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The Association Between Extreme Precipitation and Waterborne Disease Outbreaks in the United States, 1948–1994

Frank C. Curriero, PhD, Jonathan A. Patz, MD, MPH, Joan B. Rose, PhD, and Subhash Lele, PhD

According to the US National Assessment on the Potential Consequences of Climate Variability and Change,¹ determining the role of weather in the incidence of waterborne disease outbreaks is a priority public health research issue for this country. Rainfall and runoff have been implicated in individual outbreaks in the United Kingdom and the United States. A waterborne disease outbreak of giardiasis in Montana was related to rainfall,² as was the largest reported waterborne disease outbreak ever documented, which occurred in Milwaukee, Wis, in 1993. There, an estimated 403 000 cases of intestinal illness and 54 deaths occurred,³ and the outbreak was preceded by a period of heavy rainfall and runoff with a subsequent turbidity load that compromised the efficiency of the drinking water treatment plant.^{4,5}

Even outbreaks of *Escherichia coli*, generally considered a foodborne pathogen, have been linked to rainfall events. In fact, the largest reported outbreak of *E coli* O157:H7 occurred at a fairground in the state of New York in September 1999 and was linked to contaminated well water. Unusually heavy rainfall, which was preceded by a drought, coincided with this major outbreak.¹ Under conditions of high soil saturation, rapid transport of microbial organisms can be enhanced.

Part of the rationale for this study, conducted through a US Environmental Protection Agency grant for studying the effects of global climate change on public health, comes from projections of more intense rainfall that may accompany global warming. In the past century, average daily temperatures in the conterminous United States increased by approximately 1°F.⁶ Warmer air can hold more moisture, and changes in the hydrologic cycle in the United States have been evidenced by increases in cloud cover⁷ and total precipitation.⁸ Moreover, the type of precipitation has

Objectives. Rainfall and runoff have been implicated in site-specific waterborne disease outbreaks. Because upward trends in heavy precipitation in the United States are projected to increase with climate change, this study sought to quantify the relationship between precipitation and disease outbreaks.

Methods. The US Environmental Protection Agency waterborne disease database, totaling 548 reported outbreaks from 1948 through 1994, and precipitation data of the National Climatic Data Center were used to analyze the relationship between precipitation and waterborne diseases. Analyses were at the watershed level, stratified by groundwater and surface water contamination and controlled for effects due to season and hydrologic region. A Monte Carlo version of the Fisher exact test was used to test for statistical significance.

Results. Fifty-one percent of waterborne disease outbreaks were preceded by precipitation events above the 90th percentile ($P = .002$), and 68% by events above the 80th percentile ($P = .001$). Outbreaks due to surface water contamination showed the strongest association with extreme precipitation during the month of the outbreak; a 2-month lag applied to groundwater contamination events.

Conclusions. The statistically significant association found between rainfall and disease in the United States is important for water managers, public health officials, and risk assessors of future climate change. (*Am J Public Health.* 2001;91:1194–1199)

been changing in the United States, with increases in extreme precipitation events (those with an intensity of more than 2 inches per day).^{9,6,10} These rainfall patterns are consistent with expectations of a more vigorous hydrologic cycle caused by anthropogenic greenhouse gas warming of the earth's surface.^{11–13}

The purpose of our study was to analyze the relationship between precipitation and waterborne diseases, using the complete database of all reported waterborne disease outbreaks in the United States from 1948 to 1994. Rainfall intensity is assumed to be a key determining factor in the fate and transport of pathogenic microorganisms, but the relationship has never been analyzed at the national level.

