Associations between extreme precipitation and acute gastro-intestinal illness due to cryptosporidiosis and giardiasis in an urban Canadian drinking water system (1997–2009)

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ABSTRACT

Drinking water related infections are expected to increase in the future due to climate change. Understanding the current links between these infections and environmental factors is vital to understand and reduce the future burden of illness. We investigated the relationship between weekly reported cryptosporidiosis and giardiasis ($n = 7{,}422$), extreme precipitation ($>$90th percentile), drinking water turbidity, and preceding dry periods in a drinking water system located in greater Vancouver, British Columbia, Canada (1997–2009) using distributed lag non-linear Poisson regression models adjusted for seasonality, secular trend, and the effect of holidays on reporting. We found a significant increase in cryptosporidiosis and giardiasis 4–6 weeks after extreme precipitation. The effect was greater following a dry period. Similarly, extreme precipitation led to significantly increased turbidity only after prolonged dry periods. Our results suggest that the risk of cryptosporidiosis and giardiasis increases with extreme precipitation, and that the effects are more pronounced after a prolonged dry period. Given that extreme precipitation events are expected to increase with climate change, it is important to further understand the risks from these events, develop planning tools, and build resilience to these future risks.

Key words | climate change, diarrhea, extreme precipitation, water-borne illness

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INTRODUCTION

Despite continual improvements in water treatment infrastructure and analytical monitoring techniques in developed countries such as Canada, water-borne enteric disease continues to be an important public health concern (Schuster *et al.* 2005). Every year, about 90,000 illnesses and 90 deaths result from the consumption of unsafe drinking water in

doi: 10.2166/wh.2017.100

Canada (Christensen 2006). Historically, the province of British Columbia (BC) has had a high rate of water-borne disease; there were 29 water-borne disease outbreaks from 1980 to 2000, many of which resulted from water system failures or the absence of adequate treatment (British Columbia Provincial Health Officer 2001). *Cryptosporidium* and *Giardia* are two important acute gastrointestinal (AGI) pathogens threatening drinking water supplies especially due to their resistance to common water treatments (Federal-Provincial-Territorial Committee on Water and Canadian Council of Ministers of the Environment 2004). The average annual BC incidence rates of cryptosporidiosis and giardiasis from 2006 to 2010 were 2.8 and 14.7 per 100,000 population respectively (BC Centre for Disease Control 2013), higher than the national average.

Although weather-related factors such as temperature (Checkley *et al.* 2000), precipitation (Bhavnani *et al.* 2014), and snowmelt (Harper *et al.* 2011) have been associated with sporadic bacterial AGI risk in previous studies, generalization to parasitic water-borne infections is difficult due to non-specific health outcomes considered in these studies. Further, extreme precipitation events have also been implicated in previous water-borne AGI outbreaks in North America (Curriero *et al.* 2001; Auld *et al.* 2004). Comparisons between studies are difficult because multiple diseases may be considered as a single outcome, and there are differences with respect to modeling the weather-related variables. However, studies on more specific outcomes such as cryptosporidiosis and giardiasis report seasonal variability in their incidence, with some evidence of sensitivity to environmental changes such as precipitation (Lake *et al.* 2005; Britton *et al.* 2010; Lal *et al.* 2013). Weekly mean temperatures have also been associated with AGI (Allard *et al.* 2011). Climate change is expected to increase temperature and the frequency and intensity of precipitation in the future (IPCC 2013). Therefore, mitigation and adaptation to climate change requires further assessment of the vulnerability of drinking water system (DWS) to extreme weather events, and the environmental risk factors that are likely to influence sporadic water-borne disease risk in the present and the future.

In this study, we examined the association between major watershed level impacts of extreme precipitation, dry periods, and temperature, and the occurrence of cryptosporidiosis and giardiasis in a large urban center from 1997 to 2009. The study location was selected because of its large population size and readily available data.

