

Drinking water turbidity and emergency department visits for gastrointestinal illness in Atlanta, 1993–2004

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The extent to which drinking water turbidity measurements indicate the risk of gastrointestinal illness is not well understood. Despite major advances in drinking water treatment and delivery, infectious disease can still be transmitted through drinking water in the United States, and it is important to have reliable indicators of microbial water quality to inform public health decisions. The objective of our study was to assess the relationship between gastrointestinal illness, quantified through emergency department visits, and drinking water quality, quantified as raw water and filtered water turbidity measured at the treatment plant. We examined the relationship between turbidity levels of raw and filtered surface water measured at eight major drinking water treatment plants in the metropolitan area of Atlanta, Georgia, and over 240,000 emergency department visits for gastrointestinal illness during 1993–2004 among the population served by these plants. We fit Poisson time-series statistical regression models that included turbidity in a 21-day distributed lag and that controlled for meteorological factors and long-term time trends. For filtered water turbidity, the results were consistent with no association with emergency department visits for gastrointestinal illness. We observed a modest association between raw water turbidity and emergency department visits for gastrointestinal illness. Our results suggest that source water quality may contribute modestly to endemic gastrointestinal illness in the study area. The association between turbidity and emergency department visits for gastrointestinal illness was only observed when raw water turbidity was considered; filtered water turbidity may not serve as a reliable indicator of modest pathogen risk at all treatment plants.

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Introduction

Drinking water quality in the United States (US) is among the best in the world. Disease due to waterborne infections decreased dramatically during the 20th century with the implementation of the drinking water treatment practices of filtration and disinfection (Centers for Disease Control and Prevention, 1999). Despite the enormous resources dedicated to keeping the US water supply safe, pathogenic organisms are present in source waters used for drinking water (LeChevallier et al., 1991), and research suggests that drinking water contributes an estimated 4.3–16.4 million cases of gastrointestinal (GI) illness annually (Colford et al., 2006; Messner et al., 2006).

Randomized-controlled trials (RCTs) have yielded conflicting results regarding the extent to which drinking water contributes to endemic GI illness. The results of RCTs conducted in Canada (Payment et al., 1991, 1997) suggested that 14–40% of GI illness among their study population was attributable to tap water exposure, but subjects were not blinded to exposure status in these studies. In a blinded RCT conducted in Australia (Hellard et al., 2001), no association between drinking water exposure and GI illness was observed. However, the results of this study have limited generalizability to most North American water systems serving large populations, because the source water was of a pristine quality seldom found in large US cities. A blinded, crossover RCT, in which subjects' exposure groups were switched midway through the study, was conducted in the US (Colford et al., 2005). The researchers observed no difference in rates of GI illness among exposure groups. The source water for this RCT, conducted in Iowa, had many potential sources of contamination and received conventional treatment. Although this RCT employed the most sophisticated study design, the study population contained few

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children, a group that has a much greater susceptibility to infectious GI illness than the general population (Glass et al., 1991; Jin et al., 1996).

Observational studies, which are based on actual exposures and prevalent water quality, have also been conducted to examine the association between drinking water and GI illness. One method that has been employed to examine this association is time-series analysis, in which variation in water quality over time is examined in relation to variation in disease occurrence. Two studies using this design were conducted in Milwaukee, WI, in response to the large 1993 *Cryptosporidium* outbreak (Morris et al., 1996, 1998). In both studies an association was observed between turbidity, a measure of suspended particles in water and a rough proxy for microbial contamination, and hospital utilization for GI illness, even before the outbreak period. Schwartz et al. (1997, 2000) published results of investigations of drinking water turbidity in relation to hospital visits for GI illness among children and the elderly in Philadelphia. Significant positive associations between turbidity and healthcare utilization for GI illness were observed in both studies.

In this study we used time-series methods to examine the association between turbidity measures at eight drinking water treatment plants serving the five-county metropolitan Atlanta area and emergency department visits for GI illness over a 12-year period. The metropolitan Atlanta area is a well-suited location in which to conduct this type of study. The raw water serving the utilities in this area is drawn from rivers, streams, and impoundments that are impacted by many point and non-point sources of contamination, including microbial contaminants. Accordingly, the findings should be applicable to other communities as well.

Methods

Environmental Information

There are 10 major drinking water treatment plants, operated by 6 utilities, serving approximately 96% of the population in the study area. These plants use a variety of surface water sources. The production capacity of the plants ranges from 10 million gallons per day (mgd) to 150 mgd. The drinking water produced by these plants serves almost four million customers. The plants generally use conventional treatment methods, including coagulation, sedimentation, filtration, and disinfection. All of the plants use chlorine for disinfection. One plant does not use sedimentation, but uses ozone as an additional disinfectant. Three plants use ultraviolet (UV) disinfection in addition to chlorination.