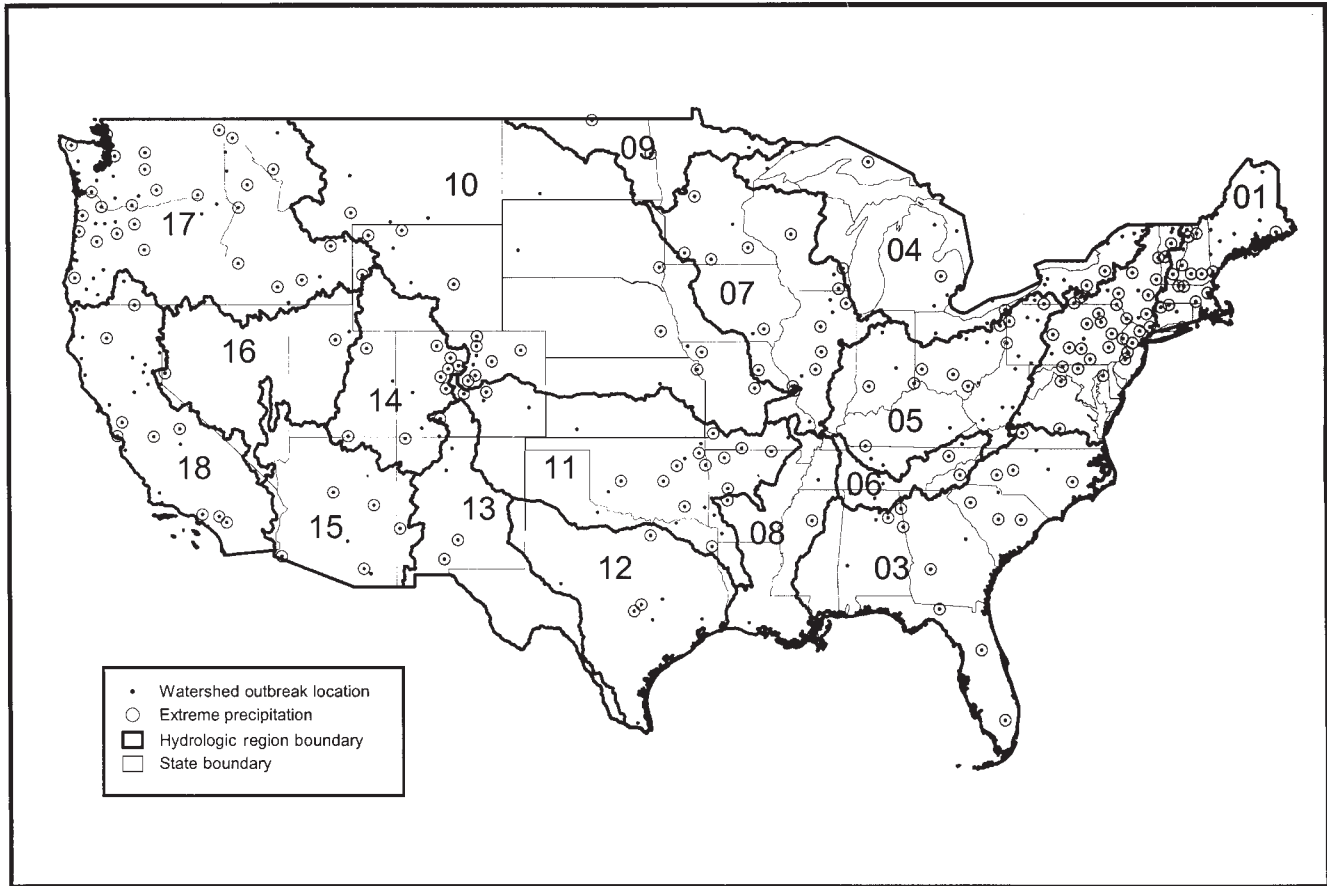
METHODS

US Waterborne Disease Outbreaks and Precipitation Data Sets

Data on all reported waterborne disease outbreaks in the United States between 1948

and 1994 were obtained from the US Environmental Protection Agency's Office of Research and Development. Included in this data set were the etiologic agent, the community and state where the outbreak occurred, and the month and year of each outbreak. The outbreak source was designated as either surface water or groundwater contamination. The community and state information was geocoded and expressed as longitude and latitude coordinates marking the affected city or county.

A waterborne disease outbreak is defined as an outbreak in which epidemiologic evidence points to a drinking water source from which 2 or more persons become ill at similar times. All recreational outbreaks and outbreaks associated with cross-connections or back-siphonage between sewage and drinking water in the distribution system, including chemical outbreaks, were removed from the database. We excluded these outbreaks to focus the analysis on source waters and watershed contamination and to exclude acci-



Note. Outbreak locations represent the centroid of the affected watershed.