METHODS

Study location and study design

We conducted this study in Greater Vancouver, BC, which is located on the temperate west coast of Canada. The study area has a population of more than two million people served by Metro Vancouver DWS. This DWS is a surface water system that receives its water from three reservoirs in protected watersheds known as Capilano, Seymour, and Coquitlam, located in the North Shore Mountains and the Coquitlam Mountain (Supplement – Figure A, available with the online version of this paper). Capilano watershed is the westernmost of the three; Seymour is located east of Capilano; Coquitlam is the easternmost. These watersheds have a combined area of 52,831 hectares and receive approximately 3.5 meters of rain and about 4.5 meters of snow pack at higher elevations annually and experience mild temperatures year-round (Metro Vancouver, 2016). The watersheds are closed to the public with the exception of registered tours. Water is stored year round in the reservoirs, then treated and distributed by the DWS to surrounding municipalities via a network of dams, water mains, pump station, storage reservoirs, and downstream disinfection stations. Each of the reservoirs supplies approximately one third of the population. However, the distribution area and the volume supplied changes according to water quality and operational demand. During our study period (1997–2009), chlorination was the only treatment used in the study DWS with the exception of Coquitlam water treatment plant, where ozonation was added in 2000. Besides watershed protection and water treatment, the DWS also relied on water quality monitoring (including turbidity and fecal coliforms).

We used a time series study design to assess the relationship between extreme precipitation, preceding dry periods, turbidity, and reported cases of cryptosporidiosis and giardiasis in the population served by this DWS. The work was approved by the research ethics board at Simon Fraser University, BC, Canada.

Datasets

All laboratory-confirmed cases of cryptosporidiosis and giardiasis in BC are reported to the BC Centre for Disease Control (BCCDC) (Galanis *et al.* 2014). All cases reported from 01 January, 1997 through 31 December, 2009 in the study area were extracted from the reportable disease database along with their addresses. In addition, we extracted the earliest date available from the following fields: date of onset; date of specimen collection; or date of reporting. Information on travel history and exposure (drinking water or otherwise) is not routinely collected and was not available for this study. There were no documented drinking water-associated outbreaks of cryptosporidiosis and giardiasis during our study period. Cases were geocoded by address of residence at the time of illness using cadastral matching, or by street address range interpolation matching. We then ascertained whether a residence received water from the Metro Vancouver DWS by: (1) matching the residence or land parcel against a reference database developed during a previous study which includes Metro Vancouver water connections (Galanis *et al.* 2014); (2) assuming all Vancouver, Richmond, and North Vancouver land parcels receive Metro Vancouver DWS; and (3) assigning select portions of West Vancouver land parcels to the Metro Vancouver DWS based on municipal documents. Geocoding and spatial data analysis were performed using ArcGIS v. 10.0 (ESRI, Redlands, CA, USA). The total number of cases reported per week was calculated to create a weekly time-series.

Daily temperature (minimum, mean, and maximum °C) and precipitation (mm) data were obtained from the Pacific Climate Impacts Consortium (PCIC) for Seymour reservoir (Supplement – Figure A) during 1997–2009. These data are spatially interpolated at a resolution of 10×10 km using historical daily gridded climate data for Canada (McKenney *et al.* 2011) and based on weather station observations. The interpolated temperature and precipitation data were used rather than actual weather station observations because they approximate the climate station observations (Supplement – Figure B, available online) and allow us to compare them with PCIC climate projections (PCIC 2015) in future work.

Daily precipitation values were aggregated to 7-day cumulative weekly precipitation values, and extreme precipitation events were defined as those exceeding the 90th percentile of the weekly precipitation distribution during the study period. The 90th percentile cutoff was based on previous research and expected increases in source water microbial loads following extreme events (Curriero *et al.* 2001; Kistemann *et al.* 2002; Bush *et al.* 2014). The preceding dry period was calculated as the number of days with precipitation <0.1 mm/day in the previous 60 days. Daily measurements of raw water turbidity data in Nephelometric Turbidity Units (NTU) were obtained from the DWS. The weekly measure of raw water turbidity was defined as the 7-day average NTU.