We obtained water quality data directly from the drinking water utilities. These data included daily summary measures of hourly turbidity measurements, in nephelometric turbidity units (NTU), taken at the treatment plant. Daily values of average and maximum filtered water turbidity were available

for five of the treatment plants from 1 July 1993 to 31 December 2004. For one plant, average filtered water turbidity data were available from 1 January 1993 to 31 December 2004, but maximum filtered water turbidity data were available only from 1 January 2000 to 31 December 2004. Both average and maximum filtered water turbidity data were unavailable from another plant for the years 2000 and 2001. Another plant did not begin operation until November 1999. Unfortunately, daily values of average raw water turbidity were not available for use in this study. Daily values of minimum and maximum raw water turbidity were available for 1 January 2002 through 31 December 2004 from all plants except one, for which data availability began 1 March 2002.

We determined the service area of each treatment plant through information provided by the utilities. We assigned each zip code in the study area to a treatment plant, where possible. In order to be included in the analysis, 80% of the zip code area had to be served by a single treatment plant. Of the 140 zip codes in the study area, we were able to assign 81 (58%) to a single treatment plant. We combined the data from two of the plants using a flow-weighted average because their water was blended before distribution. We excluded data from another plant because no zip codes could be assigned exclusively to its service.

Average daily temperature (average of the daily minimum and maximum) was measured at Hartsfield-Jackson Atlanta International Airport and obtained from the National Climatic Data Center Network.

Emergency Department Visits

Information was available on emergency department visits from all of the hospitals operating within the five-county Atlanta area (23 hospitals) and from five hospitals located outside the study area that contributed a substantial number of visits by five-county residents. The data provided by the hospitals included medical record number, date of admission, *International Classification of Diseases, 9th Revision (ICD-9)*, diagnosis codes, and zip code of residence.

The *a priori* case definition for GI illness used the primary and all available secondary ICD-9 diagnostic codes. The case definition included the following diagnoses: infectious GI illness (001–004, 005.0, 005.4, 005.89, 005.9, 006–007, 008.0, 008.42–008.44, 008.47, 008.49, 008.5, 008.6, 008.8, 009), non-infectious GI illness (558.9), and nausea and vomiting plausibly related to GI illness (787.01–787.03, 787.91). We included non-infectious GI illness in the case definition because previous research has shown that many infectious cases of GI illness are misclassified into this diagnostic category (Gangarosa et al., 1992; Hoxie et al., 1997; Schwartz et al., 1997).

Analytic Methods

All analyses were performed using SAS statistical software (SAS Institute Inc., Cary, NC, USA). We examined

univariate statistics for each of the turbidity variables and the daily count of emergency department visits. We used Spearman's rank correlation statistics to assess the correlation between turbidity measures on the same day.

We developed *a priori* analytical models to control for air temperature, day-of-week, and long-term time trends. We ran separate Poisson-generalized linear models (GLMs) (McCullagh and Nelder, 1989) for each drinking water treatment plant and calculated a weighted average of the plant-specific rate ratio parameter estimates based on the inverse of the variance. The basic model had the following conceptual form:

$$\begin{aligned} \text{Log}[E(Y)] = & \alpha + \sum_{i=0}^{20} \beta_i(\text{turbidity}_i) \\ & + \sum_{k=1}^7 \chi_k(\text{day - of - week}_k) \\ & + \sum_{m=1}^{20} \delta_m(\text{hospital}_m) \\ & + \sum_{w=1}^3 \sum_{p=1}^3 \varepsilon_{wp}(\text{temp_avg}_w)^p + g(\gamma_1, \dots, \gamma_N; t) \end{aligned}$$

where Y indicates the number of emergency department visits for GI illness in a given treatment plant's service area on a given day. We considered each of the four available turbidity exposure variables (turbidity) in separate models using a 21-day unconstrained distributed lag (Almon, 1965) encompassing turbidity on the same day as the emergency department visit and on the preceding 20 days. This model also included indicator variables for day-of-week, with a separate category included for federal holidays (day-of-week). The model included indicator variables for hospital entry and exit (hospital) because not all hospitals were able to contribute data for the entire study period. Temperature is represented in this model by a moving average of the first (temp_avg₁), second (temp_avg₂), and third (temp_avg₃) weeks preceding the day of the emergency department visit. We included quadratic and cubic terms to allow for greater flexibility in our control for average temperature. We controlled for long-term time trends using cubic splines with a knot (τ_j) each season for spring, summer, and autumn, and a knot each month for winter ($g(\gamma_1, \dots, \gamma_N; t)$). Knots placed at each month of the winter season were used to allow more degrees of freedom for control of the potential confounding impact of GI illness spikes caused by suspected rotavirus. The cubic splines were defined as follows:

$$g(\gamma_1, \dots, \gamma_N; t) = \gamma_1 t + \gamma_2 t^2 + \gamma_3 t^3 + \sum_{j=4}^N \gamma_j w_j(t),$$

where $\gamma_1, \gamma_2, \dots, \gamma_N$, were parameters to be estimated, time was denoted by t , and where $w_j(t) = (t - \tau_j)^3$ if $t \geq \tau_j$, and $w_j(t) = 0$ otherwise. The first and second derivatives of $g(t)$

are continuous, allowing time trends to be modeled as a smooth function. To avoid collinearity, we linearly transformed the cubic spline terms by multiplying the design matrix by the eigenvectors of its variance-covariance matrix. We scaled all variance estimates to account for Poisson overdispersion. Rate ratios were estimated by exponentiating the sum of the parameter estimates for each of the 21 days included in the distributed lag after multiplying each by the specified unit of increase in turbidity. The rate ratios derived from the models estimate the change in the rate of emergency department visits for GI illness for an average increment of 0.1 NTU for filtered water turbidity and 10 NTU for raw water turbidity over each 21-day period. We calculated 95% confidence intervals for all rate ratio estimates.