FIGURE 1—Waterborne disease outbreaks and associated extreme levels of precipitation (precipitation in the highest 10% [90th percentile]) within a 2-month lag preceding the outbreak month: United States, 1948–1994.

dental fecal releases associated with recreational outbreaks and infrastructure problems in the distribution system.

The conterminous United States is subdivided into 2105 hydrologic cataloging units called *watersheds*, which are geographic areas representing part or all of a surface drainage basin, a combination of drainage basins, or a distinct hydrologic feature. Watersheds act as the drinking water source for the surrounding area; thus, we chose watersheds as the geographic units for our investigation. Outbreak locations, originally designating the affected city or county, were recoded to correspond to the centroid of the associated watershed. Data on US hydrologic units, a hierarchy of geographic subdivisions including watersheds, were downloaded from the US Geological Survey.¹⁴ Figure 1 includes boundaries for the

largest subdivision in this hierarchy (watersheds are the smallest), which divides the United States into 18 distinct hydrologic regions, each containing the drainage area of a major river or the combined drainage areas of a series of rivers.

Total monthly precipitation readings for the more than 16 000 weather stations located across the United States from 1948 through 1994 were downloaded from the National Climatic Data Center.¹⁵ The weather station locations were also coded to the watershed level; each watershed, on the average, contained approximately 7 weather stations. To account for local variations, we replaced recorded total monthly precipitation for each weather station with its corresponding *z* score, which was computed on the basis of the distribution of values recorded for that month from 1948 to

1997. We considered there to be sufficient information to compute *z* scores only if the corresponding distributions contained at least 20 years of recorded data. The *z* score thresholds were chosen to indicate extreme levels of precipitation. For example, *z* scores greater than 0.84, 1.28, and 1.65 correspond, respectively, to total monthly precipitation in the highest 20%, 10%, and 5% observed for that station and month from 1948 to 1994. The maximum *z* score determined from weather station-specific *z* scores within a watershed was used as a measure of extreme precipitation for that watershed.

Statistical Analysis

Figure 1 displays the 548 waterborne disease outbreaks, plotted using the centroid of the affected watershed, within the contermi-

TABLE 1—Waterborne Disease Outbreaks, With Associated Extreme Levels of Precipitation^a in the Preceding 2 Months: United States, 1948–1994

Outbreak	Extreme Precipitation		Total
	Yes	No	
Yes	268	257	525
No	NC	NC	1 186 695
Total	NC	NC	1 187 220

Note. There were 1 187 220 watershed outbreak possibilities. Shown are the 525 outbreaks for which extreme precipitation data were available. Information regarding extreme precipitation status for watersheds not experiencing an outbreak was not compiled (NC).

^aPrecipitation in the highest 10% (90th percentile).

nous United States that were reported from 1948 to 1994. Of these outbreaks, 51% were preceded within a 2-month lag by an extreme level of precipitation in the highest 10% (or 90th percentile), as indicated in the figure. Several methods, and an accompanying large body of literature, are available to test for spatial clustering of disease events.¹⁶ In this study we were interested in testing whether the outbreaks cluster around extreme precipitation events, as opposed to solely investigating geographic clustering of outbreaks.

Information in Figure 1 can be represented with a 2×2 contingency table, watershed outbreak status×watershed extreme precipitation status. Since this information is collapsed over time, there are a total of 1 187 220 watershed outbreak possibilities (47 years×12 months×2105 watersheds). Table 1 displays extreme precipitation status for only those watersheds known to have experienced an outbreak. Enumerating the bottom row would require determining the extreme precipitation status within a 2-month lag for the remaining watershed outbreak possibilities, a computational burden we wished to avoid. The total number of outbreaks is shown to be 525, not 548, because sufficient precipitation data were not available for 23 outbreak-associated watersheds.

Associations between events in contingency tables are usually described with odds ratios followed by a χ^2 -based test of independence. Proceeding in this fashion, however, would require a completely enumerated table. Note that the percentage of coincident events reported (51%) is simply the (1,1) cell (outbreak and extreme precipitation) divided

by its marginal total (number of outbreaks). Since the row and column totals in Table 1 are fixed, the (1,1) cell determines the remaining cells and hence the odds ratio; thus, the percentage of coincident events and the odds ratio are equivalent descriptors of association. Also, because the marginal totals are fixed, the Fisher exact test¹⁷ can be used to assess the significance of the association based on the percentage of coincident events. Although the calculation of *P* values in the Fisher exact test requires fully enumerated information as well, the rationale behind the calculation can be approximated with the following Monte Carlo simulation.

