Association between heavy precipitation events and waterborne outbreaks in four Nordic countries, 1992–2012

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ABSTRACT

We conducted a matched case-control study to examine the association between heavy precipitation events and waterborne outbreaks (WBOs) by linking epidemiological registries and meteorological data between 1992 and 2012 in four Nordic countries. Heavy precipitation events were defined by above average (exceedance) daily rainfall during the preceding weeks using local references. We performed conditional logistic regression using the four previous years as the controls. Among WBOs with known onset date ($n = 89$), exceedance rainfall on two or more days was associated with occurrence of outbreak, OR = 3.06 (95% CI 1.38–6.78), compared to zero exceedance days. Stratified analyses revealed a significant association with single household water supplies, ground water as source and for outbreaks occurring during spring and summer. These findings were reproduced in analyses including all WBOs with known outbreak month ($n = 186$). The vulnerability of single households to WBOs associated with heavy precipitation events should be communicated to homeowners and implemented into future policy planning to reduce the risk of waterborne illness.

Key words | extreme precipitation, heavy precipitation, infection, outbreak, waterborne

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INTRODUCTION

There is extensive documentation of epidemiological case-reports linking heavy precipitation events to the occurrence of waterborne outbreaks (WBOs) in different parts of the world (Auld *et al.* 2004; Schmid *et al.* 2005; Smith *et al.* 2013), including the Nordic region (Laursen *et al.* 1994; Larsson *et al.* 2014). Extreme precipitation events may lead to higher density of microorganisms in water bodies and increase the risk of waterborne diseases. Surface runoff and suspension of soil in agricultural areas may introduce fecal contamination into rivers and lakes. Runoff water may overload the capacity of sewage systems causing discharge of untreated water into drinking water pipelines or other receiving waters (Jofre *et al.* 2010).

We recently conducted a review of analytical studies using epidemiological and meteorological data to quantify the association and disentangle the complex relationship between precipitation and WBO; only four relevant studies were identified. Three studies from Canada, England and Wales, and the USA reported a positive association with extremes of precipitation and WBO, while one study using global data found an inverse association between WBO and average precipitation (Guzman Herrador *et al.* 2015).

Climate change is predicted to lead to increased precipitation and more frequent extreme weather events (RegClim 2005; Goodsite *et al.* 2012). Currently, little is known about how and to what extent climate change will affect the safety of drinking water in the Nordic region and, thus, waterborne illness and potential needs for adaptation (Semenza *et al.* 2012; Ebi *et al.* 2013). In this study, we examined the association between heavy precipitation events and WBO by linking the epidemiological and meteorological registries available in the Nordic countries during 21 years. We considered two types of heavy precipitation measurements, exceedance precipitation and cumulative precipitation, in parallel analyses. In addition, we examined the influence of water supply, water source, and season. This knowledge is needed to assess the vulnerability of current water supplies and distribution systems to heavy precipitation events and for preparedness planning for risks linked to extreme precipitation events.

METHODS

Outbreaks

All notified outbreaks for which drinking water was the suspected cause were extracted from the national outbreak surveillance system registries in Denmark, Norway, Finland, and Sweden from 1992 to 2012 (Finland from 1998; Sweden until 2011) and compiled in a database. To harmonize the collected data, a web-based questionnaire was circulated to all relevant authorities involved in the outbreak investigations. A detailed overview of the characteristics of these outbreaks and how the information was gathered was published previously (Guzman-Herrador *et al.* 2015).

We used the following variables in the analyses: country and municipality of infection; date of symptom onset of the index case (day, month, and year); water source (surface water, groundwater, unknown/other); type of water supply according to the ownership of the utility (municipal/private waterworks, single household, unknown/other); season (winter, spring, summer, autumn).

Precipitation

Daily data on precipitation (amount in mm) from the municipalities with notified WBOs were provided by the national meteorological institutes in the four countries from January 1988 to December 2012. In Norway and Denmark, we used data from the most central weather station in each municipality. In Sweden and Finland, due to missing weather station data over extended periods and regions, we used gridded precipitation data.

Data analyses

The association between heavy precipitation and WBO was tested using conditional logistic regression based on a 1:4 matched case-control design. The local precipitation during the time period preceding each outbreak (cases) was compared to that of the four previous years, which served as the control period. The associations were summarized with odds ratios (ORs) and 95% confidence intervals (95% CIs).

