Journal of Applied Microbiology 2003, **94**, 37S–46S

Climate change and waterborne and vector-borne disease

P.R. Hunter
School of Medicine, Health Policy and Practice, University of East Anglia, Norwich, UK

1. SUMMARY

This paper considers the potential impact on human health from waterborne and vector-borne infections. It concentrates on the impact of two possible changes to climate; increased frequency of heavy rainfall events, with associated flooding and increased temperature. Flooding is associated with increased risk of infection in developing nations but not in the West unless water sources are compromised. There have been numerous reported of outbreaks that followed flooding that led to contamination of underground sources of drinking water. Heavy rainfall also leads to deterioration in the quality of surface waters that could adversely affect the health of those engaged in recreational water contact. It is also concluded that there may be an increase in the number of cyanobacterial blooms because of a combination of increased nutrient concentrations and water temperature. It is considered unlikely that climate change will lead to an increase in disease linked to mains drinking water, although private supplies would be at risk from increased heavy rainfall events. Although increased temperature could lead to climatic conditions favourable to increases in certain vector-borne diseases such as malaria, the infrastructure in the UK would prevent the indigenous spread of malaria.

Correspondence to: Professor P R Hunter, School of Medicine, Health Policy and Practice, University of East Anglia, Norwich NR4 7TJ, UK (e-mail: paul.hunter@uea.ac.uk).

2. INTRODUCTION

Despite considerable research activity over a number of years, it must be admitted that the actual impacts of climate change on public health are still far from clear. In part, this uncertainty reflects difficulties in predicting the local effects of global changes in climate. Even if we were certain about future local climates, there is still uncertainty over what impact these climates would have on health. The focus of this paper is on the potential impacts of climate change on both waterborne and vector-borne diseases. In addressing these problems we shall first describe the current burden of disease through these transmission pathways, then go onto discuss what is already known about the impact of climate on their epidemiology and finally we shall attempt to predict what might be the impact of climate change on future epidemiology.

Given the uncertainty in the predictions over how the climate for UK will change, this review can only address the possible effects on health in a general rather than a specific way. In particular, this paper will address the potential health impacts of two likely changes in climate; an increase in the frequency of heavy rainfall events along with associated floods and increase in temperature. Furthermore, the discussion will be restricted to microbial disease. For a wider discussion of the health impacts of climate change on human health, the Department of Health has recently published an expert review for comment (Department of Health 2001).

3. WATERBORNE DISEASE

3.1 Current situation

Globally diseases waterborne and sanitation-related infections are one of the major contributors to diseases burden and mortality (Prüss and Havelaar 2001). The main burden of disease in this category falls on the poorest societies and on children under 5 years. Many different viral, bacterial and parasitic diseases have been associated with waterborne transmission (Hunter 1997). Some diseases have been spread through drinking water and others by recreational water contact (Table 1). The

Table 1 Microbial pathogens linked to drinking water or recreational water contact

Organism	Disease	Transmission	Clinical features
Helminths			
Schistosoma spp.	Schistosomaisis	Contact with surface water infected with free swimming cercariae	Urinary and intestinal damage. Bladder cancer
Dracunculus medinensis	Dracunculiasis	Drinking water	Painful ulcers on lower limbs and feet
Protozoa			
Giardia duodenalis	Giardiasis	Faecal oral spread through drinking water or recreational water	Diarrhoea and abdominal pain, weight loss and failure to thrive
Cryptosporidium parvum	Cryptosporidiosis	Faecal oral spread through drinking water or recreational water	Diarrhoea often prolonged
Cyclospora cayetanensis	Cyclosporiasis	Faecal oral spread through drinking water	Diarrhoea and abdominal pain, weight loss and failure to thrive
Entamoeba histolytica	Amebiasis	Faecal oral spread through drinking water	Diarrhoea, may be severe dysentery
Toxoplasma gondii	Toxoplasmosis	Drinking water contaminated by feline animals	Glandular fever, foetal damage in pregnant women
Free-living amoebae	Amoebic meningoencephalitis	Aspiration of infected surface water into nose	Fatal encephalitis
Algae			
Cyanobacteria	Various	Toxins in drinking water or direct contact with surface water blooms	Dermatitis, hepatitis, respiratory symptoms, potentially fatal
Pfiesteria piscicida	Estuary-associated syndrome	Toxins in water	Respiratory and eye irritation, deficiencies in learning and memory and acute confusional states
Bacteria			
Vibrio cholerae	Cholera	Drinking water	Watery diarrhoea, may be severe
Salmonella spp.	Salmonellosis	Occasional outbreaks with drinking water	Diarrhoea, colicky abdominal pain and fever
Salmonella typhi	Typhoid	Drinking water	Fever, malaise and abdominal pain with high mortality
Shigella spp.	Shigellosis (bacillary dysentery)	Both drinking and recreational water	Diarrhoea frequently with blood loss
Campylobacter spp.	Campylobacteriosis	Both drinking and recreational water	Diarrhoea frequently with blood loss
Enterotoxigenic *E. coli*		Drinking water	Watery diarrhoea
Enterohaemorrhagic *E. coli*		Drinking water and recreational water contact	Bloody diarrhoea and haemolyic uraemic syndrome in children
Yersinia spp.	Yersiniosis	Drinking water	Fever, diarrhoea and abdominal pain
Francisella tularensis	Tularaemia	Drinking water	Typhoid-like or mucocutaneous with suppurative skin lesions
Helicobacter pylori		Drinking water	Gastritis that can progress to gastric cancer
Mycobacteria spp. not *M. tuberculosis*	Varies	Potable water systems in hospitals, some recreation	Varies, includes respiratory disease, wound infections, skin disease

Table 1 (*Contd.*)

Organism	Disease	Transmission	Clinical features
Viruses			
Hepatitis A and Hepatitis E viruses	Viral hepatitis	Drinking and recreational water contact	Hepatitis
Various, esp. Norwalk-like viruses	Viral gastroenteritis	Drinking and recreational water contact	Vomiting and diarrhoea
Enteroviruses	Various, including poliomyelitis	Drinking and recreational water contact	Various

distribution of many waterborne pathogens varies substantially from one country to another. Some pathogens such as *Vibrio cholerae*, Hepatitis E virus and schistosomiasis are restricted to certain tropical countries, others, such as cryptosporidiosis and campylobacteriosis, are probably widespread. For some pathogens apparent differences in distribution may be due to different availability of diagnostic laboratories or national infectious disease surveillance schemes.

