

The impact of climate variability and change on cryptosporidiosis and giardiasis rates in New Zealand

Emma Britton, Simon Hales, Kamalesh Venugopal and Michael G Baker

ABSTRACT

Aim: To investigate the spatial relationship between climate variability and cryptosporidiosis and giardiasis notifications in New Zealand between 1997 and 2006.

Methods: Negative binomial regression was used to analyse spatial relationships between cryptosporidiosis and giardiasis notifications in New Zealand between 1997 and 2006, and climatological average rainfall and temperature at the Census Area Unit (CAU) level. The quality of domestic water supplies, urban-rural status and deprivation were included as covariates.

Main results:

Giardiasis: There was a positive association between rainfall and giardiasis and between temperature and giardiasis.

Cryptosporidiosis: There was a positive association between rainfall and cryptosporidiosis and a negative association between temperature and cryptosporidiosis. The effect of rainfall was modified by the quality of the domestic water supply.

Conclusions: These findings suggest that climate variability affects protozoan disease rates in New Zealand. However, predicting the effect of climate change from this study is difficult, as these results suggest that the projected increases in temperature and rainfall may have opposing effects on cryptosporidiosis rates. Nevertheless, water supply quality appeared to modify the impact of increased rainfall on cryptosporidiosis rates. This finding suggests that improving water supply quality in New Zealand could reduce vulnerability to the impact of climate change on protozoan diseases.

Key words | climate, cryptosporidiosis, giardiasis, rain, temperature, water supply

Emma Britton (corresponding author)
PO Box 6502,
Wellington 6141,
New Zealand
Tel.: +64 4 938 7040
Email: emma.britton@stress-free.co.nz

Simon Hales
Kamalesh Venugopal
Michael G Baker
Department of Public Health,
University of Otago, Wellington,
23a Mein St, Newtown,
Wellington,
New Zealand

ABBREVIATIONS

CAU Census area unit
HIV Human immunodeficiency virus
IPCC Intergovernmental Panel on Climate Change
WHO World Health Organization

INTRODUCTION

Enteric disease infections are the most common cause of diarrhoea world-wide (WHO 2003). It has been estimated that globally, bacterial, viral, amoebic and protozoan

enteric infections cause 4 billion cases of diarrhoea each year (WHO 2000). In 2002–2003, the deaths of approximately 1.9 million children under the age of five were attributed to diarrhoea (Bryce *et al.* 2005). The burden of enteric disease is substantially higher in poor countries, but it is also a significant problem in industrialised countries such as New Zealand (Rose *et al.* 2000; Crump *et al.* 2001). Although enteric diseases do not cause significant mortality in developed countries, they do cause considerable discomfort for those infected and some enteric diseases can lead to debilitating, long-term sequelae (Nachamkin *et al.* 1998).

Cryptosporidium is a protozoan enteropathogen that has been estimated to cause 2–6% of the global burden of

doi: 10.2166/wh.2010.049

diarrhoeal disease in immunocompetent people and 14–24% of diarrhoeal disease in those with HIV (Guerrant 1997). The New Zealand cryptosporidiosis notification rate in 2007 was 21.9 per 100,000 population (Institute of Environmental Science and Research Ltd (ESR) 2008), which is relatively high compared to other developed countries (Snel *et al.* 2009b). *Giardia* is another protozoan enteropathogen of significance. According to Hoque *et al.* (2004) “approximately 200 million people are infected with the parasite (*Giardia*) globally”. The New Zealand giardiasis notification rate in 2007 was 33.1 per 100,000 population (Institute of Environmental Science and Research Ltd (ESR) 2008), which is again relatively high compared to other developed countries (Snel *et al.* 2009a).

The seasonal patterns of cryptosporidiosis (Snel *et al.* 2009b) and giardiasis (Hoque *et al.* 2004; Snel *et al.* 2009a) observed in New Zealand are likely to be due to a combination of factors. In New Zealand, the spring peak in cryptosporidiosis is thought to be due, in part, to the increase in the number of infectious livestock during the spring lambing and calving season (Goldsmid *et al.* 2003; Lake *et al.* 2008; Snel *et al.* 2009b). However, the seasonality of these protozoan diseases raises the possibility that seasonal variation in climatic factors, such as rainfall and temperature, could also be influencing disease rates.

One of the main routes of transmission of *Cryptosporidium* and *Giardia* to humans is through water (Rose 1997; Goldsmid *et al.* 2003). High levels of rainfall onto saturated soil could plausibly facilitate the transfer of *Cryptosporidium* oocysts in animal manure into surface water (Lake *et al.* 2005; Thurston-Enriquez *et al.* 2005). Sewage overflow during high levels of rainfall could also lead to *Cryptosporidium* oocysts and *Giardia* cysts contaminating water used for recreation or drinking (Lake *et al.* 2005). In several studies rainfall has been found to be positively correlated with the concentration of *Cryptosporidium* oocysts and/or *Giardia* cysts in surface and runoff water (Atherholt *et al.* 1998; Thurston-Enriquez *et al.* 2005; Arnone & Walling 2006; Miller *et al.* 2007). Water treatment plants may offer some protection against water-borne transmission but they may not be adequate to cope with a substantial increase in pathogens in the water source following heavy rainfall (Curriero *et al.* 2001; Naumova *et al.* 2005). The 1993 Milwaukee outbreak of

cryptosporidiosis has been attributed to a preceding period of heavy rainfall and runoff that increased the turbidity load and the number of oocysts to levels that the treatment plant could not adequately remove (MacKenzie *et al.* 1994; Rose *et al.* 2001).