We defined the WBO onset time as the notified date of symptom onset in the index cases. For outbreaks where only information about the month of occurrence was available, we set the onset date to the 15th of the month of occurrence. Outbreaks where either onset month or municipality was missing were excluded from the analyses.

In a few cases, precipitation data were partly missing in the control period. We replaced the affected control years with data from the preceding years, e.g., by extending the period to five to six years before the WBO. Alternatively, if the WBO took place early in the study period where this procedure was not possible, we selected control years forward in time. Likewise, if another WBO had occurred during the control period at the same location, this particular year was excluded, and a new control year obtained using the approach described above.

The geography and climate in the Nordic countries are varied. In some regions with coastal climate, the precipitation is high, as in Bergen where the mean weekly precipitation was 43.4 mm in the study period. In other regions with continental climate, the precipitation is low, such as Alta which had a mean weekly rainfall of only 8.3 mm. In this situation, using a common threshold for defining extreme precipitation may lead to biased results. We therefore used the method of defining exceedance precipitation according to local weather conditions to assess the association between heavy precipitation and WBOs. To complement the analyses, we performed parallel analyses using cumulative weekly precipitation. These additional results are presented in the Supplementary material.

For both types of analyses, we used a common approach. As a main analysis, the strata with known outbreak onset dates were tested for association with heavy rainfall in three weekly time periods prior to the onset date (1–7 days, 8–14 days, 15–21 days). In a secondary analysis, the full dataset, in which outbreaks where only information about the month of occurrence was available were also included, were studied for association with heavy rainfall in a four-weekly time period (1–28 days) prior to the outbreak.

In the exceedance precipitation analysis of outbreaks with known dates, exceedance events were calculated for each WBO using a local reference (municipality and time of year). The local reference was generated from daily precipitation data separately in the three calendar weeks preceding the outbreak, covering all years in the study period. An exceedance day was defined by daily precipitation exceeding the 95 percentile of this local reference value. The number of exceedance days was determined for the outbreak year and the four previous control years. Due to nonlinearity of the data, we grouped the number of exceedance days into three categories (0 days, 1 day, and 2+ days). For the analyses of the full dataset, we determined the local references from daily precipitation data in the 4-week period prior to the outbreak. The number of exceedance days was calculated as described above and grouped (0 days, 1 day, 2–3 days, 4+ days). A two-sided value of $p < 0.05$ was used to indicate statistical significance.

In the cumulative precipitation analysis of outbreaks with known onset dates, weekly cumulative precipitation was categorized into three groups (0 to <10 mm, 10 to ≤20 mm, >20 mm) to account for nonlinearity. The 10–20 mm category was used as the reference category in all analyses, in accordance with that, the mean weekly precipitation was 15.3 mm (median 12.5 mm) among all included municipalities. In the analyses of the full dataset, cumulative precipitation was categorized into three groups (0–40 mm, >40 to 80 mm, >80 mm). The 40–80 mm category was used as the reference category. A two-sided value of $p < 0.05$ was used to indicate statistical significance.

The analyses described above were repeated in stratified analyses by water source, type of water supply and season dichotomized into spring–summer and autumn–winter.

All statistical analyses were performed using R version 2.15.2.

RESULTS

Descriptive analyses

A total of 220 WBOs were notified between 1 January 1992 and 31 December 2012 in Norway, Sweden, Finland, and Denmark, of which, 186 had information available about municipality and onset month and were included in the analyses (Figure 1).

In 63% (117/186) of the outbreaks, a municipal or private water work supply was involved, while 31% (58/186) were linked to single household water supplies. In the majority of outbreaks (69% or 128/186), groundwater was the water source involved and in 24% (45/186) of the outbreaks the source was surface water. In total, 65% (120/186) of the outbreaks occurred during the spring and summer months.

Analysis of WBOs with known onset dates

Roughly half (47%, 89/186) of the notified outbreaks had known onset dates.