The general idea is to repeatedly generate sets of “outbreaks” in a random fashion, tabulating the percentage of these artificial outbreaks that coincide with extreme levels of precipitation at each step. Such a process would produce a distribution of coincident percentages under the assumption of no association, which can then be compared with the observed percentage to compute a *P* value. The following algorithm describes the process for a given set of outbreaks overlaid with extreme precipitation events.

1. Generate a set of outbreaks.
 - a. Randomly select watersheds.
 - b. Randomly select a month (1–12) and year (1948–1994) for each watershed.
2. Calculate and store the percentage of these outbreaks coincident with extreme levels of precipitation within a given preceding monthly lag.
3. Repeat steps 1 and 2 one thousand times.

The expected percentage of outbreaks coincident with extreme levels of precipitation within a given preceding monthly lag, under the assumption of no association, can be estimated by averaging the Monte Carlo distribution of percentages in step 2.

For the data shown in Table 1, if the 525 waterborne disease outbreaks are clustered both spatially and temporally within watersheds experiencing extreme levels of precipitation, then the observed 51% would be higher than the percentage expected under the assumption of no association. We were therefore interested in testing the one-sided alternative representing a positive association between outbreaks and extreme precipitation. *P* values for such a test can be obtained by dividing by 1000 the number of percentages in step 2 that are higher than their respective observed percentages.

RESULTS

Table 2 cross-tabulates the 548 reported waterborne disease outbreaks by the 18 hydrologic regions and 4 seasons. The distribution of outbreaks across the seasons (column totals) shows that the number of outbreaks is highest during the summer months and lowest during the winter months. The distribution across the hydrologic regions (row totals) may be due to specific hydrologic features present in these regions. The distributional variations across regions and seasons can be controlled for in the Monte Carlo test by restricting the randomization scheme in step 1 of that algorithm to adhere to the marginal totals shown in Table 2. Thus, each artificial set of outbreaks would have identical row and column totals, as shown in Table 2. The resulting test would then be one of conditional association between outbreaks and extreme precipitation, controlling for variations across both regions and seasons.

Of the 548 waterborne disease outbreaks reported between 1948 and 1994, 133 (approximately 24%) were known to be from surface water contamination, 197 (approximately 36%) were known to be from groundwater contamination, and 218 (approximately 40%) had an unknown water contamination source. The outbreak data also included the etiologic agents involved in each outbreak. More than

TABLE 2—Waterborne Disease Outbreaks, by Hydrologic Region and Season: United States, 1948–1994

Region	Season				Total
	Winter	Spring	Summer	Fall	
1	2	8	17	11	38
2	14	27	63	29	133
3	4	5	12	8	29
4	6	2	18	8	34
5	6	9	18	6	39
6	1	1	2	3	7
7	2	12	10	3	27
8	1	1	5	2	9
9	1	0	1	1	3
10	5	5	24	7	41
11	6	9	16	8	39
12	0	3	4	2	9
13	0	1	5	1	7
14	6	6	7	4	23
15	1	3	3	1	8
16	0	1	3	0	4
17	6	17	34	8	65
18	9	6	14	4	33
Total	70	116	256	106	548

Note. Winter = December, January, February; Spring = March, April, May; Summer = June, July, August; Fall = September, October, November.

half the outbreaks were determined to be “acute gastrointestinal illness,” about 13% were attributed to *Giardia*, and the remainder were caused by 35 other specific agents.

We used the Monte Carlo test presented above to test the significance of the overlaid information shown in Figure 1 and other associations between waterborne disease outbreaks and extreme precipitation, controlling for the possible confounding effects due to hydrologic region and season. Different scenarios were investigated by varying the preceding monthly lag time and level of extreme precipitation. Separate analyses were performed for outbreaks due to surface water contamination, outbreaks due to groundwater contamination, and the combined data, including outbreaks with an unknown water contamination source. The results, which are presented in Table 3, include for each scenario the observed percentage of outbreaks coincident with extreme precipitation events; an estimated expected percentage of coincident events, assuming no association; and the

P value testing the significance of the observed percentage.