The evidence about the burden of waterborne disease in the UK comes predominantly from recording of outbreaks. In the UK there has been some 65 recorded outbreaks of infection linked to water affecting 4112 people during the years 1991–2000. Of these outbreaks, 25 were associated with public water supplies, 16 with private water supplies, 23 with swimming pools and one with recreational contact with surface waters (Table 2) (Stanwell-Smith *et al*. 2002). By far the commonest reported pathogen was *Cryptosporidium*, although *Campylobacter* was the commonest cause of outbreaks associated with private water supplies.

In the US for the period 1991 to 1998 there were 230 waterborne outbreaks reported affecting an estimated 443 000 people (Craun *et al*. 2002). However, most of the estimated case numbers comes from a single outbreak in Milwaukee and the method of estimating cases numbers has recently been criticised for substantially overestimating the size by at least 10-fold (Hunter and Syed 2001). Of 126 drinking-water outbreaks, 109 were reported in public water systems and 17 in individual water systems. There were also 104 outbreaks were associated with recreational water activities, usually swimming.

3.2 Impact of climate on epidemiology of waterborne disease

The current evidence of the impact of climate on the epidemiology of waterborne disease is considered under three headings; the impact of heavy rainfall events, the impact of flooding and the impact of increased temperature.

3.2.1 Heavy rainfall events. In Fig. 1 the month of start of outbreaks associated with water supplies in England and Wales for the last decade is shown. Although, there are probably too few outbreaks to be certain, there does appear to be an increase in Spring (April and May) and again in September. These months do not seem to be those that are typically associated with high rainfall. However, many investigations of drinking water-associated disease have noted that particularly heavy rainfall preceded the start of the outbreak (Smith *et al*. 1989; Joseph *et al*. 1991; Bridgman *et al*. 1995; Atherton *et al*. 1995; Willocks *et al*. 1998; Miettinen *et al*. 2001). Perhaps the most dramatic waterborne outbreak following heavy rainfall and associated

Table 2 Outbreaks of waterborne disease in England and Wales from 1991 to 2000

Cause	Number of outbreaks	Number of cases
Public water supplies		
Cryptosporidium	23	2837
Campylobacter	1	281
Gastroenteritis	1	229
Total	25	3347
Private water supplies		
Campylobacter	8	178
Mixed *Campylobacter* and *Cryptosporidium*	1	43
Cryptosporidium	3	74
Gastroenteritis	2	81
Giardia	1	31
E. coli O157	1	14
Total	16	421
Recreational contact with surface water		
Viral gastroenteritis	1	7
Swimming pool contact		
Cryptosporidium	23	337
Overall total	65	4112

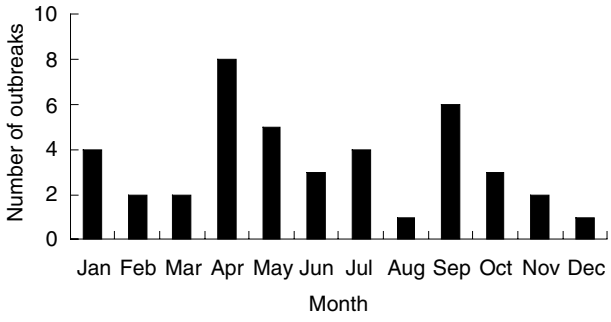

Fig. 1 Seasonal distributions of outbreaks associated with both private and public drinking water supplies from 1991 to 2000

flooding was the Walkerton outbreak of *Escherichia coli* O157:H7 in Canada which affected over 1000 people of whom 65 were admitted to hospital and six died (Anon 2000).

A recent American investigated the relationship between outbreaks waterborne disease and heavy rainfall events in a more systematic fashion (Curriero *et al.* 2001). They examined records of 548 outbreaks in the US that had been reported from 1948 through to 1994 and linked these outbreaks to rainfall data. Some 51% of all outbreaks were preceded by an extreme rainfall event.

It is not too difficult to understand the reason why heavy rainfall events can help generate impact that heavy rainfall events are associated with outbreaks of waterborne disease. Heavy rainfall may leads to changes in the direction of flow of water systems and flow through channels that would not normally occur. For example, in one outbreak of cryptosporidiosis associated with a borehole extracted groundwater, it was thought that the heavy rainfall led to water running across the surface of fields where cattle were grazing (Bridgman *et al.* 1995). The water (and cattle faeces) then pooled around the head of the borehole and leaked into the water supply. For surface water sources, heavy rainfall can lead to overflow of storm drains that may be combined with the sewage system. This can then allow substantial amounts of faecally polluted water into rivers. Surface water turbidity can also increase dramatically during heavy rainfall events and this can cause additional stress on inadequate water treatment systems.