Table 1 presents the results of the exceedance precipitation analysis. The calculated daily exceedance precipitation ranged from 3 mm to 21 mm with a mean of 10 mm. A significant association between WBO and occurrence of two or more days of exceedance precipitation during the previous week (1–7 days) was found (OR = 3.06; 95% CI 1.38–6.78). When stratified by water source, two or more days with exceedance precipitation during the previous week was found to be associated with WBOs where a groundwater source was involved (OR = 3.13; 95% CI 1.20–8.17). Outbreaks involving municipality or private waterworks supply showed no association with extreme precipitation events (OR = 2.31; 95% CI 0.87–6.14), while outbreaks with single household water supply displayed a significant association in the category 2 days or more exceedance-days (OR = 8.64; 95% CI 1.58–47.11). Furthermore, heavy precipitation was associated with outbreaks occurring during the spring and summer for 2 days or more exceedance-days (OR = 4.27; 95% CI 1.61–11.35).

Analysis of WBO with known onset month

Table 2 shows the result of the exceedance precipitation analysis of the full dataset using a 4-weekly average. The daily exceedance precipitation ranged from 3 mm to 33 mm with a mean of 11 mm. The results corroborated the findings from the analysis of WBOs with known dates for the week preceding the outbreak. Exceedance precipitation for 2–3 days was positively associated with WBOs occurring during spring and summer (OR = 2.03; 95% CI 1.22–3.38). Outbreaks where groundwater supplies were involved were associated with heavy precipitation in all exceedance precipitation categories: 1 day (OR = 2.12; 95% CI 1.29–3.50), 2–3 days (OR = 1.81; 95% CI 1.08–3.04), and 4+ days (OR = 2.30; 95% CI 1.03–5.11). Finally, outbreaks where single household water supplies were associated with 4+ days with exceedance precipitation (OR = 2.80; 95% CI 1.00–7.83).