We conducted a number of secondary analyses. We considered age-specific models to assess possible effect modification by age. We also conducted secondary analyses in which the turbidity exposure was defined as a series of 3-day moving averages, in an attempt to identify the organisms that might be most responsible for drinking water-related GI illness because different waterborne pathogens have different incubation periods between exposure and onset of symptoms. For the first model in this series, we defined the turbidity exposure as the moving average of the turbidity measures on the day of the emergency department visits (day 0) and the preceding 2 days (days 1 and 2). This model was run separately from the second model in the series for which the turbidity exposure was defined as the moving average of the turbidity measures on the 3 days preceding the emergency department visits (days 1–3). We continued this pattern through to a model encompassing the moving average of turbidity measures on days 18–20 preceding the emergency department visits. In additional sensitivity analyses we included only zip codes served completely by a single-treatment plant, alternate case definitions for GI illness, and the impact of controlling for rainfall and the impact of alternate knot placement in the analytical model.

This study received approval from the Emory University Institutional Review Board and was conducted in accordance with the Common Rule.

Results

The mean filtered and raw water turbidity levels varied by treatment plant (Table 1). The mean daily average filtered water turbidity ranged from 0.03 to 0.17 NTU, and the mean maximum daily filtered water turbidity ranged from 0.04 to 0.29 NTU. The highest hourly filtered water turbidity measurement reported during the study period was 4.0 NTU. No EPA violations for Maximum Contaminant Level or Treatment Technique by any of the treatment plants occurred during the study period. The mean minimum daily raw water turbidity during the study period ranged from 1.1

Table 1. Distribution of daily turbidity variables by treatment plant service area, Atlanta, 1993–2004.

Plant	10%	25%	50%	75%	90%	Mean (standard deviation)
<i>Daily average filtered water turbidity (NTU)^{a,b}</i>						
A	0.01	0.02	0.03	0.04	0.05	0.03 (0.01)
B	0.03	0.04	0.06	0.07	0.08	0.06 (0.02)
C	0.03	0.05	0.07	0.09	0.11	0.07 (0.04)
D	0.06	0.06	0.07	0.08	0.10	0.08 (0.02)
E	0.03	0.04	0.07	0.13	0.20	0.10 (0.10)
F	0.06	0.09	0.15	0.23	0.29	0.17 (0.10)
G	0.04	0.05	0.05	0.07	0.08	0.06 (0.02)
H	0.05	0.06	0.07	0.09	0.12	0.08 (0.04)
All ^c	0.03	0.04	0.06	0.09	0.15	0.08 (0.07)
<i>Daily maximum filtered water turbidity (NTU)^{a,b}</i>						
A	0.01	0.02	0.04	0.05	0.07	0.04 (0.03)
B	0.05	0.07	0.08	0.10	0.14	0.09 (0.06)
C	0.09	0.09	0.11	0.12	0.15	0.11 (0.04)
D	0.07	0.08	0.09	0.11	0.13	0.10 (0.03)
E	0.06	0.08	0.13	0.23	0.37	0.19 (0.19)
F	0.08	0.13	0.28	0.41	0.50	0.29 (0.19)
G	0.05	0.05	0.07	0.08	0.10	0.07 (0.04)
H	0.06	0.08	0.09	0.13	0.18	0.12 (0.07)
All ^c	0.04	0.06	0.09	0.13	0.27	0.13 (0.13)
<i>Daily minimum raw water turbidity (NTU)^{a,b}</i>						
A	2.0	2.6	3.4	5.0	7.1	4.2 (2.8)
B	1.8	2.6	4.8	9.0	15.0	7.4 (7.9)
C	5.0	6.0	9.0	16.0	34.0	16.3 (22.9)
D	1.2	1.6	2.2	4.5	7.6	3.5 (2.9)
E	3.0	4.0	6.0	11.0	18.0	8.7 (7.8)
F	0.7	0.9	1.1	1.2	1.4	1.1 (0.3)
G	3.3	4.2	6.1	10.2	20.7	11.0 (16.5)
H	1.6	2.1	3.5	12.0	20.0	7.9 (8.3)
All ^c	1.2	2.0	4.2	8.2	16.0	7.5 (12.1)
<i>Daily maximum raw water turbidity^{a,b}</i>						
A	2.8	3.6	5.0	7.4	10.9	6.5 (7.0)
B	3.0	4.5	7.7	15.2	31.0	13.5 (16.2)
C	11.0	14.5	26.0	53.0	126.0	55.0 (101.3)
D	1.5	1.9	2.8	5.4	8.7	4.2 (3.3)
E	4.0	5.0	7.9	15.0	25.5	11.9 (10.8)
F	1.1	1.3	1.5	1.7	2.0	1.5 (0.4)
G	5.1	6.5	9.9	19.4	51.6	22.0 (34.3)
H	2.4	3.1	5.3	16.0	25.0	10.3 (10.0)
All ^c	1.6	3.0	6.1	14.3	31.1	15.7 (41.9)

NTU, nephelometric turbidity unit.