Further evidence of the impact of heavy rainfall on the epidemiology of enteric pathogen comes from studies of the presence of various organisms in water. For example, there is a correlation between rainfall and the likelihood of detecting *Giardia* or *Cryptosporidium* oocysts in river water (Atherbolt *et al.* 1998) and pathogenic enteric viruses in water (Miossec *et al.* 2000). Heavy rainfall leads to storm water runoff into surface water sources, which has high counts of indicator bacteria as well as potential pathogens (Doran and Linn 1979; O'Shea and Field 1992). Heavy rainfall is also associated with high counts of indicator bacteria in river waters (Tunnicliff and Brickler 1984) and marine waters (Crowther *et al.* 2001). Given the well described relationships between counts of indicator organisms in surface water and the subsequent risk of predominantly gastrointestinal illness (Kay *et al.* 1994) it should be expected that people swimming in untreated surface waters after heavy rain would be at increased risk of illness.

There is also some evidence that heavy rainfall events may be followed by coliform re-growth in water distribution systems, presumably because of increased nutrients in water (LeChevallier *et al.* 1991). However, the health significance of this observation is unclear as non-faecal coliforms in drinking water do not appear to be associated with disease in the community (Edberg *et al.* 1986; Zmirou *et al.* 1987; Hellard *et al.* 2001).

A further issue related to heavy rainfall events is the additional nutrient input into water bodies that accompany heavy rainfall. When other conditions are appropriate, this can lead to the rapid growth and blooming of various planktonic species. This is considered further below.

3.2.2 Flooding. Flooding may follow heavy rainfall, although floods can also follow from tidal surges and rapid snow melt. Flooding of low-lying lands caused by rise in sea level secondary to melting of the ice caps is also likely to happen. Of all the types of natural disaster world-wide, flooding is the commonest and can cause enormous damage and financial loss (Malilay 1997; Greenough *et al.* 2001). No one in the UK will be unaware of the floods of recent years and the suggestion that flood events are likely to increase in future.

The health effects of flooding can be divided into those associated with the acute event and those arising after the flood has resolved. The main acute threat to health is drowning, although in the UK deaths from drowning as a result floods are few. On the other hand some 15 000 people are killed each year by floods in Bangladesh (Malilay 1997).

Although most concerns about subsequent health risk tends to focus on infectious disease, the evidence is relatively scant, at least for developed countries. The impact that heavy rainfall on the genesis of outbreaks of disease associated with drinking water systems has already been discussed. In general these outbreaks have been associated with flows of contaminated water into the groundwater or the interference with the effectiveness of water treatment. An additional outbreak was one of *Acanthamoeba* keratitis in Iowa which followed flooding that inundated a water treatment works (Meier *et al.* 1998).

For developing nations there is evidence of outbreaks following floods. Outbreaks of leptospirosis in Rio de Janeiro (Barcellos and Sabroza 2001) and in the Philippines (Easton 1999) have followed floods. Hepatitis E, malaria and

diarrhoeal disease have followed floods in Khartoom (Homeida *et al.* 1988; Novelli *et al.* 1988; Shears 1988; McCarthy 1994). Both acute diarrhoea and acute respiratory disease increased in Nicaragua following Hurricane Mitch and the associated flooding (Campanella 1999). By contrast epidemics do not tend to follow floods in developed countries (Bissell 1983; Aavitsland *et al.* 1996; Malilay 1997; Greenough *et al.* 2001).

It would seem to be the case that when infrastructure is adequate, epidemics of infection do not follow flood events unless the flooding has directly compromised the security of the water supply.

3.2.3 Temperature effects. Probably the most obvious link between waterborne disease and increased temperature relates to the blooms of various planktonic species that are directly or indirectly hazardous to human health. Several plantonic species have been implicated in causing disease in humans:

- Cyanobacteria (Blue–green algae) have been implicated in causing various clinical syndromes such as dermatitis, respiratory problems and hepatitis (Hunter 1998). Illness follows consumption of water containing toxins or contact with water or blooms during bathing.
- Dinoflagellates and diatoms are implicated in a variety of neurotoxic, diarrhetic and amnesic shell fish poisonings (Hungerford 2001). These are not directly waterborne diseases, although the shellfish accumulate toxins whilst filter feeding.
- *Pfiesteria piscicida* is a dinoflagellate which is responsible for a recently recognised syndrome know as 'estuary-associated syndrome'. This causes acute respiratory and eye irritation and has been associated with deficiencies in learning and memory and acute confusional states in people who have had contact with contaminated water or aerosols (Morris 1999).

A major factor in the appearance of blooms is the increase in nutrients in water bodies especially in inland freshwater lakes and estuaries (Reynolds 1984). However, most blooms occur during the summer months and relatively high water temperatures are necessary for algal growth and bloom formation (Maier and Dandy 1997; Jacoby *et al.* 2000; Saker and Griffiths 2001). There is a strong impression that algal blooms are becoming more common in Europe (Skulberg *et al.* 1984; Fastner *et al.* 1999).

The most evidence of the effect of temperature on risk from waterborne disease is in relation to cholera (Colwell 1996). There is now good evidence that *V. cholerae* survives in marine waters in a viable but non-cultural form that seems to be associated with algae and plankton (Islam *et al.* 1990; Colwell 1996). When temperatures rise, plankton bloom and, in appropriate areas, such blooms are followed by increases in reported cases of cholera. For example, increases in sea-surface temperature as a result of El-Niño-events have been shown to predate increases in cholera incidence in both Asia and South America (Lobitz *et al.* 2000; Pascual *et al.* 2000; Speelmon *et al.* 2000).

There has been some suggestion that higher water temperatures will lead to more prolonged survival of pathogens in the environment (Chief Medical Officer 2001). However, the evidence does not support this concern. Indeed, survival of enteric pathogens in water is usually reduced at higher temperatures. This has been shown to be the case for *Campylobacter* (Buswell *et al.* 1998; Thomas *et al.* 1999; Obiri-Danso *et al.* 2001), enterohemorrhagic *E. coli* O157:H7 (Wang and Doyle 1998; Rice and Johnson 2000), *V. cholerae* (but see above) (Okitsu *et al.* 1994) and enteroviruses (Hurst *et al.* 1989).