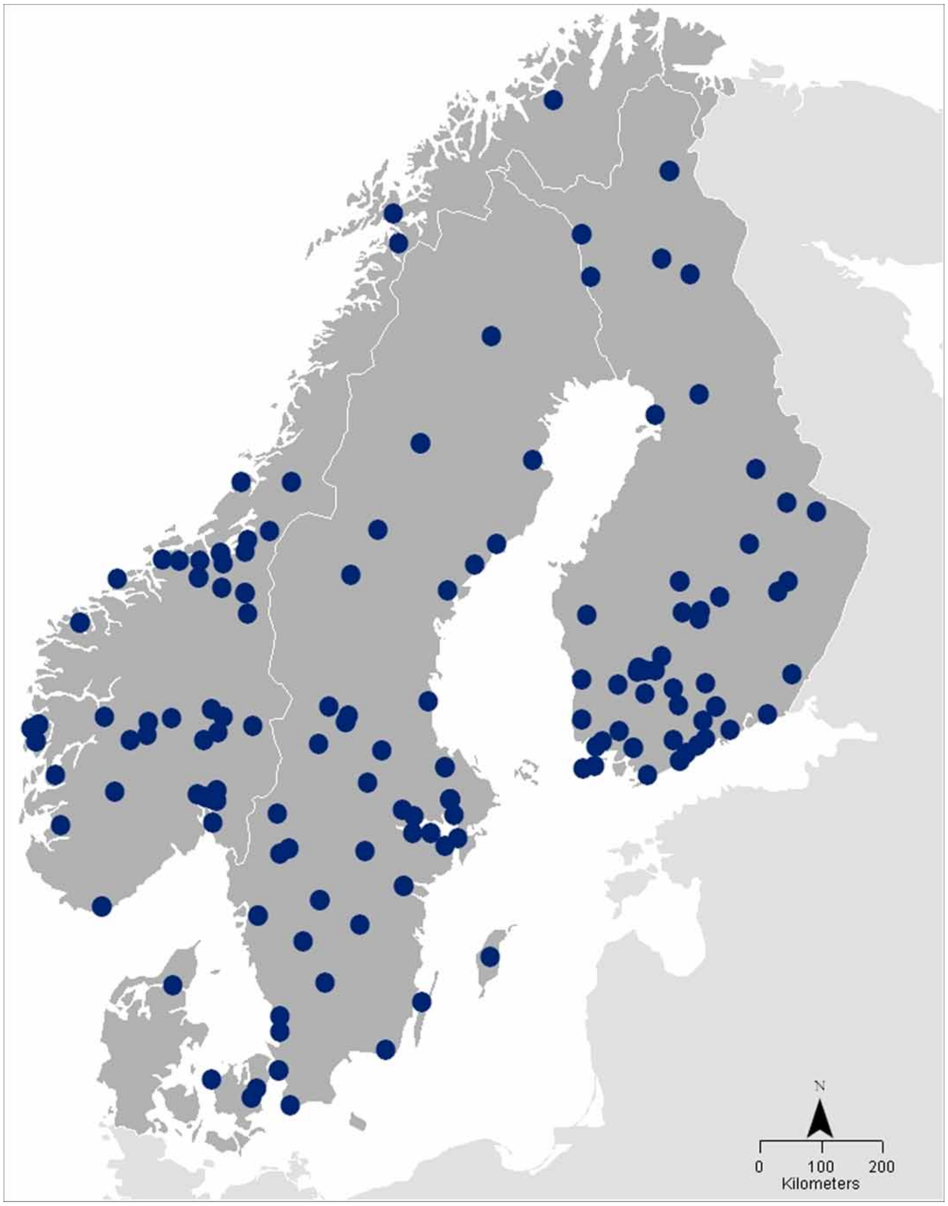

Figure 1 | Geographical distribution of WBOs in four Nordic countries 1992–2012. If more than one outbreak was reported from the municipality, only one dot is shown.

Cumulative precipitation analyses

No association was found between WBOs and weekly cumulative precipitation during the previous 3 weeks in the analysis of outbreaks with known onset dates (Table S1, available with the online version of this paper), or with 4-weekly cumulative precipitation in the analysis of outbreaks with known onset month (Table S2, available with the online version of this paper).

DISCUSSION

The current study, which includes WBOs notified over a 21-year period to the national surveillance systems in Denmark, Finland, Norway, and Sweden, supports that there is a positive association between heavy precipitation during the preceding week and the occurrence of a WBO, and in particular during spring and summer, for groundwater water sources and for single household supplies. The association

Table 1 | Distribution of exceedance-days prior to outbreak calendar date for outbreak and control years and corresponding OR obtained from conditional logistic regression using a 1:4 matching. Reference category = 0 exceedance days. Only outbreaks with known dates included ($n = 89$). Statistically significant results are shown in bold

	Cases						Week 1 prior to outbreak (1–7 days)			
	N (exceedance days)			Controls			1 day		≥ 2 days	
Sample	0	1	2+	0	1	2+	OR (95% CI)	p	OR (95% CI)	p
All	26	51	12	88	249	19	1.39 (0.82–2.37)	0.219	**3.06 (1.38–6.78)**	**0.006**
Spring–summer	20	34	9	57	184	11	1.81 (0.96–3.42)	0.069	**4.27 (1.61–11.35)**	**0.004**
Autumn–winter	6	17	3	31	65	8	0.75 (0.27–2.04)	0.570	1.45 (0.34–6.13)	0.613
Groundwater	22	36	8	62	189	13	1.80 (0.99–3.29)	0.055	**3.13 (1.20–8.17)**	**0.020**
Surface water	2	12	3	17	47	4	0.43 (0.09–2.06)	0.29	3.23 (0.63–16.61)	0.160
Single household	5	10	5	19	57	4	1.43 (0.44–4.65)	0.549	**8.64 (1.58–47.11)**	**0.013**
Municipal/private	20	37	7	66	176	14	1.41 (0.76–2.60)	0.277	2.31 (0.87–6.14)	0.092
							Week 2 prior to outbreak (8–14 days)			
All	19	65	5	60	267	29	1.31 (0.73–2.34)	0.366	0.7 (0.26–1.88)	0.477
Spring–summer	15	44	4	41	187	24	1.57 (0.80–3.10)	0.191	0.69 (0.23–2.10)	0.513
Autumn–winter	4	21	1	19	80	5	081 (0.25–2.59)	0.720	0.77 (0.09–6.67)	0.815
Groundwater	14	49	3	41	204	19	1.44 (0.72–3.86)	0.299	0.64 (0.18–2.27)	0.493
Surface water	4	12	1	14	46	8	1.12 (0.32–3.94)	0.864	0.49 (0.06–4.14)	0.515
Single household	3	16	1	17	54	9	0.60 (0.16–2.31)	0.461	0.38 (0.04–3.23)	0.375
Municipal/private	14	46	4	39	200	17	1.55 (0.78–3.06)	0.210	1.00 (0.32–3.10)	0.997
							Week 3 prior to outbreak (15–21 days)			
All	25	53	11	82	237	37	1.38 (0.80–2.38)	0.253	1.33 (0.63–2.80)	0.454
Spring–summer	19	39	5	53	174	25	1.61 (0.86–3.02)	0.140	0.87 (0.31–2.45)	0.788
Autumn-winter	6	14	6	29	63	12	0.90 (0.29–2.79)	0.849	2.18 (0.71–6.73)	0.173
Groundwater	21	39	6	61	175	28	1.55 (0.84–2.86)	0.158	0.96 (0.37–2.52)	0.937
Surface water	2	12	3	15	47	6	0.50 (0.10–2.52)	0.400	1.83 (0.45–10.34)	0.397
Single household	8	9	3	22	50	8	2.12 (0.69–6.50)	0.188	2.18 (0.46–10.34)	0.326
Municipal/private	16	41	7	57	173	26	1.19 (0.61–2.30)	0.606	1.14 (0.45–2.84)	0.785