However, the link between rainfall and protozoan disease is still controversial in the literature. A positive association was found between rainfall and cryptosporidiosis rates in a study in the North-West region of England (Naumova *et al.* 2005). According to Naumova *et al.* (2005) the “overall weekly rate of cryptosporidiosis in the region increases by 27%, (95% CI 21–33%) if the cumulative rainfall for the prior week was at the 75th percentile (or 22 mm)”. In contrast, a study in Brisbane, Australia found no association between rainfall and monthly cryptosporidiosis incidence (Hu *et al.* 2007). Similarly, Lake *et al.* (2008) did not find an association between rainfall and cryptosporidiosis in New Zealand. However, this study analysed the relationship at the national level using nationally aggregated climate data, which may not have reflected the geographic variation in rainfall exposure in New Zealand. Both Hu *et al.* (2007) and Lake *et al.* (2008) found that temperature was positively associated with cryptosporidiosis rates.

The relationship between giardiasis and climate variability has not previously been investigated in New Zealand. Specific international literature on this topic is also limited. In one study giardiasis was found to be more prevalent in the rainy season in Mexico compared to the dry season (Cifuentes *et al.* 2004). In another study, in Massachusetts, rates of giardiasis were reported to peak approximately one month after a peak in temperature (Naumova *et al.* 2007). Positive associations between water-borne disease outbreaks and heavy rainfall events have been found in three other recent studies and giardiasis is one of the most common waterborne diseases (Rose *et al.* 2000; Curriero *et al.* 2001; Thomas *et al.* 2006).

The IPCC has projected that climate change will lead to increasing temperatures, rising sea levels and an increase in the severity and frequency of extreme rainfall events, floods and droughts (IPCC 2007). Consequently, climate change is likely to affect the transmission of infectious diseases, including water-borne enteric infections (IPCC 2007). Therefore it is particularly important to have a better

understanding of the relationships between climate variability and water-borne enteric diseases. Any increase in enteric disease burden due to climate change would have major public health significance in developing countries.

There is a marked geographic variation in climate in New Zealand, (Mackintosh 2001) which allows for the relationship between climate variability and disease to be analysed spatially. The purpose of this study was therefore to investigate the spatial relationships between rainfall and ambient temperature and notifications of cryptosporidiosis and giardiasis in New Zealand over the 10-year period 1997 to 2006.

METHODS

The geographical level of analysis chosen for this study was the census area unit (CAU). CAUs are statistically defined areas that are comparable in size and distribution with the other environmental exposures of interest in this analysis.

Outcome data

The outcomes of interest in this study were the total cryptosporidiosis and giardiasis notification counts during 1997–2006 for each CAU in New Zealand. The geocoded outcome data were obtained from the national notifiable disease surveillance system, provided by the Institute of Environmental Science and Research Ltd (ESR).

Exposure data

The climate data for each CAU were derived from mathematical surfaces fitted to long run average climate station data for New Zealand for the period 1950–1980 (Leathwick *et al.* 2002b). The variable used in this analysis to represent rainfall was the average annual rainfall to evaporation ratio. This measure was used as an indicator of runoff into water sources (Leathwick *et al.* 2002a). Elevation, geographic coordinates and the relationship between the westerly winds and topography were used in fitting the rainfall surface. Monthly evaporation was calculated using the estimates of daily averaged temperature and daily solar radiation (Leathwick *et al.* 2002a).

Non-climatic factors may also affect the rates of protozoan disease, such as the quality of water treatment (Duncanson *et al.* 2000; Naumova *et al.* 2000), socio-economic deprivation (Naumova *et al.* 2000) and urban-rural status (Snel *et al.* 2009c). Therefore, the spatial patterns of these environmental factors and their potential influence on the rainfall/protozoan relationship were also examined in this study.

To classify the water quality of each CAU, a simplified version of the New Zealand Ministry of Health water distribution zone grading system was created, using the data for 1996. A water distribution zone is part of a water supply network, within which all consumers should receive drinking water of similar quality. Water within a distribution zone is supplied to all consumers from a similar source, with the same treatment. A small community will usually have a single water distribution zone, while larger towns and cities may have multiple zones. Each distribution zone serving 500 or more people has a public health grading, one for its treatment plant and source quality and one for its distribution quality (ESR (Institute of Environmental Science and Research Ltd) 2004). In our simplified classification system, water supplies with grades “A” or “a” were classified as best quality and grades “B–E” or “b–e” were classified as poorer quality. Ungraded water supplies were classified as of unknown quality. Areas that did not have a reticulated community water supply were referred to as areas with “no water supply”. The grading is an assessment of confidence in the risk to public health from the supply. Unsatisfactory gradings may reflect poor water quality, but also inadequate monitoring of water supplies or a risk of sudden deterioration, such as might occur with an unprotected water catchment or with a poorly maintained reticulation system. To reflect this vulnerability, ungraded supplies or distribution zones were attributed the highest level of risk (Hales *et al.* 2003).