3.3 The future impact of global warming on waterborne disease in the UK

Making predictions of future events is always a dangerous pastime. Nevertheless, one can make at least some intelligent guesses about what the future may hold for waterborne disease.

It seems unlikely that global warming will have a major impact on the risk of disease associated with mains water supplies in the UK. The standards of water treatment and distribution within the UK is of a very high standard compared with many nations even elsewhere in Europe. Although outbreaks of waterborne disease do still occur, they are nearly all due to *Cryptosporidium* and are associated with supplies that are still inadequately treated. Most of these high-risk supplies will have been closed or had new filtration plants installed by about 2005. Provided that the UK does not suffer serious economic collapse it is difficult to see how global warming could have a major impact on risk of waterborne disease associated with mains drinking water.

On the other hand, there are still many private supplies in use in the UK and these are frequently poorly treated. The microbiological quality of such supplies is generally very poor and can deteriorate markedly after heavy rainfall (Shepherd and Wyn-Jones 1997; Fewtrell *et al.* 1998; Rutter *et al.* 2000). If heavy rainfall events are to become more common, then the safety of private supplies (already poor) will deteriorate even further.

Heavy rainfall events are more likely to lead to marked decline in microbiological quality of inland and marine recreational waters as a result of heavy runoff. Furthermore, increased temperatures may add to the continued rise in problems due to algal blooms in Europe. Both these mechanisms would increase the probability of disease from recreational use of waters in and around the UK. However,

the epidemiological evidence of infectious disease associated with recreational water contact is that it is generally very mild and not likely to cause significant disease burden in the population.

4. VECTOR-BORNE DISEASE

4.1 Current situation

Vector-borne diseases are those diseases that are spread by insect vectors. The insects act as an essential stage in the transmission of the infection from one person to another or from animal hosts to humans. There are a large number of viral, rickettsial, bacterial and parasitic diseases that can be transmitted by insect vectors (Cook 1996) (Table 3). Various vector-borne are amongst some of the major microbial causes of morbidity and mortality in the World today. Malaria alone causes some one million deaths and 273 million cases worldwide each year (Rogers and Randolf 2000). However, with the exception of Lyme disease, vector-borne diseases do not currently cause problems for public health in the UK.

Table 3 Some examples of vector-borne diseases of clinical importance

Disease	Pathogen	Vector	Geographical distribution	Clinical effects
Viruses				
Dengue	Flavivirus	Mosquito	Africa, Caribbean, Pacific, Far East	Haemorrhagic fever
Japanese Encephalitis	Flavivirus	Mosquito	Japan, Far East	Encephalitis
West Nile	Flavivirus	Mosquito	Africa, India, Europe and North America	Encephalitis
Murray River encephalitis	Flavivirus	Mosquito	Australia, New Guinea	Encephalitis
St Louis encephalitis	Flavivirus	Mosquito	America	Encephalitis
Yellow fever	Flavivirus	Mosquito	Africa, South and Central America	Hepatitis & Haemorrhagic fever
Eastern Equine Encephalitis	Alphavirus	Mosquito	North America	Encephalitis
Crimean-Congo haemorrhagic fever	Nairovirus	Ixodic tick	Europe, Africa, Middle East, Central Asia	Haemorrhagic fever
Tick-borne encephalitis	Flavivirus	Ixodic tick	Former USSR, Europe	Encephalitis
Rift Valley Fever	Phlebovirus	Mosquito	Africa	Haemorrhagic fever
Rickettsia				
Murine typhus	*Rickettsia typhi*	Flea	Tropical countries	Typhus
Rocky Mountain Spotted fever	*R. rickettsii*	Ticks	USA	Spotted fever
Boutonneuse fever	*R. conorii*	Tick	Africa, Mediterranean, Middle East	Spotted fever
Bacteria				
Bartonellosis	*B. bacilliformis*	Sandflies	Western Slopes of the Andes	Oroya fever
Plague	*Yersinia pestis*	Flea	Africa, Asia, South America, USA	Bubonic, pneumonic or septicaemic plague
Lyme disease	*Borrelia burgdorferi*	Ticks	Europe, North America	Arthritis
Relapsing fever	*B. recurrentis*	Lice	Ethiopia, Burundi, Peru, Bolivia, North Africa, India, Asia, China	Severe relapsing fever with high mortality
Relapsing fever	e.g. *B. duttoni*	Ticks	East, Central & South Africa	Less severe relapsing fever
Protozoal parasites				
Malaria	*Plasmodium* spp.	Mosquitos	Widespread in tropics	Febrile illness with high mortality
African trypanosomiasis	*Trypanosoma brucei*	Tsetse flies	Africa	Sleeping sickness
American trypanosomiasis	*T. cruzei*	Triatomine bugs	Central and South America	Chagas disease
Leishmaniasis	*Leishmania* spp.	Sandflies	Africa, Central & South America	Cutaneous and mucosal lesions, visceral disease
Helminths				
Lymphatic filariasis	eg. *Wucheria bancrofti*	Mosquito	Tropics	Elephantiasis
Onchocerciasis	*Onchocerca volvulus*	Blackflies	Africa, Central & South America	Dermatitis, Blindness
Loaiasis	*Loa loa*	Tabanid flies	West & Central Africa	Calabar swellings

4.2 Impact of climate on epidemiology of vector-borne disease

The geographical distribution of vector-borne diseases is influenced by the geographical distribution of both vertebrate host (where one exists) and the distribution of the vector.