was observed when analyzing exceedance precipitation using the local weather data in each municipality as a reference. Conversely, our analyses did not reveal any association between WBOs and cumulative weekly precipitation during the foregoing weeks when compared to the average weekly precipitation of 10–20 mm in the region.

One notable finding was that precipitation exceedance events influenced the occurrence of outbreaks involving single household supplies while outbreaks involving waterworks showed no association with days of precipitation exceedance. Furthermore, stratification by water source suggests that exceedance events were associated with outbreaks involving groundwater. This association is unexpected because groundwater is more protected compared to surface water. However, it is possible that this finding could be due to the strong underlying association between outbreaks involving single household supplies and heavy precipitation, as the majority of single households had groundwater supply and probably seldom any treatment of the source water. Outbreaks caused by water provided through waterworks do occur, but our results do not find a significant correlation with heavy precipitation events. A more detailed analytical approach to investigate outbreaks linked to waterworks, taking into account variables such as size of the waterworks and distribution systems, should be performed to understand this relationship.

Table 2 | Distribution of exceedance-days prior to outbreak calendar date for outbreak and control years and corresponding OR obtained from conditional logistic regression using a 1:4 matching. Reference category = 0 exceedance days. All outbreaks included ($n = 186$). Statistically significant results are shown in bold

	Cases				**Controls**				**Week 1–4 prior to outbreak (1–28 days)**					
	N (exceedance days)								**1 day**		**2–3 days**		**4+ days**	
Sample	**0**	**1**	**2 to 3**	**4+**	**0**	**1**	**2 to 3**	**4+**	**OR (95% CI)**	**p**	**OR (95% CI)**	**p**	**OR (95% CI)**	**p**
All	54	64	54	14	278	227	198	41	1.46 (0.97–2.18)	0.068	1.40 (0.92–2.13)	0.113	1.79 (0.91–3.54)	0.093
Spring–summer	33	39	40	8	194	144	114	28	1.55 (0.94–2.57)	0.086	**2.03 (1.22–3.38)**	**0.006**	1.73 (0.73–4.12)	0.217
Autumn–winter	21	25	14	6	84	83	84	13	1.28 (0.64–2.54)	0.49	0.67 (0.32–1.40)	0.283	2.05 (0.66–6.33)	0.214
Groundwater	30	48	39	11	196	146	138	32	**2.12 (1.29–3.50)**	**0.003**	**1.81 (1.08–3.04)**	**0.025**	**2.30 (1.03–5.11)**	**0.042**
Surface water	22	11	11	1	68	64	42	6	0.51 (0.22–1.16)	0.108	0.80 (0.36–1.80)	0.589	0.49 (0.06–4.20)	0.516
Single household	14	19	17	8	82	69	64	17	1.60 (0.75–3.39)	0.223	1.55 (0.72–3.34)	0.261	**2.80 (1.00–7.83)**	**0.049**
Municipal/private	37	41	33	6	177	147	121	23	1.34 (0.81–2.21)	0.253	1.30 (0.77–2.21)	0.325	1.27 (0.48–3.34)	0.63

We found a significant association between precipitation exceedance and occurrence of outbreaks during the spring and summer. The absence of significance in the autumn and winter could be related to the fact that heavy precipitation in the early and late part of the year in the Nordic region is often in the form of snow, which would not affect runoff before snowmelt. It could also reflect that a number of outbreaks happening in the summer are related to single household supplies. In the Nordic countries, it is common for people to spend long periods of time during the summer at cabins at mountains or lakes, where they normally extract water from small private local wells that are not always well maintained.