^aAverage, minimum, and maximum turbidity measures indicate the arithmetic average, minimum, or maximum, respectively, of hourly turbidity measures taken at the treatment plant in a 24-h period.

^bAverage filtered water turbidity data available: 7/1/1993–12/31/2004, except Plant C (1/1/1993–12/31/2004), Plant D (11/1/1999–12/31/2004), and Plant F (7/1/1993–12/31/1999; 1/1/2002–12/31/2004); maximum filtered water turbidity data available: 7/1/1993–12/31/2004, except Plant C (1/1/2000–12/31/2004), Plant D (11/1/1999–12/31/2004), and Plant F (7/1/1993–12/31/1999; 1/1/2002–12/31/2004); minimum and maximum raw water turbidity data available: 1/1/2002–12/31/2004, except Plant D (3/1/2002–12/31/2004).

^cAll plants combined.

Table 2. Daily emergency department visits for gastrointestinal illness, by plant service area, Atlanta, 1993–2004.

Plant	Mean daily visits	Percent of total emergency department visits for gastrointestinal illness
A	4.3	6.0
B	17.8	6.0
C	0.8	5.0
D	1.2	5.5
E	12.0	5.5
F	11.8	6.1
G	8.3	5.4
H	3.7	5.6
All plants combined	7.8	5.7

to 16.3 NTU, and the mean maximum daily raw water turbidity ranged from 1.5 to 55.0 NTU. The highest hourly raw water turbidity measurement reported during the study period was 1984 NTU. Although filtered water turbidity varied little by season, raw water turbidity levels peaked in winter. The average and maximum filtered water turbidity measures were highly correlated ($r=0.91$), as were the minimum and maximum raw water turbidity measures ($r=0.95$). The filtered and raw water turbidity measures showed little correlation with each other (all $|r|<0.1$).

Twenty-eight hospitals provided data on 7,642,118 emergency department visits in the five-county Atlanta area over the 12-year study period. After restricting to those zip codes for which a single treatment plant of service could be assigned, 4,179,340 emergency department visits remained; 240,925 (5.8%) for GI illness. The average daily number of emergency department visits varied by treatment plant service area, reflecting the different population sizes of the plants' service areas, as the proportion of total emergency department visits for GI illness was very similar across plants (Table 2). Counts of GI illness varied markedly by season, with large winter peaks, particularly among children. These peaks corresponded to peaks in visits for diagnosed rotavirus (although the latter counts were much smaller than the former counts, due to lack of laboratory confirmation in the majority of cases), which occurred almost exclusively among children. No drinking water-related disease outbreaks were reported in the Atlanta area during the study period.

The residuals (observed minus expected counts) correlated only weakly with those for neighboring dates in the *a priori* models using GLM procedures (all $r<0.07$) indicating the splines were probably accounting well for autocorrelation.

Filtered Water Turbidity

Overall, we observed little association between filtered water turbidity and GI illness, with a summary rate ratio estimate of 0.98 (95% confidence interval (CI) = 0.96–1.01) for a 0.1 NTU average incremental increase in average filtered water

Table 3. Rate ratio estimates and 95% confidence intervals from *a priori* models for the association of daily drinking water turbidity measures with emergency department visits for gastrointestinal illness in Atlanta, 1993–2004.

	Average filtered water turbidity ^a	Maximum filtered water turbidity ^a	Minimum raw water turbidity ^b	Maximum raw water turbidity ^b
Summary	0.98 (0.96, 1.01)	0.99 (0.98, 1.01)	1.06 (1.04, 1.08)	1.02 (1.01, 1.03)
<i>Stratified by drinking water treatment plant</i>				
Plant A	0.64 (0.32, 1.26)	0.79 (0.56, 1.11)	1.08 (0.90, 1.30)	1.10 (0.99, 1.23)
Plant B	1.05 (0.92, 1.20)	1.01 (0.95, 1.07)	1.07 (1.03, 1.11)	1.02 (1.00, 1.04)
Plant C	0.96 (0.81, 1.15)	1.23 (0.69, 2.22)	1.05 (0.97, 1.14)	1.01 (0.98, 1.03)
Plant D	0.36 (0.12, 1.14)	0.47 (0.22, 1.01)	0.63 (0.26, 1.53)	0.81 (0.41, 1.62)
Plant E	0.98 (0.95, 1.00)	0.98 (0.97, 1.00)	1.08 (1.04, 1.12)	1.06 (1.03, 1.09)
Plant F	1.00 (0.94, 1.07)	1.01 (0.97, 1.04)	2.07 (0.61, 7.01)	1.29 (0.48, 3.48)
Plant G	1.68 (1.26, 2.24)	1.26 (1.07, 1.47)	1.06 (1.02, 1.09)	1.02 (1.00, 1.04)
Plant H	0.68 (0.45, 1.03)	0.85 (0.68, 1.06)	0.93 (0.83, 1.03)	0.94 (0.86, 1.03)
<i>Stratified by age group</i>				
0–5 years	0.94 (0.90, 1.00)	0.98 (0.95, 1.01)	1.11 (1.08, 1.15)	1.04 (1.03, 1.06)
6–18 years	1.00 (0.93, 1.08)	1.00 (0.95, 1.04)	1.01 (0.94, 1.08)	0.99 (0.96, 1.02)
19–64 years	0.99 (0.96, 1.02)	0.99 (0.97, 1.01)	1.03 (1.00, 1.06)	1.01 (0.99, 1.02)
65+ years	1.00 (0.92, 1.09)	0.99 (0.94, 1.04)	0.99 (0.92, 1.06)	1.02 (0.99, 1.06)