CAUs were classified as urban or rural, using the version of the Statistics New Zealand urban/rural profile classification system that is based on population density (Statistics New Zealand Aotearoa 2008). A simplified version of the NZDep2001 classification was used to analyse the influence of deprivation. NZDep2001 is an index of deprivation in small areas, which is derived

from factor analysis using census variables relevant to social and material deprivation (Salmond & Crampton 2002). In our study NZDep2001 categories 1–5 were classed as socioeconomically advantaged and NZDep2001 categories 6–10 were classed as socioeconomically deprived.

Analytic methods

We imported maps of CAU boundaries, protozoan disease notifications, average temperature, rainfall, water distribution zones, rurality and socioeconomic deprivation into a Geographic Information System (GIS). Climate and water quality data were summarized within the CAU boundaries and exported to a statistical package for regression analysis. A negative binomial regression model was chosen in order to account for over-dispersion. This model was compared with other count models using the Stata countfit test and was assessed as being the best model for the data. The correlation coefficients between the water supply distribution and source quality grades ranged between 0.62 (poorer quality), 0.83 (unknown quality) and 1 (no community reticulated water supply). The effect of water source quality and water distribution quality had to therefore be analysed in separate models to avoid multicollinearity. Subsequently for both cryptosporidiosis and giardiasis there were two multivariate regression models created. The *source* model included variables for the rainfall to evaporation ratio, temperature and indicator variables for urban/rural, deprivation and water supply *source* quality. The *distribution* model included variables for the rainfall to evaporation ratio, temperature and indicator variables for urban/rural, deprivation and water supply *distribution* quality.

RESULTS

Descriptive characteristics of CAUs

Tables 1 and 2 display the sample characteristics of the 1713 CAUs included in the analysis. Missing data meant that 131 (7.1%) CAUs were excluded. However, these CAUs had very small populations or were unpopulated islands or harbours and so their exclusion was unlikely to affect the overall results. The mean notification count per CAU was 5 for cryptosporidiosis and just under 10 for giardiasis over the 10-year period of interest, with considerable variability between CAUs.

Geographical analysis

Inspection of the GIS maps suggested that cryptosporidiosis and giardiasis notifications were more frequent in rural areas and in the South Island. The cryptosporidiosis map is presented in Figure 1. Several areas were also identified that appeared to have high rainfall to evaporation ratios and high levels of protozoan disease notifications. A substantial number of CAUs in New Zealand did not have a reticulated community water supply, and many of the water supplies had poor quality gradings. Many of the areas that did not have the best quality water supply appeared to correspond to areas with high rates of protozoan disease notification.

Regression analysis

The results of the regression analyses are displayed in Tables 3 and 4. An increased rainfall to evaporation ratio was associated with increased rates of both cryptosporidiosis and giardiasis notifications. This association was found to be significant in the unadjusted univariate analysis

Table 1 | Descriptive Characteristics of 1713 Census Area Units in New Zealand (continuous variables)

Variable	Mean	SD	Range
Total population of CAU	2178.69	1519.36	6–8820
Cryptosporidiosis (counts over ten years)	4.77	9.58	0–140
Giardiasis (counts over ten years)	9.41	15.31	0–218
Average annual rainfall evaporation ratio	28.08	16.03	8.56–189.60
Average annual temperature (°C)	12.69	1.80	5.65–15.91

Table 2 | Descriptive Characteristics of 1713 Census Area Units in New Zealand (categorical variables)

Variable	Percentage of CAUs
<i>Rurality</i>	
Urban	73.5%
Rural	26.5%
<i>Deprivation</i>	
Socioeconomically advantaged	50.1%
Socioeconomically deprived	49.9%
<i>Water supply source quality</i>	
No community reticulated water supply	25.5%
Best quality water supply source	28.1%
Poorer quality water supply source	34.3%
Unknown quality water supply source	12.1%
<i>Water supply distribution quality</i>	
Best quality water supply distribution	25.8%
Poorer quality water supply distribution	32.0%
Unknown quality water supply distribution	16.6%

[cryptosporidiosis IRR 1.03, 95% CI 1.021, 1.029; giardiasis IRR 1.02, 95% CI 1.016, 1.024] and remained significant after adjusting for temperature, rurality, deprivation and water supply grading, [cryptosporidiosis (source model) IRR 1.01, 95% CI 1.005, 1.014; cryptosporidiosis (distribution model) IRR 1.01, 95% CI 1.004, 1.013; giardiasis (both models) IRR 1.02, 95% CI 1.013, 1.022].

The average annual temperatures ranged in our study between 5.65 and 15.91°C. In the univariate analysis, an increase in mean ambient temperature was associated with a decrease in rates of both cryptosporidiosis and giardiasis at the CAU level. The negative association remained significant for cryptosporidiosis rates in the multivariate analysis [cryptosporidiosis (source model) IRR 0.98, 95% CI 0.977, 0.986; cryptosporidiosis (distribution model) IRR 0.98, 95% CI 0.975, 0.984]. However, the association between temperature and giardiasis rates became weakly positive in the multivariate model, which was not significant in the source model and only reached borderline significance in the distribution model [giardiasis (distribution model) IRR 1.004, 95% CI 1.0001, 1.007].

In the multivariate analysis, rural CAUs had rates of cryptosporidiosis that were 1.8 times higher than urban CAUs [cryptosporidiosis (source model) $p < 0.001$, 95% CI 1.532, 2.126; cryptosporidiosis (distribution model)

$p < 0.001$, 95% CI 1.548, 2.145]. A separate analysis of this association using an expanded urban/rural classification system identified that there was a dose-response relationship, with increasing rurality associated with increasing rates of cryptosporidiosis. In contrast, the urban/rural classification was not significantly associated with giardiasis in the multivariate analysis. Across all models it was consistently found that CAUs that were classified as socioeconomically advantaged had higher rates of notified cryptosporidiosis and giardiasis compared to CAUs that were socioeconomically deprived.