Results for the association depicted in Figure 1 (combined data, monthly lag 0, 1, 2, and 90th percentile extreme precipitation) indicate that after controlling for variations across regions and seasons, we would have expected 43.2% of the outbreaks to be coincident with extreme precipitation if there was no association between outbreaks and extreme precipitation. The observed percentage of outbreaks coincident with levels of extreme precipitation—51.0%—was highly significant ($P=.002$). *P* values of less than .001 in Table 3 indicate the strongest evidence of an association; they occurred when the random selection of watershed outbreaks, for the 1000 iterations performed in step 1 of the Monte Carlo algorithm, did not produce a percentage of outbreaks coincident with this level of extreme precipitation that was higher than the observed percentage.

The association between outbreaks and extreme precipitation remained statistically sig-

nificant at the .05 level across all of the scenarios we considered for the combined data. The analysis stratified by water contamination source showed that outbreaks due to surface water contamination were most significant for extreme precipitation during the month of the outbreak. Outbreaks due to groundwater contamination, however, showed highest significance for extreme precipitation 2 months prior to the outbreak. This might be expected, considering the direct vs complex routes of exposure.

DISCUSSION

This study represents the first quantitative analysis of the relationship between extreme precipitation and waterborne disease outbreaks at the national level and over an extended period. Our findings show a statistically significant association between weather events and disease. However, we recognize that multiple factors are involved, which must occur simultaneously in time and space. Elements of an outbreak event include (1) a source of contamination (infected humans, domestic animals, or wildlife); (2) fate and transport of the contaminant from source to drinking water supplies; (3) inadequate treatment; and (4) detection and reporting of the outbreak.¹⁸ Given the variability of these factors across the United States, the robustness of our findings demonstrates the important role of extreme wet-weather events in microbial fate and transport and as a contributing factor in US waterborne disease outbreaks.

Incorporating data on other causal components will be important in the development of better predictive models extending beyond this study's limitations. We have partially controlled for source of outbreak by conducting analyses at the watershed level. Watersheds might be expected to maintain some consistency in land use patterns; however, these patterns, inevitably, have changed over the 47 years analyzed. Several state-specific analyses that could include more detailed land use and treatment facility information would, therefore, be of benefit as a follow-up to this national-level study.

Our study is limited by the temporal resolution of the waterborne disease outbreak

TABLE 3—Monte Carlo Simulation Results for the Association Between Waterborne Disease Outbreaks and Extreme Precipitation: United States, 1948–1994

Monthly Lag	Extreme Precipitation Percentile								
	Surface Water Contamination			Groundwater Contamination			Combined		
	80th	90th	95th	80th	90th	95th	80th	90th	95th
Monthly lag 0									
Observed, %	39.1	28.9	22.7	31.2	21.4	13.5	33.3	22.8	16.8
Monte Carlo, %	26.9	17.4	11.7	28.8	18.6	12.4	27.7	17.9	12.0
<i>P</i>	.001	<.001	.001	.229	.173	.314	.001	<.001	.002
Monthly lag 0,1									
Observed, %	55.1	41.7	33.9	53.9	39.3	26.2	52.3	38.3	28.8
Monte Carlo, %	45.5	31.2	21.7	48.0	33.0	22.7	46.5	31.9	22.0
<i>P</i>	.022	.003	.002	.059	.039	.132	.003	.001	<.001
Monthly lag 0,1,2									
Observed, %	65.9	50.8	42.9	71.6	52.1	36.8	68.0	51.0	39.4
Monte Carlo, %	58.9	42.3	30.3	61.6	44.4	31.6	59.9	43.2	30.7
<i>P</i>	.063	.023	.001	.002	.021	.062	<.001	.002	<.001
Monthly lag 1									
Observed, %	34.6	22.8	18.1	33.2	22.8	14.5	31.6	20.3	14.9
Monte Carlo, %	26.8	17.4	11.6	28.7	18.5	12.3	27.5	17.7	11.8
<i>P</i>	.033	.060	.026	.083	.070	.183	.005	.047	.009
Monthly lag 1,2									
Observed, %	54.8	36.5	31.0	57.8	41.7	28.6	54.4	37.5	27.8
Monte Carlo, %	45.4	31.0	21.5	47.7	32.6	22.4	46.3	31.6	21.7
<i>P</i>	.023	.109	.003	.002	.009	.027	<.001	.001	<.001