^aUnit of change for rate ratio estimates for filtered water turbidity measures was 0.1 NTU over 21 days encompassing day of emergency department visit and preceding 20 days.

^bUnit of change for rate ratio estimates for raw water turbidity measures was 10 NTU over 21 days encompassing day of emergency department visit and preceding 20 days.

turbidity and 0.99 (95% CI=0.98–1.01) for maximum filtered water turbidity. Although the majority of the plant-specific rate ratio estimates were consistent with the null (Table 3), the rate ratio estimate for Plant G was 1.68 (95% CI=1.26–2.24) using the average filtered water turbidity exposure metric and was 1.26 (95% CI=1.07–1.47) when maximum filtered water turbidity was considered.

Raw Water Turbidity

We observed a modest association with emergency department visits for GI illness for both minimum and maximum raw water turbidity. The summary rate ratio estimate for a 10 NTU average incremental increase in daily minimum raw water turbidity was 1.06 (95% CI=1.04–1.08) and when daily maximum raw water turbidity was considered, the summary rate ratio estimate was 1.02 (95% CI=1.01–1.03). The rate ratio estimates from the plant-specific models also displayed heterogeneity with the raw water turbidity exposure (Table 3), but were generally consistent with a positive association with GI illness.

Secondary Analyses

When we considered each age group separately, we observed little association of GI illness with filtered water turbidity measures (Table 3). For raw water turbidity, however, the majority of the rate ratio estimates for the different age groups were greater than one. The association of raw water turbidity with GI illness for children age 5 years and younger was somewhat stronger than for the other age groups.

When we considered turbidity as a series of 3-day moving averages, results were consistent with those from models using our *a priori* lag structure (Figure 1). All rate ratio estimates from models for which filtered water turbidity was used as the exposure metric were consistent with the null. All the rate ratio estimates from models for which raw water turbidity was used as the exposure metric were greater than one. The strongest associations were observed for lags incorporating turbidity measures approximately 6 through 9 days before the date of the emergency department visits. Similar results were observed when the daily maximum raw water turbidity measure was considered as the exposure metric, although the rate ratio estimates were attenuated.

The results of the other secondary analyses are presented in Table 4.

Discussion

Drinking water utilities and regulatory agencies have long been concerned that turbidity is too crude a measure of particle concentration to be used as an indicator of pathogen occurrence in drinking water (Trussell, 2006). Although turbidity removal is often correlated with pathogen removal (Niemiński, 1992; LeChevallier and Norton, 1993; Hendricks et al., 1998; U.S. Environmental Protection Agency, 1999), the association between absolute turbidity and pathogen concentration in raw and filtered water is often weak (Logsdon et al., 1985; LeChevallier et al., 1991; Edzwald and Kelley, 1998; Payment, 1998; Payment and