CAUs with no water supplies had higher rates of both cryptosporidiosis and giardiasis compared with the CAUs with the best quality water supply (although the increase was not significant in the giardiasis distribution model). Notably the rate of cryptosporidiosis in the multivariate analysis was 1.33 times higher in CAUs with no water supply compared to those with the best quality source for their water supply

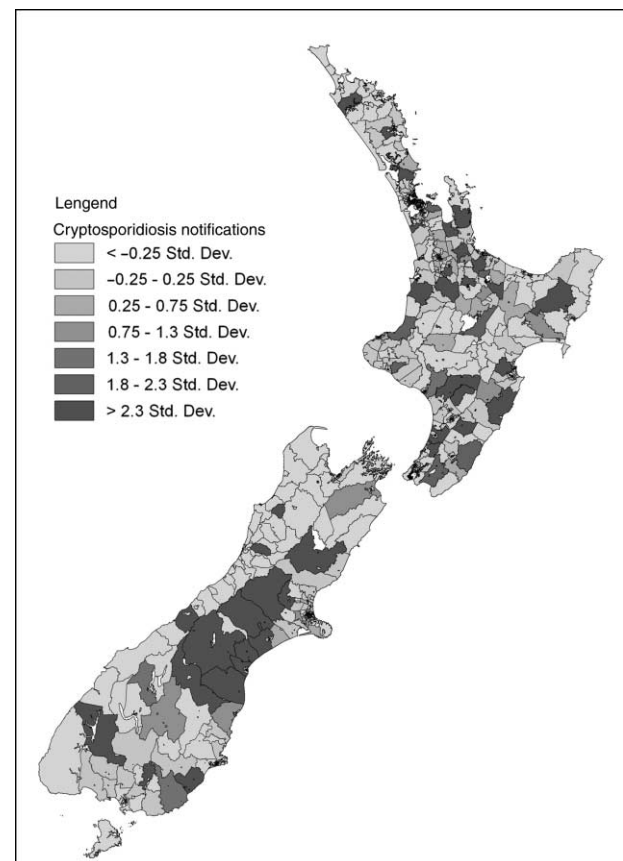
**Figure 1** | Map of cryptosporidiosis notifications per CAU during 1997–2006 in New Zealand.

Table 3 | Univariate and multivariate incidence rate ratios for cryptosporidiosis and selected environmental variables at the CAU level in New Zealand

Variable	Univariate analysis	Multivariate analysis	
		Source ^a	Distribution ^b
Rainfall	1.03(1.021, 1.029) ^{c†}	1.01(1.005, 1.014) [†]	1.01(1.004, 1.013) [†]
Temperature	0.97(0.966, 0.973) [†]	0.98(0.977, 0.986) [†]	0.98(0.975, 0.984) [†]
Rural compared to urban	3.14(2.732, 3.606) [†]	1.80(1.532, 2.126) [†]	1.82(1.548, 2.145) [†]
SE ^d deprived compared to SE advantaged	0.58(0.508, 0.661) [†]	0.77(0.687, 0.869) [†]	0.78(0.694, 0.879) [†]
No water supply compared to best quality water supply source	3.24(2.712, 3.858) [†]	1.33(1.097, 1.608) [†]	
Poorer quality compared to best quality water supply source	2.20(1.879, 2.573) [†]	1.29(1.098, 1.520) [†]	
Unknown quality compared to best quality water supply source	1.67(1.351, 2.069) [†]	0.85(1.098, 1.520)	
No water supply compared to best quality water supply distribution	2.62(2.181, 3.147) [†]		1.21(1.0003, 1.462) [*]
Poorer quality compared to best quality water supply distribution	1.54(1.305, 1.824) [†]		1.10(0.944, 1.290)
Unknown quality compared to best quality water supply distribution	1.42(1.162, 1.727) [†]		0.86(0.707, 1.038)

^aIncluded variables for rainfall to evaporation ratio, temperature, and indicator variables for urban/rural, deprivation and water supply source quality.

^bIncluded variables for rainfall to evaporation ratio, temperature, and indicator variables for urban/rural, deprivation and water supply distribution quality.

^c95% CI in parentheses.

^dSE = Socioeconomic.

^{*} $p < 0.05$.

[†] $p < 0.001$.

[cryptosporidiosis (source model) $p < 0.001$, 95% CI 1.097–1.608]. CAUs with poorer quality water supply sources had significantly higher rates of cryptosporidiosis compared to CAUs with water supplies that had the best quality source. There was no association for cryptosporidiosis with the quality of water supply distribution.

Conversely for giardiasis, water supplies with poorer quality distribution had significantly lower rates of giardiasis notifications compared to CAUs with the best quality water supply distribution. There was no association for giardiasis with the quality of water supply source.