4.2.1 Temperature effects. Temperature can affect both the distribution of the vector and the effectiveness of pathogen transmission through the vector. Gubler *et al.* (2001) list a range of possible mechanisms whereby changes in temperature impact on the risk of transmission of vector-borne disease:

- Increase or decrease in survival of vector
- Changes in rate of vector population growth
- Changes in feeding behaviour
- Changes in susceptibility of vector to pathogens
- Changes in incubation period of pathogen
- Changes in seasonality of vector activity
- Changes in seasonality of pathogen transmission

There is also good epidemiological evidence of disease risk in humans linked to climate variability. Most of this evidence comes from studies of malaria. For example, there is evidence that malaria prevalence in both South America and Asia varies in relation to El-Niño-events (Bouma and van der Kaay 1996; Bouma *et al.* 1996, 1997; Bouma and Dye 1997). This relationship between El-Niño and increased malaria risk is partly due to increased temperature and partly due to increased rainfall leading to increased mosquito breeding sites because of surface water collections. Climate has also been shown to have a direct effect on the risk of outbreaks of St Louis encephalitis (SLE). SLE is generally restricted to areas south of the 20°C June isotherm, although it has spread northerly in particularly warm years (Hess *et al.* 1963; Shope 1980). Furthermore outbreaks of SLE tend to follow periods of hot weather where the temperature exceeds 30°C for seven consecutive days (Murray *et al.* 1985; Monath and Tsai 1987). Evidence for other vector-borne pathogens is less clear. Indeed, a study of reported cases of Lyme disease in the UK showed no correlation with mean summer temperatures (Cannell *et al.* 1999).

4.2.2 Rainfall effects. Gubler *et al.* (2001) list a range of possible mechanisms whereby rainfall can impact on the risk of transmission of vector-borne disease:

- Increased surface water can provide breeding sites for vectors
- Low rainfall can also increase breeding sites by slowing river flow
- Increased rain can increase vegetation and allow expansion in population of vertebrate host
- Flooding may eliminate habitat for both vectors and vertebrate hosts
- Flooding may force vertebrate hosts into closer contact with humans

The link between El-Niño and malaria has already been discussed. This link is due, in part, to the increased amount of surface water providing breeding sites for mosquitoes (Bouma and van der Kaay 1996; Bouma *et al.* 1996, 1997; Bouma and Dye 1997). Decreased rainfall has been shown to be associated with epidemics of SLE when the vector, *Culex pipiens*, starts to breed in urban drainage systems (Mitchell *et al.* 1980). Heavy rains have also been shown to precipitate epidemics of SLE in Florida as the rainfall event stimulates blood-feeding by *Culex nigripalpus* (Day and Curtis 1989).

4.3 The future impact of global warming on vector-borne disease in the UK

Most concern about the potential impact of climate change on vector-borne disease has focused on the potential reintroduction of malaria to the UK. Indeed Malaria was endemic to the UK until the early part of the last century (Dobson 1994). Climate scenarios suggest that within the next few decades, summer temperatures could become conducive to the spread of vivax malaria in some areas of England (Rogers *et al.* 2001). However, climate alone is not a sufficient requirement for the spread of malaria. There has to be a pool of parasitaemic individuals to act as the reservoir of infection. There are many regions that have adequate climate for transmission of malaria but do not experience indigenous malaria, such as the United States and Southern Europe. The absence of malaria in these regions is due to adequate public health and medical infrastructure where mosquito breeding is controlled and infected individuals diagnosed and treated. It is difficult to envisage a situation where the public health infrastructure would breakdown and indigenous malaria return to the UK without a significant economic collapse. One possible exception to this is the potential for small localised outbreaks of 'airport malaria' whereby infected mosquitoes or individuals arrive in the UK from infected areas abroad. Such outbreaks are already well documented (Guillet *et al.* 1998; Van den Ende *et al.* 1998). Whether a warming climate will increase the risk of such events occurring remains to be seen.

With the current knowledge about Lyme Disease, it is not possible to predict what if any effect climate change will have on its epidemiology.

5. CONCLUSIONS

With the current available evidence and scenarios for climate change in the UK it would appear that the public health effects of climate change, at least as far as water- and

vector-borne disease is concerned, are likely to be relatively negligible when compared to other public health concerns. However, we cannot afford to be complacent. The recent introduction of West Nile encephalitis into New York and elsewhere in the United States serve as a warning of other, unanticipated, threats of vector-borne disease (Epstein 2001). Such sudden emergence of infectious disease can rarely be predicted in advance. We do not know sufficient about the epidemiology of many infectious diseases to adequately predict the full impact of climate change. Furthermore, we have no idea how many potential pathogens are sharing this planet with us that are awaiting the right conditions for their chance at stardom by becoming an emerging infectious disease.

There is also another very important point to make. This review has concentrated on the potential impact of climate change on the UK. The adverse impact of any change is likely to be far more damaging on less wealthy societies. Adverse health consequences of climate change may be yet another example of the observation that often the adverse consequences of the lifestyles of the wealthy are felt, not by those enjoying the benefits of the those lifestyles but by the poor. In this author's view the West has a moral responsibility towards the poorest nations for the potential adverse impacts that they are likely to experience as a result of our inability to control our own excess energy consumption.

6. REFERENCES

Aavitsland, P., Iversen, B.G., Krogh, T., Fonahn, W. and Lystad, A. (1996) Infections during the 1995 flood in Ostlandet. Prevention and incidence. *Tidsskrift for Den Norske Laegeforening* **116**, 2038–2043.

Anon. (2000) Waterborne outbreak of gastroenteritis associated with a contaminated municipal water supply, Walkerton, Ontario, May–June 2000. *Canada Communicable Disease Report* **26**, 170–173.

Atherbolt, T.B., LeChevallier, M.W., Norton, W.D. and Rosen, J.S. (1998) Effect of rainfall on Giardia and Cryptosporidium. *Journal of the American Water Works Association* **90**, 66–80.

Atherton, F., Newman, C.P.S. and Casemore, D.P. (1995) An outbreak of waterborne cryptosporidiosis associated with a public water supply in the UK. *Epidemiology and Infection* **115**, 123–131.