Statistical analysis

To characterize how recent precipitation was associated with case counts, and whether this relationship differed by the preceding dry period, we used Poisson regression with a distributed lag nonlinear regression model (DLNM) to investigate a range of possible temporal relationships with precipitation (Gasparrini *et al.* 2010). Detailed parameterization of DLNMs is presented in the supplementary material (Supplement – Statistical Model, available online). Traditional lagged regression models impose a rigid, linear combination of past predictors on the association between exposure and outcome. With DLNM, we were able to account for the effect of time using cubic regression splines for a smooth, non-linear function of recent weekly total precipitation amounts going back up to 8 weeks. We set three knots for the regression splines at evenly spaced quantiles of the overall precipitation distribution, and at evenly spaced values of the time lag (up to 8 weeks). This permitted increased spline model flexibility, at the extremes of the precipitation distribution and at the shorter time lags.

We included a weekly precipitation up to a lag of 8 weeks based on the expected delay between precipitation and reporting of AGI, which has ranged from 2 days to 2 months for case reports, outbreaks, and hospitalizations in previous work (Aramini *et al.* 2000; Curriero *et al.* 2001; Thomas *et al.* 2006). The effect of recent temperature was incorporated using a 3-week moving average of weekly mean temperature. Extended dry or wet periods were incorporated using an interaction between precipitation and a dichotomous variable for the preceding consecutive dry period. This was defined as 0 if fewer than 30 of the past

60 days had precipitation <0.1 mm/day, or 1 if 30 or more of the past 60 days had precipitation <0.1 mm/day. To account for seasonality in cryptosporidiosis and giardiasis unrelated to weather, we included sine and cosine terms with annual periods and a cubic spline term with five degrees of freedom per year. To account for differences in reporting and access to healthcare during weeks with public holidays (Allard *et al.* 2011), we included an indicator variable for those weeks. Finally, to account for steady population growth over the study period, we included the logarithm of time. We also investigated the effect of extreme precipitation on turbidity over 6 weeks using DLNM in a linear regression framework. The Population Attributable Risk (PAR) was also calculated to estimate the proportion of cryptosporidiosis and giardiasis in the population that is attributable to extreme precipitation (Gasparrini & Leone 2014).

Numerous models were fitted using quasi-maximum likelihood to select covariates (e.g., temperature) and modeling parameters (e.g., degrees of freedom for spline functions). The best fitting model was determined using the Quasi-Akaike Information Criterion (QAIC) goodness-of-fit statistic. All statistical analyses were carried out in R 3.0.2 (R Core Team 2014) using package dlnm 2.0.6.

RESULTS

A total of 7,422 cases of cryptosporidiosis ($n = 969$) and giardiasis ($n = 6,453$) were reported in the study area during 1997–2009. The number of cases reported per week ranged from 0 to 19, with the highest number of cases reported from July to September (Figure 1(a)). Total weekly precipitation during the study period ranged from 0 to 307 mm per week, with a weekly mean of 41 mm (Figure 1(b)). Precipitation was recorded during 89% of the weeks, with higher precipitation occurring during the fall and winter. The 90th percentile of weekly total precipitation was 95.1 mm for the entire period; the 90th percentiles for the dry (April–September) and rainy (October–March) season were 54 mm/week and 128.4 mm/week respectively. The number of days in the preceding 60 days with precipitation >0.1 mm/day ranged from 3 to 57 with a mean of 29 days (Supplement – Figure C, available with the online version of this paper). Weekly average temperature was 5.8 °C with a range of -5.6 to 25.6 °C. The average turbidity per week ranged from 0.2 to 21.5 NTU with a median of 0.48 NTU (mean: 0.87, Supplement – Figure C).

The best fitting model included variables for holiday weeks, precipitation, season, long-term trend, and the interaction between dry days and precipitation. Temperature did not appear to have a significant impact on reported cases and was dropped from the final model (Table 1). The number of cryptosporidiosis and giardiasis cases reported was lower in weeks with holidays (RR (CI): 0.74 (0.45–0.89)).