The regression models were rerun restricted within subgroups of water quality. This was to determine whether the rainfall to evaporation ratio or other variables had a different effect on cryptosporidiosis or giardiasis rates within CAUs with different water source quality or distribution quality. One of the key findings from this analysis was that the effect of rainfall on cryptosporidiosis risk was modified by characteristics of the local water supply. Within CAUs with the best graded water supply source, for every one unit increase in the rainfall to

evaporation ratio the cryptosporidiosis rate was predicted to decrease by 0.96 [95% CI 0.939, 0.988]. Among CAUs with no water supply, for a one unit increase in the rainfall to evaporation ratio the cryptosporidiosis rate was predicted to increase by 1.02 [95% CI 1.009, 1.025]. There was no significant variation in the effect of rainfall across categories of water source for giardiasis.

The effect of interaction between the rainfall to evaporation ratio and water supply quality on giardiasis and cryptosporidiosis rates was also tested in subsequent models. However, the results were not used in this analysis as the inclusion of this interaction doubled to quadrupled the standard errors, indicating multicollinearity.

DISCUSSION

Key findings

A higher rainfall to evaporation ratio was associated with increased rates of both cryptosporidiosis and giardiasis

Table 4 | Univariate and multivariate incidence rate ratios for giardiasis and selected environmental variables at the CAU level in New Zealand

Variable	Univariate analysis	Multivariate analysis	
		Source ^a	Distribution ^b
Rainfall	1.02(1.016, 1.024) ^{c†}	1.02(1.013, 1.022) [†]	1.02(1.013, 1.022) [†]
Temperature	0.99(0.991, 0.997) [†]	1.003(0.999, 1.007)	1.004(1.0001, 1.007) [*]
Rural compared to urban	1.58(1.392, 1.788) [†]	1.12(0.963, 1.310)	1.13(0.966, 1.313)
SE deprived compared to SE advantaged	0.73(0.654, 0.812) [†]	0.75(0.673, 0.832) [†]	0.74(0.669, 0.826) [†]
No water supply compared to best quality water supply source	1.54(1.329, 1.788) [†]	1.22(1.023, 1.445) [*]	
Poorer quality compared to best quality water supply source	0.89(0.778, 1.016)	0.91(0.780, 1.051)	
Unknown quality compared to best quality water supply source	0.92(0.766, 1.099)	0.98(0.800, 1.201)	
No water supply compared to best quality water supply distribution	1.48(1.269, 1.717) [†]		1.18(0.998, 1.400)
Poorer quality compared to best quality water supply distribution	0.82(0.717, 0.946) [†]		0.85(0.740, 0.978) [*]
Unknown quality compared to best quality water supply distribution	0.88(0.743, 1.033)		0.95(0.797, 1.136)

^aIncluded variables for rainfall to evaporation ratio, temperature, and indicator variables for urban/rural, deprivation and water supply source quality.

^bIncluded variables for rainfall to evaporation ratio, temperature, and indicator variables for urban/rural, deprivation and water supply distribution quality.

^c95% CI in parentheses.

^{*} $p < 0.05$.

[†] $p < 0.001$.

notifications at the CAU level between 1997–2006 in New Zealand. This association was found to be significant in the unadjusted univariate analysis and remained significant after adjusting for temperature, rurality, deprivation and water supply grading. This result is consistent with the findings of Naumova *et al.* (2005) in North West England. However, a previous study did not find an association between rainfall and cryptosporidiosis in New Zealand (Lake *et al.* 2008). That study analysed the temporal relationship at the national level, so could not take into account the geographic variation in climate occurring at the much finer CAU level of analysis we have reported here.

The negative association between temperature and cryptosporidiosis was significant in the univariate and multivariate analysis, which suggests that a higher mean ambient temperature could be protective against cryptosporidiosis. This result is consistent with the laboratory findings of Ives *et al.* (2007) who demonstrated that higher temperatures were associated with increased rates of inactivation of cryptosporidiosis (comparing temperatures

of 30°C, 22°C and 5°C). However, Hu *et al.* (2007) and Lake *et al.* (2008) found positive temporal associations between temperature and cryptosporidiosis.

Urban/rural status was a strong predictor of cryptosporidiosis in both the univariate and multivariate regression analyses. Similar results have previously been found in a geographical analysis of cryptosporidiosis rates in New Zealand (Snel *et al.* 2009b). However, the urban/rural classification was not significantly associated with giardiasis in the multivariate analysis, a finding which is also consistent with previous New Zealand analyses (Snel *et al.* 2009a). The differences in results between these two protozoan diseases might be explained by differences in transmission pathways. Cryptosporidiosis can be transmitted by infected animals such as cattle and sheep (zoonotic), whereas giardiasis is more likely to be transmitted by an infected human or by human sewage (anthroponotic) (Heymann 2004; Snel *et al.* 2009a,b,c). This difference in the relative importance of human and animal reservoirs may explain why rurality is associated with higher cryptosporidiosis rates but not giardiasis rates.

The finding, that CAUs classified as socioeconomically advantaged had higher rates of notified cryptosporidiosis and giardiasis, is similar to the results of a previous geographical analysis of giardiasis and cryptosporidiosis rates in New Zealand (Snel *et al.* 2009a,b,c). This finding could suggest that living in a socioeconomically deprived CAU is a protective factor against cryptosporidiosis and giardiasis. However, the use of notification data may be less likely to identify cases of disease in deprived areas, because the population in these areas may be less likely to access health care and laboratory testing services when they have a diarrhoeal illness (for a variety of reasons including transport barriers). Previous analyses of giardiasis and cryptosporidiosis found that people hospitalised with these diseases showed the more familiar gradient of higher rates for those from the socioeconomically deprived areas (Snel *et al.* 2009a,b).