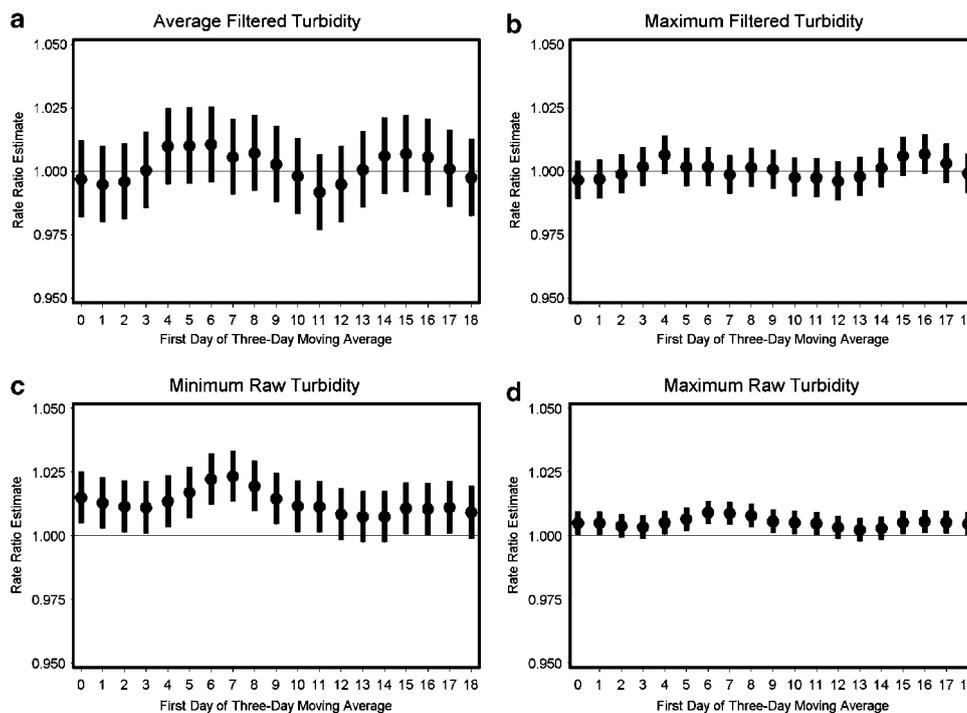


Figure 1. Rate ratio estimates (circles) and 95% confidence intervals (vertical lines) for a 3-day moving average increase of 0.1 NTU in (a) daily average and (b) daily maximum filtered water turbidity and 10 NTU in (c) daily minimum and (d) daily maximum raw water turbidity and emergency department visits for gastrointestinal illness in Atlanta, 1993–2004.

Table 4. Rate ratio estimates and 95% confidence intervals from primary analysis and sensitivity analyses assessing the association of daily drinking water turbidity measures with emergency department visits for gastrointestinal illness in Atlanta, 1993–2004.

	Average filtered water turbidity ^a	Maximum filtered water turbidity ^a	Minimum raw water turbidity ^b	Maximum raw water turbidity ^b
Primary analysis ^c	0.98 (0.96, 1.01)	0.99 (0.98, 1.01)	1.06 (1.04, 1.08)	1.02 (1.01, 1.03)
<i>Sensitivity analysis: include only zip codes served 100% by a single treatment plant^d</i>	1.03 (0.96, 1.09)	1.00 (0.96, 1.03)	1.06 (1.03, 1.09)	1.02 (1.00, 1.03)
<i>Sensitivity analysis: alternate case definitions^e</i>				
Infectious only	0.96 (0.89, 1.05)	0.99 (0.94, 1.04)	1.02 (0.94, 1.12)	1.02 (0.98, 1.06)
Primary ICD-9	0.99 (0.96, 1.02)	1.00 (0.98, 1.02)	1.07 (1.04, 1.10)	1.02 (1.01, 1.04)
Broad	0.99 (0.98, 1.01)	0.99 (0.98, 1.01)	1.03 (1.01, 1.05)	1.01 (1.00, 1.02)
<i>Sensitivity analysis: control for rainfall in the analytical model</i>	1.01 (0.98, 1.04)	0.99 (0.98, 1.01)	1.04 (1.01, 1.07)	1.01 (1.00, 1.03)
<i>Sensitivity analysis: alternate knot placement in time spline to control for long-term time trends</i>				
Seasonal knots	1.00 (0.97, 1.02)	1.00 (0.99, 1.01)	1.06 (1.04, 1.09)	1.02 (1.01, 1.03)
Monthly knots	0.95 (0.90, 1.01)	0.97 (0.95, 1.00)	1.04 (1.01, 1.08)	1.01 (1.00, 1.03)

^aUnit of change for rate ratio estimates for filtered water turbidity measures was 0.1 NTU over 21 days encompassing day of emergency department visit and preceding 20 days.

^bUnit of change for rate ratio estimates for raw water turbidity measures was 10 NTU over 21 days encompassing day of emergency department visit and preceding 20 days.

^cPrimary analysis: Plant-specific GLM models with turbidity included as a 21-day distributed lag (days 0–20 preceding the emergency department visits), indicators for day-of-week, hospital entry/exit; separate moving averages of temperature for weeks 1, 2, and 3 preceding the emergency department visits, with quadratic and cubic terms; cubic splines with seasonal knots during spring, summer, and autumn, and monthly knots during winter. Summary results calculated using weighted-average of the plant-specific rate ratio estimates, with weights based on the inverse of the variance.

^dPrimary analysis included zip codes served 80% or more by a single treatment plant.

^eInfectious-only alternate case definition included ICD-9 codes (primary and all secondary; including all extensions): 001-004, 005.0, 005.4, 005.89, 005.9, 006-007, 008.0, 008.42-008.44, 008.47, 008.49, 008.5, 008.6, 008.8, 009; primary ICD-9 alternate case definition included primary ICD-9 codes (including all extensions): 001-004, 005.0, 005.4, 005.89, 005.9, 006-007, 008.0, 008.42-008.44, 008.47, 008.49, 008.5, 008.6, 008.8, 009, 558.9, 787.01-787.03, 787.91; broad alternate case definition included ICD-9 codes (primary and all secondary; including all extensions): 001-009, 276, 787, 789, 558.3, 558.9.

Hunter, 2001). Our results, which suggested little association between filtered water turbidity and rates of emergency department visits for GI illness, may reflect this limitation. Although we observed an association between raw water turbidity and rates of GI illness, it is filtered water turbidity that is regulated by EPA and State standards, and we found no association between this measure and emergency department visits for GI illness.

