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Water quality as a predictor of gastrointestinal illness following incidental contact water recreation

Samuel Dorevitch [a, *], Stephanie DeFlorio-Barker [a], Rachael M. Jones [a], Li Liu [b]

[a] Division of Environmental and Occupational Health Sciences, University of Illinois at Chicago School of Public Health, 2121 W. Taylor Street M/C 922, Chicago, IL 60612, USA

[b] Division of Epidemiology and Biostatistics, University of Illinois at Chicago School of Public Health, 2121 W. Taylor Street M/C 922, Chicago, IL 60612, USA

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A B S T R A C T

Microbial measures of water quality are predictors of gastrointestinal illness among swimmers in some settings but not in others. Little is known whether water quality measures predict illness among people who engage in popular water recreation activities such as paddling, rowing, fishing, or boating ("incidental contact water recreation"). We sought to evaluate indicator microbes, protozoan pathogens, and turbidity as predictors of gastrointestinal illness following incidental contact water recreation. A cohort study of incidental contact water recreation was conducted in the Chicago, USA area. Recreation took place on inland lakes, rivers, Lake Michigan, and an urban waterway heavily impacted by wastewater effluent. Water samples were analyzed for *Escherichia coli*, enterococci, somatic coliphages, F+ coliphages, *Giardia* spp. and *Cryptosporidium* spp. (oo)cysts, and for turbidity. Median enterococci concentrations were 71.0 and 199.8 colony forming units/100 mL at general use and effluent-dominated waters, respectively. Among 4694 study participants with complete covariate data, 193 (4.1%) developed gastrointestinal illness within three days of water recreation. In multivariable logistic regression analysis, water quality metrics did not predict gastrointestinal illness among water recreators. Several variables other than water quality were associated acute gastrointestinal illness. The odds of such illness was increased by approximately two-fold by the presence of a chronic gastrointestinal condition, water exposure to the face, and by approximately 50% among those who fished (as opposed to other incidental contact activities). The odds of illness were reduced by approximately 50% among individuals who frequently used a water body for recreation. Unlike studies of swimmers at wastewater-impacted beaches that observed associations between water quality and illness incidence, this study did not. Public health protections for incidental contact recreation might focus on reducing exposure, particularly among fishers, those with chronic gastrointestinal conditions, and new recreators.

1. Introduction

Epidemiologic studies of water recreation have consistently found that swimmers develop gastrointestinal illness more frequently than non-swimmers at freshwater (Wade et al., 2008, 2006), marine (Arnold et al., 2013; Colford et al., 2007; Wade et al., 2010) and riverine (Ferley et al., 1989) beaches. Controlled exposure studies, in which participants were randomly assigned to either remain on the beach (avoiding water contact) or to perform head immersion in beach water, have also consistently found that water-exposed individuals are more likely to develop gastrointestinal illness than the unexposed (Fleisher et al., 2010; Kay et al., 1994; Wiedenmann et al., 2006).

Less consistent are findings of studies that have used microbial measures of water quality to predict the occurrence of illness. For example, at two California beaches, swimmers were more likely than non-swimmers to develop illness, but among swimmers, densities of fecal indicator bacteria measured by culture or quantitative polymerase chain reaction (qPCR) were not predictive of gastrointestinal illness occurrence (Arnold et al., 2013; Colford et al., 2007). Likewise, a controlled exposure study set in Florida found that water-exposed individuals were more likely to develop illness than unexposed individuals (Fleisher et al., 2010), though within the water-exposed group, no association was observed

* Corresponding author.
E-mail address: sdorevit@uic.edu (S. Dorevitch).

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between gastrointestinal symptoms and enterococci (measured by culture and qPCR) or Bacteroidales (measured by qPCR) (Sinigalliano et al., 2010).

Studies of the health risks of swimming have utilized “fecal indicator bacteria” (FIB), microbes that indicate the presence of fecal contamination, including *Escherichia coli* and/or enterococci, as predictors of illness. Although pathogens – microbes that cause illness in humans – can be measured in surface water, few epidemiologic studies of water recreation have included pathogen measurements, in part because they are difficult and costly to perform. Adenovirus, enterovirus, and norovirus were evaluated as predictors of illness among swimmers at Mission Bay, CA (Colford et al., 2007), though pathogen detection was infrequent and not predictive of illness. Coliphages, viruses that infect *E. coli*, have shown some promise as predictors of illness among individuals randomized to water exposure (head immersion) in inland waters (Wiedenmann et al., 2006), among swimmers in relatively clean marine water (Colford et al., 2007), and among users of a white-water slalom course fed in part by treated wastewater (Lee et al., 1997).