Extreme precipitation was significantly associated with increased cryptosporidiosis and giardiasis from 4–6 weeks after extreme precipitation, compared with no precipitation (Figure 2(a)). The relative rates (RR) and their 95% confidence intervals for weeks 4, 5, and 6 were 1.13 (1.01–1.21), 1.17 (1.07–1.23), and 1.15 (1.04–1.18), respectively. There was a significant interaction between precipitation and preceding dry period ($P < 0.02$) (Table 1). Further, the relative effect of extreme precipitation was higher following a 2-month period having ≥30 dry days compared with a 2-month period having <30 dry days (Figure 2(b) and 2(c)). The PAR of cryptosporidiosis and giardiasis due to extreme precipitation was estimated to be 21% (95% CI: 14–27).

The 90th percentile precipitation was associated with increases in turbidity until week 3 (Supplement – Figure D, available online) and the effect of precipitation on turbidity was different by preceding dry period (Supplement – Figure E, available online). When extreme precipitation followed a period with ≥30 dry days, the effect on turbidity was more pronounced compared with extreme precipitation during wetter periods.

DISCUSSION

We examined the association between extreme precipitation and the risk of cryptosporidiosis and giardiasis, and found that extreme precipitation had a significant effect with a lag of 4–6 weeks in a large, urban population served by the DWS. This effect was more pronounced when extreme precipitation followed an extended dry period, after adjusting for seasonality, long-term trends, and delays on reporting due to holidays.

Numerous studies have found associations between high precipitation and AGI outbreaks (Curriero *et al.* 2001; Auld