Many microorganisms are too small to be detected by conventional turbidimeters. The utility of turbidity as a metric of microbial water quality stems from the assumption that as the concentration of suspended particles, such as clay and silt, increases in the water, so do the levels of microorganisms. How well the concentration of microorganisms in water may be correlated with changes in the concentration of larger particles and changes in turbidity is highly variable, depending on the conditions leading to the turbidity change (Gauthier et al., 2003). Turbidity in surface waters generally increases after rainfall (Atherholt et al., 1998; Gauthier et al., 2003). However, a heavy rainfall following a period of drought may be more likely to produce runoff that will suspend microbial pathogens that are concentrated in fecal deposits near the shore into the water. During conditions of regular rainfall, however, runoff may continue to wash clay and silt into the water and increase the turbidity, but this may not introduce as many pathogens as the “first flush” rainfall. A different phenomenon may impact the value of turbidity as an indicator of microbial water quality for filtered water. The size and charge of a particle determine its likelihood of being removed from the raw water during filtration (Van der Bruggen et al., 1999). Clay and silt may be more likely to be removed during filtration than some microorganisms due to their size and charge. Some treatment processes may markedly alter the turbidity of the treated water with little or no change in the concentration of some microbial pathogens, especially if the microorganisms are not adsorbed to particulates. Therefore, the turbidity of filtered water may be less correlated with the concentration of microorganisms than the turbidity of raw water.

The only other related time-series study that considered both raw and filtered water turbidity was conducted in France and examined the association between turbidity and sales of over-the-counter antidiarrheal medications (Beaudeau et al., 1999). These researchers found an association between raw water turbidity and antidiarrheal drug sales in the following 3 weeks, but not with filtered water turbidity. Although the authors provided little detail on the statistical methods used, the results of that time-series study appear to be consistent with those of our study. The evidence from these two studies considered together is strengthened because very different outcome measures of GI illness were each associated with raw water turbidity.

Our overall results did not show an association between increases in filtered water turbidity and emergency depart-

ment visits for GI illness. However, in the plant-specific analysis, a positive association was observed for Plant G. If this association reflects drinking water quality, it could be explained by differences in raw water quality or treatment effectiveness at this utility compared to the other utilities. Plant G had the second highest mean raw water turbidity of the treatment plants examined in this study. The source of water for this plant is a river that receives treated wastewater 3.5 miles upstream of the raw water intake, making it highly vulnerable to pathogen contamination.

Results stratified by age group were also generally consistent with little or no association of GI illness with filtered water turbidity. For raw water turbidity, the strongest associations in the age-specific analyses were observed for the youngest children. These results are consistent with other studies in which GI illness tends to more heavily impact the young, likely due to their underdeveloped and naïve immune systems (Glass et al., 1991; Jin et al., 1996).

In this study, our causal question of interest is whether the rate of emergency department visits for GI illness for the population residing in a given treatment plant’s service area is related to pathogen level at the plant as reflected in turbidity measures. Thus, the exposure of interest is water quality as it leaves the plant, not water quality at the point of consumption. Because our exposure of interest is a measurement of water quality as it leaves the treatment plant serving the study population at their residences, individual-level behavior at the point of consumption, such as drinking bottled water, drinking water outside the residential service area, or use of home treatment devices, are not sources of bias. Rather than a bias, the association of interest we are seeking to estimate is truly reduced by the fact that the population of interest does not rely exclusively on municipal water for its drinking water, and this therefore influences the public health impact of water quality at the treatment plant. If, on the other hand, our causal question was whether ingestion of a particular pathogen at a particular level causes illness, individual-level characteristics at the point of consumption could be a source of bias.

The use of turbidity measured at the treatment plant as a surrogate for pathogen level measured at the treatment plant is a source of measurement error. We expect that this source of error is unrelated to risk, conditional on true pathogen level, and therefore any bias due to this error will be in the direction of the null. This limitation is important to consider given the null results we observed for the filtered water turbidity exposure. Another source of information bias was our inclusion of zip codes that were served up to 20% by a treatment plant other than the one from which the turbidity exposure was taken, although sensitivity analyses in which only zip codes served entirely by a single treatment plant were considered yielded similar results to the main analyses.

Determining the exposure window for GI illness due to drinking water exposure is difficult given the many factors

impacting the lag time between the turbidity measurement at the treatment plant and the emergency department visit for GI illness. This lag time encompasses the storage and travel time of the water from the treatment plant to the home, the incubation period of the pathogen, and the time from illness onset to presentation at an emergency department. In previous time-series studies, many lag structures were considered in multiple models, and the authors presented only the statistically significant results (Schwartz et al., 1997, 2000). These authors subsequently clarified their results, by demonstrating the overall consistency of the results for different lags, even among those estimates that were not statistically significant (Schwartz and Levin, 1999). However, the results as initially reported raised concerns about the possibility of statistically significant associations being observed by chance due to multiple testing. To mitigate this concern from the outset, our primary analysis used an *a priori* lag structure (a 21-day distributed lag) and reserved exploration of alternative lag structures for secondary analyses.

We observed modest positive associations between raw water turbidity and emergency department visits for GI illness. Although positive associations were observed throughout the 21-day lag period, the strongest associations were observed for increased turbidity 6–9 days before reporting to an emergency department for GI illness. This lag period is consistent with all three of the major types of organisms causing waterborne disease. Generally, enteric viruses have short incubation periods (24–48 h) (Chin, 2000), and enteric protozoa have a longer incubation period (7–14 days) (Chin, 2000). The incubation periods for bacterial waterborne pathogens vary, but generally fall between those of viruses and protozoa. Therefore, a 6- to 9-day lag window is reasonable to capture the majority of waterborne pathogens when the travel time of water in the distribution system is taken into account. (Estimated travel times in these systems ranged from a few hours to a few days, and less commonly as much as 2 weeks.)