Epidemiologic studies that evaluated water quality as a predictor of short-term health risks following water recreation have generally addressed swimming (or “full contact water recreation”), while only a few relatively small studies have addressed incidental contact water recreation, such as canoeing, kayaking, fishing, rowing, or boating (Fewtrell et al., 1992; Lee et al., 1997). As a result, while incidental contact water recreation is popular and takes place on some waters where swimming is prohibited, water quality standards that safely support such recreation have yet to be established nationally in the US. We previously reported that in the Chicago Health, Environmental Exposure, and Recreation Study (CHEERS), users of Chicago area surface waters for incidental contact water recreation activities were at risk for developing acute gastrointestinal illness (AGI). Participants used either the engineered Chicago Area Waterways System, which includes the Chicago River and is predominantly treated, but non-disinfected wastewater effluent, or general use waters that could support full-contact water recreation. The risk of AGI attributable to incidental contact recreation was 13.7 (95% confidence interval 3.1, 27.4) and 15.1 (2.6, 25.7) per 1000 uses at effluent dominated and general use locations, respectively (Dorevitch et al., 2012b). The primary objective of the present study is to evaluate microbial measures of water quality, including coliphages and the protozoan pathogens *Giardia* spp. and *Cryptosporidium* spp., as predictors of gastrointestinal illness occurrence among incidental contact water recreators.

2. Materials and methods

2.1. Overview

Prior publications provide details about the setting, short-term health risks of incidental contact water recreation (Dorevitch et al., 2012b), estimated volume of water swallowed during water recreation (Dorevitch et al., 2011b), pathogens detected in stool samples from CHEERS participants who developed gastrointestinal symptoms (Dorevitch et al., 2012a), and measures of viral (Aslan et al., 2011) and protozoan (Dorevitch et al., 2011a) pathogens in the waters studied. Briefly, incidental contact water recreators as well as individuals who engaged in non-water recreation (such as jogging, cycling, walking, and team sports) were recruited at boat launches, harbors, piers, and beaches in the Chicago area. Data collection methods, including survey instruments, were based on the US Environmental Protection Agency's National Environmental and Epidemiologic Assessment of Recreational water (NEEAR) study (Wade et al., 2008, 2006, 2010). Participants underwent a pre-recreation interview to establish eligibility, and a post-recreation interview to evaluate water exposure during recreation as well as other risk factors for illness. Water exposure was assessed by asking participants a series of questions about swallowing water as well as head/face, and trunk exposure. Ordinal response options included none, a few drops, splashed, drenched, or submerged. These response options were validated as being associated with varying degrees of water exposure using a chemical tracer in a swimming pool (Dorevitch et al., 2011b). Participants were interviewed by telephone on approximately days 2, 5, and 21 post-recreation to evaluate the occurrence of symptoms. For their time and effort participants received a T-shirt and a $15 gift card upon completion of the post-recreation interview (in the field). At the completion of telephone follow-up each was sent a check for $35. Follow-up data were available from 11,297 individuals, or 94.5% of the 11,733 who completed the field interviews and did not have gastrointestinal symptoms at baseline. In the present analysis, we focus on the 7710 study participants who engaged in incidental contact water recreation on either the effluent-dominated or the general use waters.

Definition of illness: AGI was defined as the occurrence of 1) any vomiting and/or 2) at least three loose stools in a 24 h period, and/or 3) nausea or stomachache that interfere with daily activity, or 4) nausea with stomach ache, consistent with the NEEAR definition of AGI (Wade et al., 2008, 2006, 2010). Based on Kaplan–Meier analysis of illness onset among CHEERS participants (Dorevitch et al., 2012b), AGI was defined as the occurrence of these symptoms during the three days following enrollment (rather than the 10–12 day period used in NEEAR). The 0–3 day window was selected because since the publication of NEEAR findings, it has become clear from Kaplan–Meier analyses of CHEERS data (Dorevitch et al., 2012b) as well as other cohort studies conducted at California beaches (Arnold et al., 2013; Colford et al., 2012) that the difference between water recreators and non-water recreators in the rate of new onset AGI symptoms is greatest during that brief, initial time period following water recreation. Individuals with any gastrointestinal symptoms when starting water recreation were excluded from analyses of AGI.

2.2. Water sample analysis

Grab samples of surface water (<10 cm from the surface) were collected every two hours during water recreation using a telescoping pole from boat launches and piers at locations where recreation began and ended. Recreation and recruitment took place at 1–4 recreational areas per study day, and water sampling locations at each recreational area were constant throughout the duration of the study. Grab samples were for analysis of *E. coli*, enterococci, somatic coliphage, F+ coliphage, and turbidity. Twenty liter samples were collected approximately every 6 h for protozoan (oo)cyst analysis. Grab samples were analyzed by membrane filtration for *E. coli* (EPA Method 1603) and enterococci (EPA Method 1600) using five different dilutions per sample. Culture results used in data analyses were those from the dilution that produced approximately 20–60 colony forming units (CFU) per plate (USEPA R&D, 1978). These analyses were performed by certified commercial laboratories. Scientific Methods, Inc. (Granger, IN) analyzed somatic and F+ coliphage analyses by EPA Method 1602, and Giardia *spp*. and *Cryptosporidium* spp. (oo)cyst analyses by EPA Method 1623 following continuous flow centrifugation of 20 L samples as described previously (Dorevitch et al., 2011a). Turbidity was measured on site using HF Scientific MicroTPW portable turbidimeters. Quality assurance measures included the use of blinded field blanks, replicate samples, and spiked samples. Participants were enrolled into the study over periods that ranged from 1 to 12 h per location per day of recruitment. The location-specific daily mean of each water quality measure was linked to the health survey data of all participants enrolled that day at that location (Arnold et al., 2013; Wade et al., 2008).