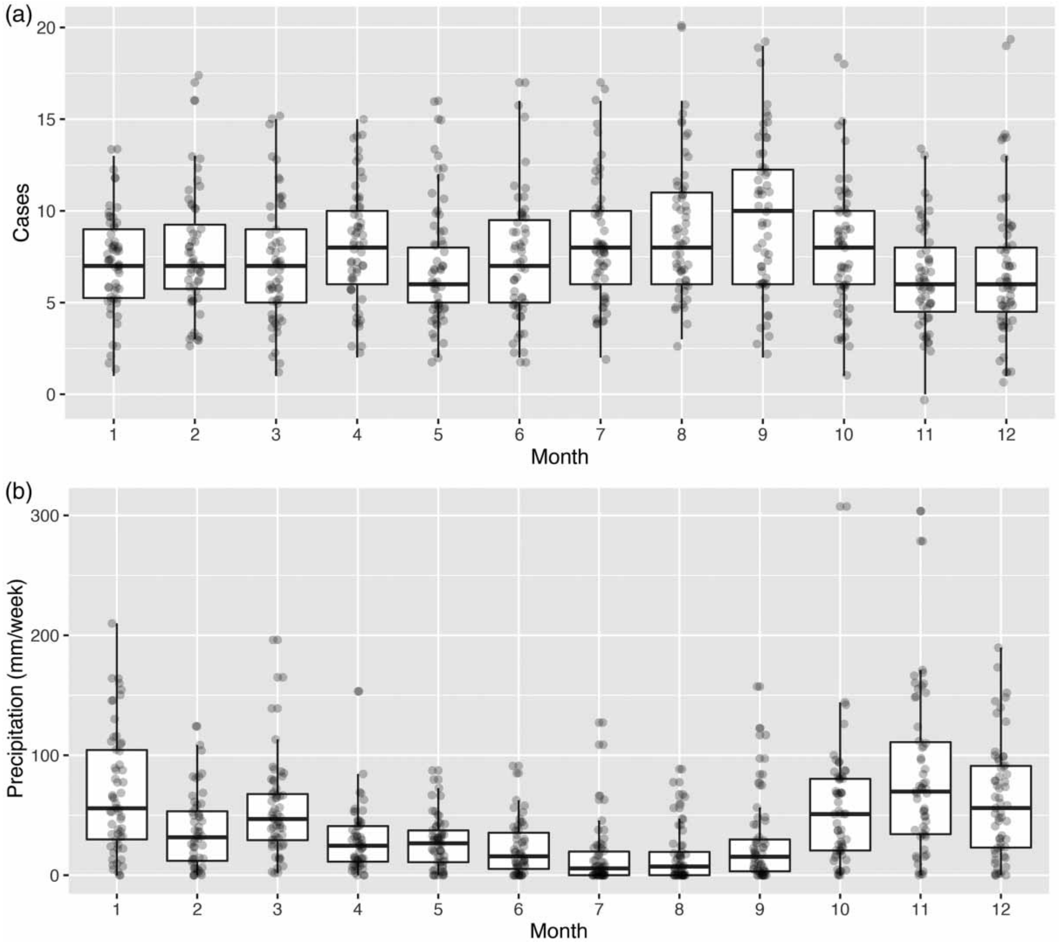

Figure 1 | Boxplots of (a) number of cases of cryptosporidiosis and giardiasis and (b) precipitation per week, grouped by months, in Metro Vancouver DWS, BC, Canada, 1997–2009. The upper whisker extends from the hinge to the highest value that is within 1.5 * IQR of the hinge, where IQR is the inter-quartile range.

Table 1 | The effects of environmental characteristics and model parameters on the risk of cryptosporidiosis and giardiasis in Metro Vancouver DWS, British Columbia, Canada, 1997–2009

Variable[a]	**RR (CI)**[b]	**Wald *P* value**	**LRT (*P*-value)**[c]
Holiday week			
No	Ref	–	
Yes	0.74 (0.45–0.89)	<0.01	
Temperature (C) (0–3 week)	1.03 (0.86–1.34)	0.54	
Fourier term	–	–	<0.01
Spline term	–	–	0.03
Precipitation function	–	–	0.01
Dry days * precipitation function	–	–	<0.01

[a] Temperature is modeled as linear variable representing 3-week moving average, Fourier term adjusts for seasonality; spline term adjusts for trend; precipitation function represents two dimensional parameters for precipitation across its value and lags.

[b] Relative rates (95% confidence intervals).

[c] *P*-values associated with likelihood ratio tests.

