to variations in climatic conditions. Evidence of ongoing changes in health risks and outcomes due to climate change needs to be sought and by forging new collaborations with climate scientists and mathematical modellers, health researchers can estimate how future scenarios of climate change are likely to affect health risks and changes in burdens of disease (McMichael, 2008).

Exposure of humans and animals to recreational water-transmitted pathogens may take place either through ingestion or by direct contact with contaminated recreational waters. Climate change is likely to influence behaviour of humans and animals, and of pathogens; however, it is unknown how this behaviour will change. For instance, due to increased atmospheric temperature, surface water recreation may increase if people seek refreshment through bathing more often. However, when temperature increase is such that people rather shield from the heat inside their houses, exposure to recreational water may decrease. This requires insight into social behaviour patterns.

Though atmospheric temperature and rainfall are recorded by IPCC and KNMI, both do not specifically record and project data on water temperature and relative humidity since these are seen as secondary effects of climate change. In the KNMI Next scenarios for 2013, climate scenario users such as RIVM are more closely involved, facilitating collection of essential information such as relative humidity. Access to data on water temperature changes from knowledge institutes such as Deltares needs to be facilitated in order to be able to shed light on policy questions involving climate changes and infectious diseases.

A distinct effect of climate change on different water types and pathogens can be expected, and interaction of climate factors may cause changes in pathogen behaviour that are difficult to predict. For instance, pathogens of sole human source that cause human infections through exposure to indoor pools only, are not directly affected by climate change. However, when visits to indoor swimming pools increase due to higher atmospheric temperatures, the introduction of pathogens into swimming pools may increase thus stressing the importance of proper hygiene measures. Moreover, climate change may affect the nature of waterborne infectious diseases in the human population for which indoor pools may be the preferred pathway, thus increasing the health burden. In the Netherlands, the source water for

padding pools and interactive features is tap water of excellent quality, but this may be different in other parts of the world. Increased atmospheric temperature due to climate change will provoke water temperature rise in these relatively small water bodies, but whether there is an increased health risk or not largely depends on the types of pathogens introduced through users, and animals that have access to these facilities. The introduction of pathogens such as *Vibrio*, *Pseudomonas aeruginosa*, and *Aeromonas*, which proliferate in water at elevated water temperatures, may result in an increased health risk.