Each of the four available turbidity measures considered has a different implication regarding an association with GI illness. A high average filtered water turbidity or minimum raw water turbidity suggests a more long-term source of contamination compared to maximum filtered water turbidity or raw water turbidity, for which high levels may be indicative of isolated incidents leading to spikes in turbidity. Because we examined many models, the implications of a particular statistically significant result should be interpreted with caution.

We present the rate ratio estimates based on a unit change of 0.1 NTU for filtered water turbidity and of 10 NTU for raw water turbidity. These increments correspond to approximately the interquartile range for turbidity measures from all plants combined, but not necessarily to the actual range of variation in turbidity measured for a particular treatment plant. These increments were used so that we could

summarize and compare results across treatment plants. A different unit of change in turbidity would change the magnitude of the rate ratio estimates, but it would not impact their direction relative to the null, or whether the 95% confidence intervals encompass the null.

We were unable to confirm an infectious cause for all of the cases of GI illness we included in our outcome group, having to rely largely on symptoms consistent with an infectious agent. Our case definition, using ICD-9 diagnostic codes, was designed to maximize the inclusion of cases of infectious GI illness and the exclusion of non-infectious GI illness. Many other case definitions are possible, and in sensitivity analyses we considered three alternate definitions: a highly specific case definition, including only cases of GI illness for which an infectious organism was isolated; a definition based only on primary ICD-9 codes (instead of all available codes, as was used in our primary case definition); and a broad case definition, additionally including more general GI symptoms, such as abdominal pain. The analyses in which the more restrictive infectious definition was considered did not have sufficient power to detect the modest associations observed when our *a priori* case definition was used. The results from the models in which cases of GI illness were defined using only primary ICD-9 codes were almost identical to those observed in our primary analysis, with slightly wider confidence intervals due to the decreased sample size. When the broad case definition was considered we observed similar results to those seen when our *a priori* case definition was used, although the risk ratio estimates were attenuated, as expected given the less specific definition.

We were only able to include ED visits from 58% of the zip codes in the study area, accounting for 58% of all ED visits in our database. However, the proportion of visits for GI illness was similar among the included and excluded subjects, as was the proportion of patients paying with Medicaid, the age distribution of the patients, and the zip code median income, minimizing concerns regarding selection bias and generalizability.

The complete participation of the emergency departments and drinking water utilities serving the study area allowed us to compile a large database, a major asset of the study. The outcome group for our study, people visiting an ED for GI illness, is not representative of all people in metropolitan Atlanta with GI illness. We studied only cases of GI illness severe enough to warrant an ED visits, and that population is likely to be of lower socioeconomic status (SES) than the general population (Walls et al., 2002). Although these cases represent only a small proportion of all infectious cases of GI illness, they may be those of greatest public health interest. Despite the fact that we focused on more severe cases of GI illness, and that we had moderate levels of misclassification, we were still able to detect an association between emergency department visits for GI illness and raw water turbidity due to the statistical power provided by our large database.

A strength of the time-series approach is that the same population over time is being compared so it is not necessary to control for a number of factors, such as SES, that might differ from area to area. Confounding can still occur, however, due to temporally varying factors. We attempted to control for covariates that may have been temporally associated with both turbidity levels and emergency department visits for GI illness by including air temperature and day of the week as variables in the analytical model. We did not control for rainfall because turbidity is in the theoretical pathway of an association between rainfall and GI illness. In sensitivity analyses, we considered models including a 21-day moving average of rainfall. The rate ratios estimated in these analyses were attenuated compared to those estimated from the *a priori* models, but were consistent with an association between raw water turbidity, but not filtered water turbidity, and emergency department visits for GI illness.

We attempted to account for long-term time trends that could confound our analysis using a cubic spline with six knots per year, with one per season for spring, summer, and autumn, and one per month for winter. The choice of knot placement must balance the risk of overcontrolling, potentially reducing the variation due to exposure, with the risk of undercontrolling, which could lead to residual confounding. In sensitivity analyses, we considered only seasonal knots (4 year⁻¹) and only monthly knots (12 year⁻¹) in the cubic spline. When models with the seasonal knots were considered, the results were similar to those from the *a priori* models. The rate ratio estimates were systematically attenuated from models in which the monthly knot spline was included, but the results were consistent with the conclusions from the *a priori* models.

Our results suggest that pathogen exposure through drinking water may modestly contribute to endemic GI illness in this study area. The association between turbidity and GI illness was only observed when raw water turbidity was considered. Conversely, filtered water turbidity may not be a reliable indicator of modest pathogen risk from treated drinking water for filtered water turbidities less than 0.3 NTU. The development of more refined indicators of water quality and health risk, such as standardized and reliable particle counters (Trussell, 2006) or the use of more sensitive microbial indicators, should continue to be pursued.

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