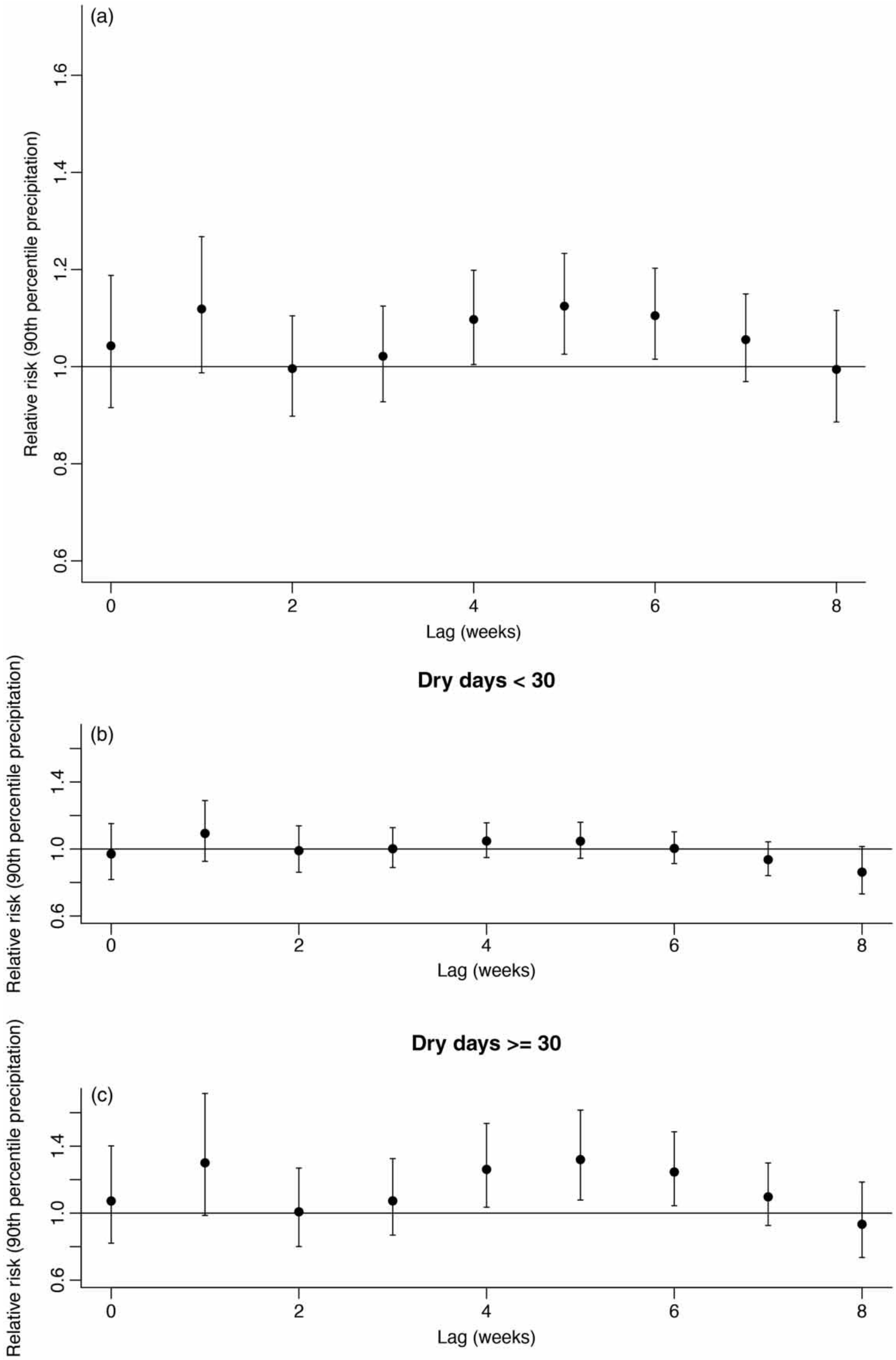

Figure 2 | Change in counts of cryptosporidiosis and giardiasis in Metro Vancouver DWS, BC, Canada over an 8-week period following extreme precipitation (a) and by preceding number of dry days (b) and (c). Dots represent point estimates (relative rates) and bars represent 95% CI. Variables in the model are holiday weeks, precipitation, season (Fourier terms), trend, and interaction between dry days and precipitation.

et al. 2004; Thomas *et al.* 2006), as well as with sporadic bacterial AGI (Harper *et al.* 2011; Uejio *et al.* 2014). Further, correlations between increased precipitation and increased *Cryptosporidium* oocyst and *Giardia* cyst concentrations in river water have also been reported (Atherholt *et al.* 1998). In contrast to others, our study considered highly specific outcomes (laboratory-confirmed diseases) that are known to be associated with drinking water.

The finding of an association between extreme precipitation and parasitic infections at 4–6 weeks is consistent with the latency of these diseases and known delays in reporting. The effect of extreme precipitation on turbidity can last 1–3 weeks. The incubation period of these pathogens is 2 days to 3 weeks, with a median of 7–10 days for both outcomes (Chin 2000). In BC, it takes a median of 1–2 weeks from onset of illness to reporting of cases for other enteric diseases, including salmonellosis, shigellosis, listeriosis, and Shiga-toxin producing *Escherichia coli* (STEC) infection (Galanis *et al.* 2015). The waxing and waning of parasitic infection symptoms may delay healthcare seeking and testing and further extend this interval.