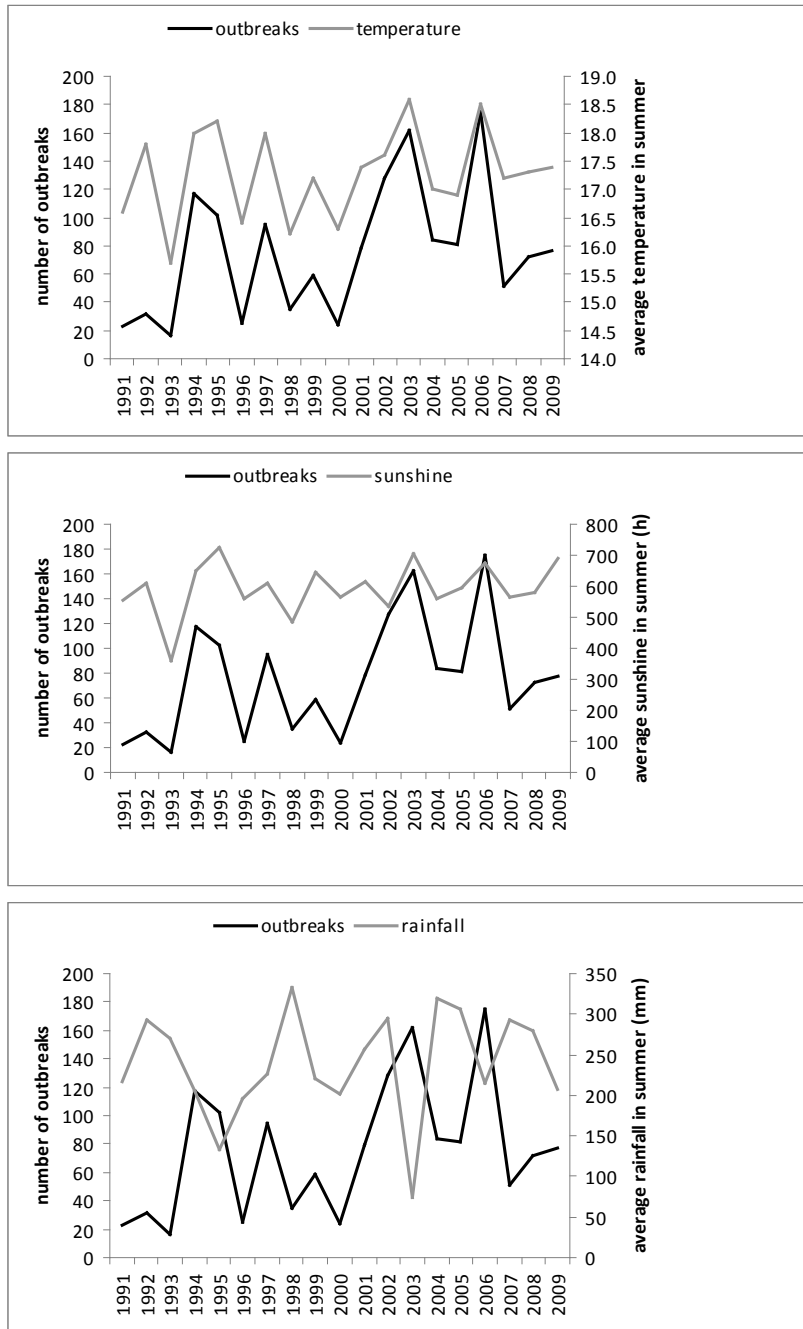


Figure 2 The number of waterborne disease outbreaks associated with recreational water use reported in the Netherlands, 1991-2009, in relation to average temperature, hours of sunshine and rainfall in summer

Anthropogenic and zoonotic pathogen influx into untreated recreational waters may increase at extreme precipitation events, but these may be controlled with sewage treatment and increased capacity for rainwater storage, and appropriate effectuation of bathing water profiles in the current European Bathing Water Directive.

As a result of climate change, conditions may become more favourable for introduction and settlement of exotic waterborne pathogens, but also for proliferation of waterborne pathogens that are at present of limited importance for public health in Western Europe, such as the amoebas *Acanthamoeba* and *Naegleria fowleri* and pathogenic *Vibrio* species that prefer elevated water temperatures such as *V. vulnificus* and pandemic strains of *V. cholerae*, but also certain toxic algae such as *Fibrocapsa japonica* and *Chattonella antiqua* (Peperzak, 2005).

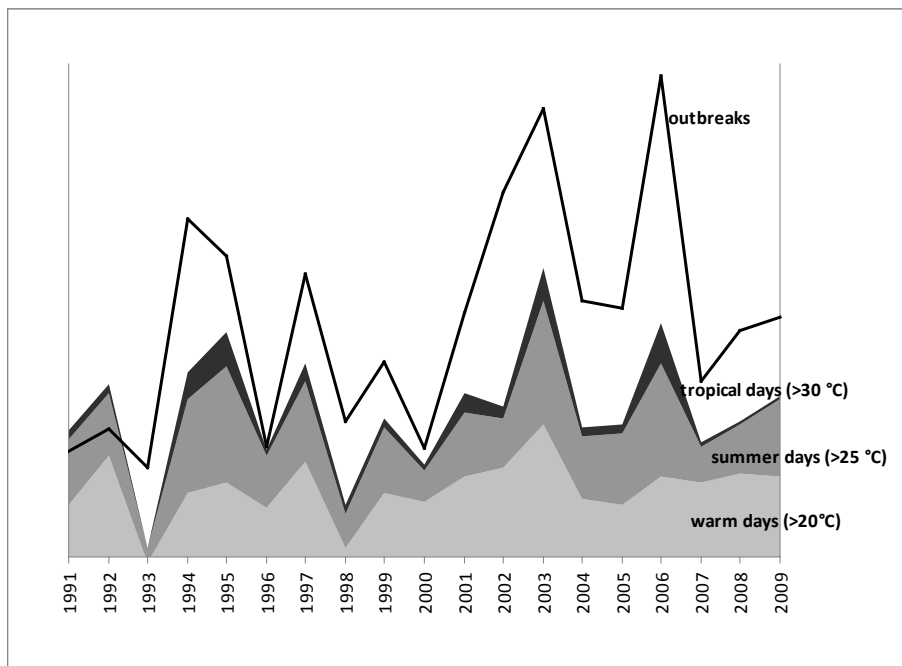


Figure 3 The number of waterborne disease outbreaks associated with recreational water use reported in the Netherlands, 1991-2009, in relation to the number of warm, summer and tropical days in summer

6 Conclusions and recommendations

1. **Prioritise and quantify recreational waterborne infectious disease**
 With respect to the impact of climate change, there is a need to prioritise and quantify waterborne infectious diseases in general, and recreational water infectious diseases in particular.
2. **Keep a close watch on emerging and zoonotic threats**
 Emerging zoonotic threats can be identified through (inter)national alerts and study of international literature on (changing) pathogen behaviour and waterborne disease incidence in relation to climate opportunities.
3. **Ongoing recreational water surveillance**
 Surveillance should not only address faecal indicator parameters as required by bathing water legislation, but should also focus on pathogens that have the potential to cause increased recreational water-related illness as a result of e.g. elevated water temperatures due to global atmospheric temperature increase, such as *Vibrio*.
4. **Investigation of outbreaks in relation to climate**
 Reported cases and outbreaks of recreational waterborne infectious disease are studied in order to identify the causative agent and investigate its presence and behaviour, also in relation to climate factors.
5. **Study of specific pathogens with environmental growth potential**
 Through a combination of environmental microbiology and epidemiology, and laboratory experiments, pathogens with environmental growth potential can be studied in order to gain insight in the possible responses of these recreational waterborne pathogens to climate factors.

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For an overview of the possible impact of climate change on water quality in the Netherlands, the reader is referred to RIVM Report 607800007 by Verweij et al.

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