CAUs with no reticulated community water supply were found to have higher rates of both cryptosporidiosis and giardiasis compared with the CAUs with the best quality water supply, in both the univariate and multivariate models. This association was stronger for cryptosporidiosis than giardiasis and was not significant in the giardiasis *distribution* model. Within the CAUs that had the best quality water supply *source*, an increase in the rainfall to evaporation ratio was associated with a significantly reduced rate of cryptosporidiosis. This finding suggests that the CAUs with the best quality water supply *source* are better protected against the effects of rainfall on rates of cryptosporidiosis.

CAUs with poorer quality water supply *sources* had significantly higher rates of cryptosporidiosis compared to CAUs with water supplies that had the best quality *source*. However, in both univariate and multivariate analysis, water supplies with poorer quality *distribution* had significantly lower rates of giardiasis notifications compared to CAUs with the best quality water supply *distribution*. This is a counter-intuitive result, which is difficult to explain. However, it may potentially be due to reporting bias. Areas with the best quality water may also be areas where the population may have better access to health care and subsequently may have higher notification rates (although, this is not the pattern seen for cryptosporidiosis).

Limitations and strengths

Notification data were used to identify those with the outcome of interest and this inevitably underestimated disease occurrence in the community. This source of data only includes those who sought medical attention from a doctor, were investigated using the correct laboratory tests, and who were subsequently notified to the medical officer of health. The reporting pyramid means that only a small fraction of community cases of enteric disease are ultimately reported to national surveillance agencies (Wheeler *et al.* 1999). These surveillance effects could have biased the results as they are likely to vary between areas of New Zealand. They could also have contributed systematic underestimation of disease rates within the more deprived or more rural CAUs due to the cost or accessibility of health care. Spatial autocorrelation was not adjusted for in the analysis so there is the potential that this may have affected the estimation of the standard errors.

A strength of this study was that it analysed environmental exposures with outcomes at the CAU level, instead of the national level, which enabled it to take into account the geographic variation in exposures across New Zealand. However, it is important to note that even at this more homogenous level, aggregated data may not accurately describe individual exposure, (ecological fallacy) (Beale *et al.* 2008). Additionally, in analysing spatial data, changes in the size and shape of the areal units used could affect the analysis (Modifiable Areal Unit Problem) (Beale *et al.* 2008). Misclassification of exposure could have occurred due to the CAU being incorrectly recorded in the notification data, which has been found to be an issue especially in rural areas (Skelly *et al.* 2002). The climate data did not cover the specific time period of the disease outcome data. However, the climate data used were derived from thirty years of data for each CAU, so is likely to represent an accurate picture of the spatial pattern of exposure within CAUs.

Confounding

It was not possible to control for all potential confounders at the population level. However, this study was analysing long-term spatial patterns of disease and long-term climatic

and environmental factors, so factors that varied in the short term, such as seasonal factors, could not have confounded the results. Nevertheless there were some potential confounders that were not controlled for in this analysis. Snel *et al.* (2009a,b,c) found that, in New Zealand, rates of cryptosporidiosis and giardiasis were higher in children and in those of New Zealand European ethnicity. Unfortunately, for this study the demographic information was not available for the cryptosporidiosis and giardiasis notification data, and so the potential confounders of age, gender and ethnicity were not able to be included in the model.

CONCLUSIONS

A key strength of this study is that the associations are based on long-term observations, which increases the applicability of the results to the gradual effects of climate change. Global climate change is projected to increase the amount of rainfall in the western and southern parts of New Zealand, with an increase in the frequency of heavy rainfall in the west (Hennessy *et al.* 2007). Therefore, if the associations found in this study are causal, other things being equal, this study suggests that CAUs in these areas may experience increased rates of cryptosporidiosis and giardiasis due to climate change. However, CAUs with higher average temperatures had reduced rates of cryptosporidiosis and temperature is projected to increase due to climate change (Hennessy *et al.* 2007). Therefore these results suggest that the overall effect of climate change on cryptosporidiosis notifications may follow a complex spatial pattern in New Zealand, as the projected increase in temperature and increase in rainfall may have opposing effects.

Rural CAUs and CAUs that do not have a water supply were found in this study to have higher rates of cryptosporidiosis and giardiasis notifications. The results of this study also suggest that having the best quality water supply could be protective against the effects of increased rainfall on rates of cryptosporidiosis at the CAU level. These findings have implications for public health planning and climate change adaptation strategies. They suggest that improving CAU water supply quality in New Zealand, especially in rural

areas, could be a method of reducing vulnerability to the impact of climate change on protozoan diseases. Even without the effects of climate change, our findings provide support for increasing the provision of community reticulated water supplies as a strategy to lower rates of these enteric diseases.

ETHICS APPROVAL

The study protocol was approved by the Multi-region Ethics Committee, Ministry of Health, Wellington, New Zealand, which is constituted and operates in accordance with the Operational Standard for Ethics Committees, on May 1 2008. The ethics committee did not require us to obtain informed consent, as it was an ecological observational study.

ACKNOWLEDGEMENTS

New Zealand Population Health Charitable Trust, University of Otago, Institute of Environmental Science and Research Ltd (ESR).