Projections of the climate in the Nordic regions suggest increasing temperature, which in turn will lead to increased water runoff due to snowmelt. In addition, rainfall patterns are expected to shift towards more frequent or more intense extreme precipitation, particularly during the warmer months (Goodsite *et al.* 2012). Our results reinforce that important vulnerabilities of WBOs to climate change exist, particularly for single households and during the spring and summer period.

Although not observed in our study, a significant association of WBOs with cumulative precipitation in the previous week using a similar approach has been reported in a study from England and Wales based on 89 WBO between 1910 and 1999 (Nichols *et al.* 2009). Consistent with our study, a Canadian study including 92 WBO between 1975 and 2001 found that daily rainfall events exceeding the 93rd percentile increased the odds for WBO (Thomas *et al.* 2006). In the USA, a study conducted on 548 outbreaks between 1948 and 1994 also reported a positive association with WBO and precipitation events above the 90th and 80th percentile in the preceding month (Curriero *et al.* 2001).

The use of exceedance precipitation has the advantage of accounting for the climatic variability between different regions instead of using a common threshold. In addition, the use of exceedance is designed to capture more extreme precipitation events compared to cumulative weekly rain. In our analyses using the 95th percentile, the daily exceedance for some municipalities was above 20 mm and higher than the cumulative weekly level in the reference category of 10 to 20 mm. It is important to recognize that the choice of the cut-off for the weekly cumulative reference level will affect the results obtained.

We performed additional analyses to test the effects of varying the percentile level used to define exceedance precipitation from 92.5 to 97.5. Higher percentile levels resulted in more significant results, higher ORs compared and smaller sample sizes in the upper precipitation categories compared to lower percentile levels.

Several limitations have to be acknowledged in this study. In particular, the notified WBOs likely represent just the tip of the iceberg of the true disease burden, since many patients with uncomplicated gastroenteritis do not seek medical attention, and therefore health authorities would not become aware of possible outbreaks. This is especially relevant for the colder months when viruses that lead to gastrointestinal illness are common, which may result in WBOs going unnoticed. WBOs related to large waterworks are more likely to be recognized than those that involve a single household water supply or those that occur due to distribution network failures as these would affect a smaller proportion of the population. Our data may be subject to detection bias as geographical differences in reported WBOs might reflect differences in reporting routines rather than a higher risk in specific regions. Also, less than half of the notified outbreaks analyzed in this study had known onset dates and could be used in analyses on short-term precipitation exposure. The absence of significance, or large CIs in some of our analyses could be an artifact due to lack of power, as a result of small sample sizes.

Another potential limitation that has to be taken into account is that heavy precipitation events tend to be localized. Since *municipality* was the geographical unit of analysis for this study, it is possible that in some cases the precipitation measurement that we have used might not have reflected the real precipitation occurring in the specific location of the outbreak. Also, extreme rainfall and runoff have been suggested to implicate the increase of endemic levels of gastrointestinal disease in the absence of any disease outbreaks reported (Tornevi *et al.* 2013).

Our results may be useful to better understand how climate change and changes in precipitation may influence the burden of waterborne illness in the Nordic region by inferring models projecting the occurrence of WBOs under different climate scenarios. In order to address the existing gaps in knowledge, other types of more sensitive epidemiological registries could also be used. For example, data from syndromic surveillance systems, such as the number of consultations due to acute gastroenteritis (Drayna *et al.* 2010), or notifications of certain waterborne microorganisms (Britton *et al.* 2010), could help to better assess the influence of heavy precipitation events and runoff on waterborne diseases.

CONCLUSION

Our results suggest an association between WBOs and heavy precipitation in the Nordic countries. The results highlight single household supplies as particularly vulnerable to extreme weather events. This is important information that should be communicated to homeowners in order to make them aware of the importance of correct maintenance of their wells. Public health authorities should also be encouraged to develop better regulations and strategies to reduce the risk of waterborne illness.

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meteorological issues. All authors provided scientific input. All authors participated in manuscript writing and revision. All authors read and approved the final manuscript.

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