There are several pathways by which extreme precipitation can lead to cryptosporidiosis and giardiasis (Supplement – Figure F, available with the online version of this paper). We found increased turbidity over the 3-week period following extreme precipitation. Extreme precipitation may directly increase turbidity or act indirectly by increasing overland runoff into water systems, thereby increasing pathogen transfer from environmental reservoirs (e.g., animal manure) into surface water (Lake *et al.* 2005; Galway *et al.* 2014). It could also promote resuspension of infectious cysts/oocysts from tributary river sediments (Atherholt *et al.* 1998). Furthermore, the increase in water turbidity following precipitation can reduce the efficacy of drinking water treatment (Aramini *et al.* 2000; Schwartz *et al.* 2000). Chlorination was the main treatment used in the study DWS during 1997–2009, and ozonation was added to one of the three reservoirs starting in 2000. Chlorination alone is not effective against *Cryptosporidium,* whereas *Giardia* requires high concentrations of chlorine and extended contact time to be effective (British Columbia Provincial Health Officer 2001). An approach integrating physical removal (e.g., filtration) and disinfection barriers is the most effective way to reduce protozoa in drinking water (Health Canada 2012).

The effect of extreme precipitation on cryptosporidiosis and giardiasis was found to be greater following a prolonged dry period when compared with a relatively wet period. We also found a marked difference in the effect of extreme precipitation on source water turbidity following dry periods. Similarly, a study from Ecuador reported an increased incidence of non-specific diarrhea after dry periods and decreased incidence after wet periods (Carlton *et al.* 2014). Association between heavy precipitation following dry periods and *E. coli* outbreaks has also been reported (Effler *et al.* 2001). Prolonged dry periods may lead to soil compaction which, when followed by heavy precipitation, facilitates overland run off into reservoirs (Lake *et al.* 2005; Britton *et al.* 2010), leading to increased turbidity and increased pathogen loads. After the most readily accessible pathogens are flushed from the watershed, prolonged rainfall could reduce the concentration of the remaining pathogens. Similarly, another study from BC reported increased risk of AGI in the fall (Galanis *et al.* 2014), which is when rains begin after dry summers and spikes in turbidity occur in the study area (Supplement – Figure C). It is important that watersheds are protected and the source water is treated to mitigate these effects.

We did not find a significant association between temperature and AGI. Temperature is speculated to affect the risk of infection by favoring pathogen infectivity, shedding in animal reservoirs, as well as increasing opportunities for pathogen–host interactions (Semenza *et al.* 2012). During springtime higher temperature may also contribute to increases in stream flow and turbidity due to rapid snowmelt (Harper *et al.* 2011; Galway *et al.* 2014). While we included a 3-week moving average of weekly mean temperature, the effect of temperature was likely captured by the background seasonal terms in the model. Previous studies have reported seasonal differences in the relationship between temperature and AGI (Checkley *et al.* 2000; Lake *et al.* 2005) suggesting that observed association between temperature and disease can also be influenced by seasonal factors not related to temperature (Levy *et al.* 2016).

The DLNM allowed us to flexibly incorporate the non-linear effects of precipitation on disease as well as the delayed effects. Both linear (Bhavnani *et al.* 2014; Galway *et al.* 2014) and non-linear (Bush *et al.* 2014) associations between precipitation and disease have been investigated.

The appropriateness of the form of the relationship seems to be driven by the nature of the data.

Given that our study investigates impacts of precipitation via residential drinking water, we implicitly assumed that exposure to cryptosporidiosis and giardiasis occurred at home. It is possible, however, that cases were exposed to other drinking water sources as well, such as those in the workplace. Nevertheless, commuting patterns in Metro Vancouver indicate that the majority of residents also work in Metro Vancouver (Skelton 2014) and thus remain on the same DWS. It is possible that illness might have been acquired by direct contact with infected humans and animals, recreational water use, food, or other transmission pathways. Despite some inevitable misclassification, extreme precipitation was associated with an increase in turbidity and with the risk of cryptosporidiosis and giardiasis indicating that the route of transmission was probably by drinking water. Our study population received water from three different reservoirs with varying water quality as well as varying susceptibility to turbidity events and contamination. Further, heavy precipitation may not only affect the water source but also contribute to microbial contamination in the water distribution systems. The magnitude of associations observed for the precipitation–disease relationships are relatively small in this study; however, the impact of extreme precipitation on a population is much larger. According to a previous study from Canada, it is estimated that for every 300 cases of enteric illness in the community, only one case is reported (Majowicz *et al.* 2005). Therefore, reported gastrointestinal illnesses represent only a small fraction of true disease burden in the community, and small increases in risk may lead to large increases in cases in the population. Further, the estimated PAR indicated that 21% of the cryptosporidiosis and giardiasis cases in our population were due to extreme precipitation and indicate that a large amount of disease in the population can be prevented by mitigating the effects of extreme precipitation on DWSs.