REFERENCES

- Arnone, R. D. & Walling, J. P. 2006 Evaluating *Cryptosporidium* and *Giardia* concentrations in combined sewer overflow. *J. Water Health* 4(2), 157–165.
- Atherholt, T. B., Le Chavallier, M. & Rosen, J. S. 1998 Effect of rainfall on *Giardia* and *Cryptosporidium*. *J. Am. Water Works Assoc.* 90, 66–80.
- Beale, L., Abellan, J., Hodgson, S. & Jarup, L. 2008 Methodologic issues and approaches to spatial epidemiology. *Environ. Health Perspect.* 116(8), 1105–1110.
- Bryce, J., Boschi-Pinto, C., Shibuya, K. Black, R. & WHO Child Health Epidemiology Reference Group 2005 WHO estimates of the causes of death in children. *Lancet* 365(9465), 1147–1152.
- Cifuentes, E., Suarez, L., Espinosa, M., Juarez-Figueroa, L. & Martinez-Palomo, A. 2004 Risk of *Giardia* Intestinalis infection in children from an artificially recharged groundwater area in Mexico city. *Am. J. Trop. Med. Hyg.* 71(1), 65–70.
- Crump, J. A., Murdoch, D. R. & Baker, M. G. 2001 Emerging infectious diseases in an island ecosystem: the New Zealand perspective. *Emerg. Infect. Dis.* 7(5), 767–772.

- Curriero, F. C., Patz, J. A., Rose, J. B. & Lele, S. 2001 The association between extreme precipitation and waterborne disease outbreaks in the United States, 1948–1994. *Am. J. Public Health* **91**(8), 1194–1199.
- Duncanson, M., Russell, N., Weinstein, P., Baker, M., Skelly, C., Hearnden, M. & Woodward, A. 2000 Rates of notified cryptosporidiosis and quality of drinking water supplies in Aotearoa, New Zealand. *Water Res.* **34**(15), 3804–3812.
- ESR (Institute of Environmental Science and Research Ltd) 2004 *Drinking water for New Zealand*. Available online: <http://www.drinkingwater.co.nz/default.asp>. Accessed March 29, 2008.
- Goldsmid, J. M., Speare, R. & Bettiol, S. 2005 The parasitology of foods. In *Foodborne Micro-Organisms of Public Health Significance* (ed. A. Hocking), pp. 705–720. Southwood Press Pty Limited, Marrickville.
- Guerrant, R. L. 1997 Cryptosporidiosis: an emerging highly infectious threat. *Emerg. Infect. Dis.* **3**(1), 51–57.
- Hales, S., Black, W., Skelly, C., Salmond, C. & Weinstein, P. 2005 Social deprivation and the public health risks of community drinking water supplies in New Zealand. *J. Epidemiol. Commun. Health* **57**(8), 581.
- Hennessy, K. B., Fitzharris, B. C., Bates, N., Harvey, S. M., Howden, L., Hughes, J., Salinger, J. & Warrick, R. 2007 Australia and New Zealand. In *Climate Change 2007: Impacts, Adaptation and Vulnerability: Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (ed. M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden & C. E. Hanson), pp. 507–540. Cambridge University Press, Cambridge.
- Heymann, D. L. (ed.) 2004 *Control of Communicable Diseases Manual*, 18th edition, American Public Health Association, Washington.
- Hoque, E., Hope, V., Scragg, R., Baker, M. & Shrestha, R. 2004 A descriptive epidemiology of giardiasis in New Zealand. *N. Z. Med. J.* **117**(1205), U1149.
- Hu, W., Tong, S., Mengersen, K. & Connell, D. 2007 Weather variability and the incidence of cryptosporidiosis: comparison of time series Poisson regression and SARIMA models. *Ann. Epidemiol.* **17**, 679–688.
- Institute of Environmental Science and Research Ltd (ESR) 2008 *Notifiable and other diseases in New Zealand: Annual report 2007*. ISSN: 1176-6220. Institute of Environmental Science and Research Limited (ESR), Wellington.
- IPCC (Intergovernmental Panel on Climate Change) 2007 *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds. Core Writing Team, R. K. Pachauri & A. Reisinger). IPCC, Geneva, Switzerland.
- Ives, R. L., Kamarainen, A. M., John, D. E. & Rose, J. B. 2007 Use of cell cultures to assess *Cryptosporidium parvum* survival in natural ground waters and surface waters. *Am. Soc. Microbiol.* **73**(18), 5968–5970.
- Lake, I. R., Bentham, G., Kovats, R. S. & Nichols, G. L. 2005 Effects of weather and river flow on cryptosporidiosis. *J. Water Health* **3**, 469–474.
- Lake, I. R., Pearce, J. & Savill, M. 2008 The seasonality of human cryptosporidiosis in New Zealand. *Epidemiol. Infect.* **136**(10), 1383–1387.
- Leathwick, J. R., Morgan, F., Wilson, G., Rutledge, D., Mcleod, M. & Johnston, K. 2002a *Land environments of New Zealand. Nga Taiao o Aotearoa. Technical guide*. Ministry for the Environment.
- Leathwick, J. R., Wilson, G. & Stephens, R. T. T. 2002b *Climate Surfaces for New Zealand. Landcare Research Contract Report LC9798/126*. Hamilton: Landcare Research NZ Ltd.
- MacKenzie, W., Hoxie, N. J., Proctor, M., Gradus, M. S., Blair, K., Peterson, D. E., Kazmierczak, J. J., Addiss, D. G., Fox, K. R., Rose, J. B. & Davis, J. P. 1994 A massive outbreak in Milwaukee of *Cryptosporidium* infection transmitted through the public water supply. *N. Engl. J. Med.* **331**, 161–167.
- Mackintosh, L. 2001 *Overview of New Zealand Climate*. Available online: <http://www.niwa.cri.nz/edu/resources/climate/overview>. Accessed December 8, 2008.
- Miller, W., Lewis, D. J., Lennox, M., Pereira, M., Tate, K. W., Conrad, P. & Atwill, E. R. 2007 Climate and on-farm risk factors associated with *Giardia duodenalis* cysts in storm runoff from California coastal dairies. *Appl. Environ. Microbiol.* **73**(21), 6972–6979.
- Nachamkin, I., Allos, B. & Ho, T. 1998 Campylobacter species and Guillain-Barré syndrome. *Clin. Microbiol. Rev.* **11**(3), 555–567.
- Naumova, E. N., Chen, J. T., Griffiths, J. K., Matyas, B. T., Estes-Smargiassi, S. & Morris, R. D. 2000 Use of passive surveillance data to study temporal and spatial variation in the incidence of giardiasis and cryptosporidiosis. *Public Health Rep.* **115**, 115–447.
- Naumova, E. N., Christodouleas, J., Hunter, P. R. & Syed, Q. 2005 Effect of precipitation on seasonal variability in cryptosporidiosis recorded by the North West England surveillance system in 1990–1999. *J. Water Health* **3**(2), 185–196.
- Naumova, E. N., Jagai, J. S., Matyas, B. T., DeMaria, A., Jr, MacNeill, I. B. & Griffiths, J. K. 2007 Seasonality in six enterically transmitted diseases and ambient temperature. *Epidemiol. Infect.* **135**, 281–292.
- Rose, J. B. 1997 Environmental ecology of *Cryptosporidium* and public health implications. *Annu. Rev. Public Health* **18**, 135–161.
- Rose, J. B., Daeschner, S., Easterling, D. R., Curriero, F. C., Lele, S. & Patz, J. A. 2000 Climate and waterborne disease outbreaks. *J. Am. Water Works Assoc.* **92**(9), 77–87.
- Rose, J. B., Epstein, P. R., Lipp, E. K., Sherman, B. H., Bernard, S. M. & Patz, J. A. 2001 Climate variability and change in the United States: potential impacts on water and foodborne diseases caused by microbiologic agents. *Environ. Health Perspect.* **109**(S2), 211–221.