Barcellos, C. and Sabroza, P.C. (2001) The place behind the case: leptospirosis risks and associated environmental conditions in a flood-related outbreak in Rio de Janeiro. *Cadernos de Saude Publica* **17**(suppl), 59–67.

Bissell, R.A. (1983) Delayed-impact infectious disease after a natural disaster. *Journal of Emergency Medicine* **1**, 59–66.

Bouma, M.J. and Dye, C. (1997) Cycles of malaria associated with El-Niño in Venezuela. *Journal of the American Medical Association* **278**, 1772–1774.

Bouma, M.J. and Van der Kaay, H.J. (1996) The El-Niño southern oscillation and the historic malaria epidemics on the Indian subcontinent and Sri Lanka: an early warning system for future epidemics? *Tropical Medicine and International Health* **1**, 86–96.

Bouma, M.J., Dye, C. and Van der Kaay, H.J. (1996) Falciparum malaria and climate change in the North West Frontier Province of Pakistan. *American Journal of Tropical Medicine and Hygiene* **55**, 131–137.

Bouma, M.J., Proveda, G., Rojas, W., Chavasse, D., Quinones, M., Cox, J. and Patz, J. (1997) Predicting high-risk years for malaria in Columbia using parameters of El-Niño southern oscillation. *Tropical Medicine and International Health* **2**, 1122–1127.

Bridgman, S., Robertson, R.M.P., Syed, Q., Speed, N., Andrews, N. and Hunter, P.R. (1995) Outbreak of Cryptosporidiosis associated with a disinfected groundwater supply. *Epidemiology and Infection* **115**, 555–566.

Buswell, C.M., Herlihy, Y.M., Lawrence, L.M., McGuiggan, J.T., Marsh, P.D., Keevil, C.W. and Leach, S.A. (1998) Extended survival and persistence of Campylobacter spp. in water and aquatic biofilms and their detection by immunofluorescent-antibody and -rRNA staining. *Applied & Environmental Microbiology* **64**, 733–741.

Campanella, N. (1999) Infectious diseases and natural disasters: the effects of Hurricane Mitch over Villanueva municipal area, Nicaragua. *Public Health Reviews* **27**, 311–319.

Cannell, M.G.R., Palutikof, J.P. and Sparks, T.H. (1999) *Indicators of Climate Change in the UK*. London: Department of the Environment, Transport and the Regions.

Chief Medical Officer (2001) *Getting Ahead of the Curve. A Strategy for Combating Infectious Diseases (Including Other Aspects of Health Protection)*. London: Department of Health.

Colwell, R.R. (1996) Global climate change and infectious disease: the cholera paradigm. *Science* **274**, 2025–2031.

Cook, G.C. (1996) *Manson's Tropical Diseases*, 20th edn. London: WB Saunders.

Craun, G.F., Calderon, R.L. and Nwachuku, N. (2002) Causes of waterborne outbreaks reported in the United States, 1991–98. In *Drinking Water and Infectious Disease: Establishing the Link* ed. Hunter, P.R., Waite, M. and Ronchi, E. pp. 105–117. Boca Raton: CRC Press.

Crowther, J., Kay, D. and Wyer, M.D. (2001) Relationships between microbial water quality and environmental conditions in costal recreational waters: the Fylde Coast, UK. *Water Research* **35**, 4029–4038.

Curriero, F.C., Patz, J.A., Rose, J.B. and Lele, S. (2001) The association between extreme precipitation and waterborne disease outbreaks in the United States, 1948–1994. *American Journal of Public Health* **91**, 1194–1199.

Day, J.F. and Curtis, G.A. (1989) Influence of rainfall on *Culex nigripalpus* (Diptera: Culicidae) blood-feeding behaviour in Indian River County, Florida. *Annals of the Entomological Society of America* **82**, 32–37.

Department of Health (2001) *Health Effects of Climate Change in the UK – An Expert Review for Comment*. London: Department of Health.

Dobson, M. (1994) Malaria in England: a geographical and historical perspective. *Parasitologia* **36**, 35–60.

Doran, J.W. and Linn, D.M. (1979) Bacteriological quality of runoff water from pastureland. *Applied and Environmental Microbiology* **37**, 985–991.

Easton, A. (1999) Leptospirosis in Philippine floods. *British Medical Journal* **319**, 212.

Edberg, S.C., Piscitelli, V. and Cartter, M. (1986) Phenotypic characteristics of coliform and non-coliform bacteria from a public

water supply compared with regional and national clinical species. *Applied and Environmental Microbiology* **52**, 474–478.

Epstein, P.R. (2001) Climate change and emerging infectious diseases. *Microbes and Infection* **3**, 747–754.

Fastner, J., Neumann, U., Wirsing, B., Weckesser, J., Wiedner, C., Nixdorf, B. and Chorus, I. (1999) Microcystins (hepatotoxic heptapeptides) in German fresh water bodies. *Environmental Toxicology* **14**, 13–22.

Fewtrell, L., Kay, D. and Godfree, A. (1998) The microbiological quality of private water supplies. *Journal of the Chartered Institution of Water and Environmental Management* **12**, 98–100.

Greenough, G., McGeehin, M., Bernard, S.M., Trtanj, J., Riad, J. and Engelberg, D. (2001) The potential impacts of climate variability and change on health impacts of extreme weather events in the United States. *Environmental Health Perspectives* **109**(suppl 2), 191–198.

Gubler, D.J., Reiter, P., Ebi, K.L., Yap, W., Nasci, R. and Patz, J.A. (2001) Climate variability and change in the United States: potential impacts on vector- and rodent-borne diseases. *Environmental Health Perpectives* **109**(suppl 2), 223–233.