Note. Shown are results for outbreaks known to be from surface water contamination, outbreaks known to be from groundwater contamination, and the combined data, including outbreaks with an unknown water contamination source. Listed for each monthly lag and extreme precipitation scenario are the observed percentage of outbreaks coincident with extreme precipitation, the Monte Carlo-expected percentage of coincident events, and the corresponding *P* value.

data. These data have been reported in the same way for approximately 50 years. Improved understanding and better prevention might be achieved if outbreak data included start and end dates rather than simply the month of occurrence.¹⁸

Reporting bias is a key component in the waterborne disease outbreak data. Experts estimate that we may be seeing only a small fraction of the actual outbreaks.¹⁹ With such a bias, many of the cluster detection methods that focus primarily on geographic clustering of diseases would clearly be inappropriate. The method we applied, which is focused more on the clustering of outbreaks around extreme precipitation, is appropriate under the assumption that outbreak reporting is independent of surrounding monthly precipitation.

Although the United States is thought to have high-quality drinking water, the risk of contamination from leaking septic tanks or

agricultural runoff remains. One pathogen, *Cryptosporidium*, a protozoan that completes its life cycle within the intestine of mammals, is shed in high numbers of infectious oocysts that are dispersed in feces. It is highly prevalent in ruminants and readily transmitted to humans.²⁰ In a cross-sectional analysis of 50 live-stock farms sampled within the 100-year floodplain in Lancaster County, Pennsylvania, manure samples from 64% of the farms tested positive for *C parvum*.²¹ Therefore, it is biologically plausible that increases in rainfall and runoff intensity would result in more contamination of source waters by this parasite.

Our results are also consistent with findings from other studies. For example, Atherholt et al. found that concentrations of *Cryptosporidium* oocysts and *Giardia* cysts in the Delaware River were positively correlated with rainfall.²² In 1998, a drinking water outbreak of cryptosporidiosis that occurred in Brushy

Creek, Tex, was linked to storms that led to sewage contamination of wells and creeks.²³ *Cryptosporidium* oocysts are very small (~5 microns) and are difficult to remove from water; a recent study found that 13% of finished water still contained *Cryptosporidium* oocysts,²⁴ indicating some passage of microorganisms from source to treated drinking water.

Municipal water systems, even today, can be overburdened by extreme rainfall events. For example, many communities still have combined sewer systems designed to carry both storm water and sanitary wastewater to a sewage treatment plant. During periods of heavy rainfall or snowmelt, the stormwater can exceed the capacity of the sewer system or treatment plant, and these systems are designed to discharge the excess wastewater directly into surface water bodies.^{25,26} For northern latitudes and high-elevation regions, the addition of temperature values

could further enhance the analysis by addressing the contribution of snowmelt.

During the heavy rainfall that accompanied the very strong El Niño of 1997 and 1998, a survey of a southwest Florida estuary found higher concentrations of fecal indicator organisms than occurred throughout the rest of the year,^{27,28} implicating heavy rainfall as a risk factor for waterborne or seafood-borne disease. In urban watersheds, more than 60% of the annual load of all contaminants is transported during storm events.²⁹ In general, turbidity increases during storm events, and studies have recently shown a correlation between increases in turbidity and illness in communities.^{30,31}

In summary, there is mounting evidence that heavy precipitation and runoff events significantly contribute to the risk of waterborne disease outbreaks. In the future, incorporation of other site-specific parameters, particularly land use patterns and treatment facility specifications, may allow for the development of more localized predictive models that can benefit water managers and public health planners. Our findings provide further insight into the linkage between weather and human disease that can be applied to risk assessments of future climate change. ■

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Contributors

F.C. Curriero developed the statistical methodology and performed all data analyses. J.A. Patz was the principal investigator for this study and conceived and led the overall design of this project. J.B. Rose obtained all the outbreak data and was responsible for plotting them, using a geographic information systems (GIS) format; provided information on the details of the database; and reviewed the article. S. Lele provided expert guidance on the statistical analyses and made revisions to the manuscript.

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