In order to mitigate the effect of extreme precipitation, we need resilient water treatment systems, infrastructure, and watershed management to prevent contamination of drinking water.

A multi-barrier approach incorporating watershed protection, appropriate treatment, optimized filtration, disinfection, a well-maintained distribution system, and monitoring the effectiveness of treatment is regarded as the best approach to reduce protozoa in drinking water (Health Canada 2012). Previous research from our study area found that following periods of increased turbidity, the rates of healthcare utilization for gastroenteritis increased in this watershed in 1992–1998 (Aramini *et al.* 2000). Subsequently, Metro Vancouver made significant improvements to ensure safe drinking water and decrease the incidence of waterborne illness utilizing a multi-barrier approach. Watersheds are protected: improved water treatment technologies include filtration and ozonation to achieve 3-log removal/inactivation (99.9% removal) of *Cryptosporidium* and *Giardia*, secondary disinfection and monitoring for turbidity, *Giardia* and *Cryptosporidium*. Water filtration and ultraviolet disinfection were implemented in the Seymour reservoir in 2010, and engineering upgrades completed in 2015 now also allow the Capilano reservoir water to be treated at Seymour by filtration and ultraviolet disinfection. Besides ozonation, ultraviolet disinfection was also added to treat water at the Coquitlam reservoir in 2014. When we analyzed the 3 years after partial filtration came into effect (2010–2012), the association between extreme precipitation and the risk of cryptosporidiosis or giardiasis was no longer evident (Supplement – Figure G, available online). These preliminary findings show a positive impact possibly attributed to filtration; further years of data would provide stronger evidence of this association. By addressing key drinking water quality risks, Metro Vancouver provides a model for other systems. This reflects the importance of drinking water treatment enhancements implemented by Metro Vancouver to alleviate the effect of extreme precipitation on drinking water quality. Given that the frequency of extreme precipitation is expected to increase with climate change, adaptation, and mitigation to such events using a multi-barrier approach is especially relevant in the context of changing climate (IPCC 2013).

CONCLUSION

In conclusion, our results suggest that the risk of cryptosporidiosis and giardiasis in an unfiltered DWS is associated with extreme precipitation mediated through drinking water, with a greater effect evident after a prolonged dry period. Substantial burden of water-borne disease in the population can be prevented by mitigating the effects of extreme precipitation on DWSs. With more climate variability, extreme rain events, and prolonged dry periods are likely to become more frequent in the future and the burden of AGI may increase. As such, it is vital to further understand the risks posed by climate change, to develop planning tools, and to adopt mitigation technologies like improved treatment so that DWSs become more resilient to these future risks.

ACKNOWLEDGEMENTS

This research was supported by funding from the Public Health Agency of Canada for the study titled 'The Impact of Climate Change on Drinking Water and Health in Vulnerable Drinking Water Systems'. We would like to thank Rossitta Yung, Antonio Gasparrini, Stephen Sobie, Jordan Brubacher, and Sylvia Struck for their assistance in study design, data acquisition, intellectual inputs in the analysis, and interpretation of results. We also thank Metro Vancouver for providing water turbidity data.

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First received 2 May 2017; accepted in revised form 2 July 2017. Available online 2 September 2017