Guillet, P., Germain, M.C., Giacomini, T., Chandre, F., Akobeto, M., Faye, O., Kone, A., Manga, L. and Mouchet, J. (1998) Origin and prevention of airport malaria in France. *Tropical Medicine and International Health* **3**, 700–705.

Hellard, M.E., Sinclair, M.I., Forbes, A.B. and Fairley, C.K. (2001) A randomised, blinded, controlled trial investigating the gastrointestinal health effects of drinking water quality. *Environmental Health Perspectives* **109**, 773–778.

Hess, A.D., Cherubin, C.E. and La Motte, L.C. (1963) Relation of temperature to activity of western and St Louis encephalitis viruses. *American Journal of Tropical Medicine and Hygiene* **12**, 657–667.

Homeida, M., Ismail, A.A., El Tom, I., Mahmoud, B. and Ali, H.M. (1988) Resistant malaria and the Sudan floods. *Lancet* **2**, 912.

Hungerford, J.M. (2001) Seafood toxins. In *Guide to Foodborne Pathogens* ed. Labbé, R.G. and García, S. pp. 267–283. New York: John Wiley and Sons.

Hunter, P.R. (1997) *Waterborne Disease: Epidemiology and Ecology*. Chichester: Wiley.

Hunter, P.R. (1998) Cyanobacterial toxins and human health. *Journal of Applied Bacteriology* **84**(suppl), 35S–40S.

Hunter, P.R. and Syed, Q. (2001) Community Surveys of self-reported diarrhoea can dramatically overestimate the size of outbreaks of waterborne cryptosporidiosis. *Water Science and Technology* **43**(12), 27–30.

Hurst, C.J., Benton, W.H. and McClellan, K.A. (1989) Thermal and water source effects upon the stability of enteroviruses in surface freshwaters. *Canadian Journal of Microbiology* **35**, 474–480.

Islam, M.S., Draser, B.S. and Bradley, D.J. (1990) Long-term persistence of toxigenic *Vibrio cholerae* O1 in the mucilaginous sheath of a blue-green alga, *Anabaena variabilis*. *Journal of Tropical Medicine and Hygiene* **93**, 133–139.

Jacoby, J.M., Collier, D.C., Welch, E.B., Hardy, F.J. and Crayton, M. (2000) Environmental factors associated with a toxic bloom of Microcystis aeruginosa. *Canadian Journal of Fisheries and Aquatic Sciences* **57**, 231–240.

Joseph, C., Hamilton, G., O'Connor, M., Nicholas, S., Marshall, R., Stanwell-Smith, R., Sims, R., Ndawula, E., Casemore, D., Gallagher, P. and Harnett, P. (1991) Cryptosporidiosis in the Isle of Thanet: an outbreak associated with local drinking water. *Epidemiology and Infection* **107**, 509–519.

Kay, D., Fleisher, J.M., Salmon, R.L., Jones, F., Wyer, M.D., Godfree, A.F., Zelenauch-Jacquotte, Z. and Shore, R. (1994) Predicting likelihood of gastroenteritis from sea bathing: results from randomised exposure. *Lancet* **344**, 905–909.

LeChevallier. M/W/, Schulz. W/ and Lee, R.G. (1991) Bacterial nutrients in drinking water. *Applied and Environmental Microbiology* **57**, 857–862.

Lobitz, B., Beck, L., Huq, A., Wood, B., Fuchs, G., Faruque, A.S.G. and Colwell, R. (2000) Climate and infectious disease: use of remote sensing for detection of *Vibrio cholerae* by indirect measurement. *Proceedings of the National Academy of Science* **97**, 1438–1443.

Maier, H.R. and Dandy, G.C. (1997) Modelling cyanobacteria (blue-green algae) in the River Murray using artificial neural networks. *Mathematics and Computers in Simulation* **43**, 377–386.

Malilay, J. (1997) Floods. In *The Public Health Consequences of Disasters* ed. Noji, E.K. pp. 287–301. Oxford: Oxford University Press.

McCarthy, M.C., He, J., Hyams, K.C., el-Tigani, A., Khalid, I.O. and Carl, M. (1994) Acute hepatitis E infection during the 1988 floods in Khartoum, Sudan. *Transactions of the Royal Society of Tropical Medicine & Hygiene* **88**, 177.

Meier, P.A., Mathers, W.D., Sutphin, J.E., Folberg, R., Hwang, T. and Wenzel, R.P. (1998) An epidemic of presumed Acanthamoeba keratitis that followed regional flooding. Results of a case-control investigation. *Archives of Opthalmology* **116**, 1090–1094.

Miettinen, I.T., Zacheus, O., von Bonsdorff, C.-H. and Vartiainen, T. (2001) *Water Science and Technology* **43**, 67–71.

Miossec, L., Le Guyader, F., Haugarreau, L. and Pommepuy, M. (2000) Magnitude of rainfall on viral contamination of the marine environment during gastroenteritis epidemics in human coastal population. *Revue d Epidemiologie et de Sante Publique* **48**(suppl 2), 2S62–2S71.

Mitchell, C.J., Francy, D.B. and Monath, T.P. (1980) Arthropod vectors. In *St. Louis Encephalitis* ed. Monath, T.P. Washington DC: American Public Health Association.

Monath, T.P. and Tsai, T.F. (1987) St. Louis encpephalitis: lessons from the last decade. *American Journal of Tropical Medicine and Hygiene* **37**, 40S–59S.

Morris Jr, J.G. (1999) Pfiesteria, "the cell from hell", and other toxic nightmares. *Clinical Infectious Diseases* **28**, 1191–1196.

Murray, R.A., Hable, L.A., Mackey, K.J., Wallace, H.G., Peck, B.A., Mora, S.J., Ginsberg, M.M. and Emmons, R.W. (1985) Epidemiological aspects of the 1984 St Louis emcephalitis epidemic in southern California. *Proceedings of the Californian Mosquito Vector Control Association* **53**, 5–9.