- Salmond, C. & Crampton, P. 2002 *NZDep2001 Index of deprivation user's manual*. Available online: [http://www.moh.govt.nz/moh.nsf/Files/phi-users-manual/\\$file/phi-users-manual.pdf](http://www.moh.govt.nz/moh.nsf/Files/phi-users-manual/$file/phi-users-manual.pdf). Accessed March 29, 2008.
- Skelly, C., Black, W., Hearnden, M., Eyles, R. & Weinstein, P. 2002 Disease surveillance in rural communities is compromised by address geocoding uncertainty: a case study of campylobacteriosis. *Aust. J. Rural Health* **10**, 87–93.
- Snel, S., Baker, M. & Venugopal, K. 2009a The epidemiology of giardiasis in New Zealand, 1997–2006. *N. Z. Med. J.* **122**(1290), 62–75.
- Snel, S., Baker, M. & Venugopal, K. 2009b The epidemiology of cryptosporidiosis in New Zealand, 1997–2006. *N. Z. Med. J.* **122**(1290), 47–61.
- Snel, S. J., Baker, M. G., Venugopal, K., French, N. & Learmonth, J. 2009c A tale of two parasites: the comparative epidemiology of cryptosporidiosis, giardiasis in New Zealand 1997–2006. *Epidemiol. Infect.* **137**(11), 1641–1650.
- Statistics New Zealand Aotearoa 2008 *New Zealand: an urban/rural profile*. Available online: <http://www.stats.govt.nz/urban-rural-profiles/default.htm>. Accessed March 28, 2008.
- Thomas, M. K., Charron, D. F., Waltner-Toews, D., Schuster, C., Maarouf, A. R. & Holt, J. D. 2006 A role of high impact weather events in waterborne disease outbreaks in Canada, 1975–2001. *Int. J. Environ. Health Res.* **16**(3), 167–180.
- Thurston-Enriquez, J. A., Gilley, J. E. & Eghball, B. 2005 Microbial quality of runoff following land application of cattle manure and swine slurry. *J. Water Health* **3**, 157–171.
- Wheeler, J. G., Sethi, D., Cowden, J., Wall, P. G., Rodrigues, L. C., Tompkins, D. S., Hudson, M. J. & Roderick, P. J. 1999 Study of infectious intestinal disease in England: rates in the community, presenting to general practice, and reported to national surveillance. *BMJ.* **318**, 1046–1050.
- WHO (World Health Organization) 2003 *Water-related diseases*. Available online: http://www.who.int/water_sanitation_health/diseases/diarrhoea/en/. Accessed November 8, 2008.
- WHO (World Health Organization) 2000 *Global water supply and sanitation assessment 2000 Report*. Available online: http://www.who.int/docstore/water_sanitation_health/Global1.htm#1.1. Accessed November 8, 2008.

First received 15 March 2009; accepted in revised form 21 December 2009. Available online 9 March 2010