Novelli, V., El Tohami, T.A., Osundwa, V.M. and Ashong, F. (1988) Floods and resistant malaria. *Lancet* **2**, 1367.

Obiri-Danso, K., Paul, N. and Jones, K. (2001) The effects of UVB and temperature on the survival of natural populations and pure cultures of *Campylobacter jejuni*, *Camp. coli*, *Camp. lari* and urease-positive thermophilic campylobacters (UPTC) in surface waters. *Journal of Applied Microbiology* **90**, 256–267.

Okitsu, T., Morozumi, H., Murase, T., Suzuki, R., Matsushima, A. and Yamai, S. (1994) Survival of *Vibrio cholerae* O139 Synonym

Bengal in water from a river. *Journal of the Japanese Association for Infectious Diseases* **68**, 744–750.

O'Shea, M.L. and Field, R. (1992) Detection and disinfection of pathogens in storm-generated flows. *Canadian Journal of Microbiology* **38**, 267–276.

Pascual, M., Rodó, X., Ellner, S.P., Colwell, R. and Bouma, M.J. (2000) Cholera dynamics and El-Niño-Southern Oscillation. *Science* **289**, 1766–1769.

Prüss, A. and Havelaar, A. (2001) The global burden of disease study and applications in water, sanitation and hygiene. In *Water Quality: Guidelines, Standards and Health* ed. Fewtrell, L. and Bartram, J. pp. 43–59. London: IWA Publishing.

Raynolds, C.S. (1984) *The Ecology of Freshwater Phytoplankton*. Cambridge: Cambridge University Press.

Rice, E.W. and Johnson, C.H. (2000) Short communication: survival of *Escherichia coli* O157:H7 in dairy cattle drinking water. *Journal of Dairy Science* **83**, 2021–2023.

Rogers, D.J. and Randolph, S.E. (2000) The global spread of malaria in a future, warmer world. *Science* **289**, 1763–1766.

Rogers, D.J., Randolph, S.E., Lindsay, S. and Thomas, C. (2001) Vector-borne diseases and climate change. In *Health effects of climate change in the UK – an expert review for comment*. pp. 85–98. London: Department of Health.

Rutter, M., Nichols, G.L., Swan, A. and De Louvois, J. (2000) A survey of the microbiological quality of private water supplies in England. *Epidemiology and Infection* **124**, 417–425.

Saker, M.L. and Griffiths, D.J. (2001) Occurrence of blooms of the cyanobacterium Cylindrospermopsis raciborskii (Woloszynska) Seenayya and Subba Raju in a north Queensland domestic water supply. *Marine and Freshwater Research* **52**, 905–915.

Shears, P. (1988) The Khartoum floods and diarrhoeal diseases. *Lancet* **2**, 517.

Shepherd, K.M. and Wyn-Jones, A.P. (1997) Private water supplies and the local authority role: results of a UK national survey. *Water Science and Technology* **35**, 41–45.

Shope, R.E. (1980) Arbovirus-related encephalitis. *Yale Journal of Biology and Medicine* **53**, 93–99.

Skulberg, O.M., Codd, G.A. and Carmichael, W.W. (1984) Toxic blue-green algal blooms in Europe – a growing problem. *Ambio* **13**, 244–247.

Smith, H.V., Patterson, W.J., Hardie, R., Greene, L.A., Benton, C., Tulloch, W., Gilmour, R.A., Girdwood, R.W.A., Sharp, J.C.M. and Forbes, G.I. (1989) An outbreak of cryptosporidiosis caused by post-treatment contamination. *Epidemiology and Infection* **103**, 703–715.

Speelmon, E.C., Checkley, W., Gilman, R.H., Patz, J., Caleron, M. and Manga, S. (2000) Cholera incidence and El-Niño-related higher ambient temperature. *Journal of the American Medical Association* **283**, 3072–3074.

Stanwell-Smith, R., Andersson, Y. and Levy, D.A. (2002) National Surveillance systems. In *Drinking Water and Infectious Disease: Establishing the Link* ed. Hunter, P.R., Waite, M. and Ronchi, E. pp. 25–40. Bocata Raton: CRC Press.

Thomas, C., Hill, D.J. and Mabey, M. (1999) Evaluation of the effect of temperature and nutrients on the survival of Campylobacter spp. in water microcosms. *Journal of Applied Microbiology* **86**, 1024–1032.

Tunnicliff, B. and Brickler, S.K. (1984) Recreational water quality analyses of the Colorado River corridor in Grand Canyon. *Applied and Environmental Microbiology* **48**, 909–917.

Van den Ende, J. , Lynen, L., Elsen, P., Colebunders, R., Demey, H., Depraetere, K., De Schrijver, K., Peetermans, W.E., Pereira de Almeida, P. and Vogelaers, D. (1998) A cluster of airport malaria in Belgium in 1995. *Acta Clinica Belgica* **53**, 259–263.

Wang, G. and Doyle, M.P. (1998) Survival of enterohemorrhagic *Escherichia coli* O157:H7 in water. *Journal of Food Protection* **61**, 662–667.

Willocks, L., Crampin, A., Milne, L., Seng, C., Susman, M., Gair, R., Moulsdale, M., Shafi, S., Wall, R., Wiggins, R. and Lightfoot, N. (1998) A large outbreak of cryptosporidiosis associated with a public water supply from a deep chalk borehole. *Communicable Disease and Public Health* **1**, 239–243.

Zmirou, D., Ferley, J.P., Collin, J.F., Charrel, M. and Berlin, J. (1987) A follow-up study of gastro-intestinal diseases related to bacteriologically substandard drinking water. *American Journal of Public Health* **77**, 582–584.