Data quality of microbe measures was evaluated by analysis of 1) initial and ongoing recovery studies of spike matrix samples, 2) precision of split-sample analyses, and 3) holding time. Between August 1, 2008 and May 8, 2009 mean recoveries for *E. coli* and enterococci were acceptable, but recovery within individual spiked samples was highly variable and field blanks were occasionally positive, while samples from highly polluted waters were often negative for enterococci and *E. coli*. Data quality remained excellent during this period for coliphages and protozoan parasites, which were collected, processed, and transported by the same staff as those who collected the samples for FIB analysis, but were analyzed at a different laboratory (Scientific Methods, Inc., Granger, IN). As a result of this persistent problem, a different commercial laboratory (Microbac, Inc., Merrillville, IN) was used for the remainder of the study for analyses of FIB. Sporadically, during the period of generally acceptable performance, the quality monitoring criteria were not met and data were also considered missing for *E. coli* (16 of 99 dates) and enterococci (20 of 99 dates). Epidemiologic data analysis excluded *E. coli* and enterococci data from dates that quality monitoring criteria were not met. Water quality was described in two ways: as a summary of water quality measurements, and as a summary of water quality measurements weighted by the number of people who participated in the study each day at each location. The un-weighted approach reflects surface water quality while the weighted approach reflects the water quality exposures of study participants.

2.3. Data analysis

Logistic regression was used to model the occurrence of AGI. Seven sets of models were run for effluent dominated waters and seven sets for general use waters. Each set of models containing one measure of water quality (one of the two indicator bacteria, two indicator viruses, two protozoan pathogens, or turbidity) plus covariates. Covariates considered to be potential confounders were season (summer vs. spring or fall), age category ($\leq$10 years, 11–64 years, $\geq$65 years), gender, race (white vs. other), recreational activity (fishing, rowing, other), swallowing water during recreation (any vs. none), face got wet (any vs. none), face/head was drenched or submerged (vs. lower degrees of exposure), a history of chronic gastrointestinal condition, and frequent use of the same water location group (effluent-dominated or general use) in the past year (defined post-hoc as 15 or more times as this cut-point resulted in the strongest association with GI illness occurrence). Washing hands after recreation but prior to eating/drinking was considered as a potential confounder. Eating specific foods in the 72 h before recreation was not considered, as prior analyses found that the ingestion of undercooked meat, fresh produce, pre-packaged sandwich, raw or runny eggs, shellfish, or sushi were unassociated with illness in multivariate models (Dorevitch et al., 2012b). Additionally, variables that were evaluated as potential effect modifiers (described below) but for which interaction terms did not approach statistical significance were also considered for inclusion in models as confounders. All models were run using a single set of observations that had complete data for covariates other than water quality.

Potential modifiers of associations between water quality and illness were defined a priori: 1) whether the study participant used waters dominated by wastewater effluent vs. general use waters; 2) the occurrence of precipitation within the prior 48 h; and 3) the number of times a participant used the same water location group (effluent dominated vs. general use) in the prior year (Lee et al., 1997), which may impact susceptibility to infection. For users of effluent-dominated waters only, two other potential effect modifiers were considered a priori: the perceived health risk of water recreation on the Chicago River system, as perceived risk has been shown to impact symptom reporting (Fleisher and Kay, 2006); and the occurrence of combined sewer overflow events within the 72 h prior to recreation. To identify potential effect modifiers, AGI was modeled using three predictors: a measure of water quality, a potential effect modifier, and the interaction term of the two (for example, precipitation, *E. coli*, and precipitation**E. coli*). A separate set of models was run for each of the seven measures of water quality. Interaction terms significant at a $p \leq 0.30$ level were included as effect modifiers in subsequent full models (which contained the potential confounders noted in the prior paragraph). Three-way interactions (e.g., water quality * location group * precipitation) were not explored. Instead models stratified by location group were fitted, for example water quality * precipitation, for effluent-dominated and separately for general use waters.

Three variations of each of the seven sets of models (each containing a different measure of water quality), for each water location group, were run, parameterizing water quality one of three ways: as continuous variables on a linear scale, on a $\log_{10}$ scale, as binary variables dichotomized at the 75th percentile value, and as an estimate of ingested dose (on linear and log10 scales). The 75th percentile values were specific to each location group. The ingested dose of microbes was estimated using results from the post recreation survey, in which participants were asked whether they had swallowed water during recreation, and if so, whether they had swallowed "a drop or two," "a teaspoon," or "a mouthful or more." The estimated dose of microbe ingested was the product of the day-location microbe density and the estimated volume of water ingested by individual participants. Though not a microbe dose, volume ingested*turbidity was calculated as well.

A change in estimate (CIE) approach was used to reduce a full model (containing all covariates under consideration) to a more parsimonious model while retaining confounders. This was accomplished by using the SAS® CIE macro (Atashili and Ta, 2007) to sequentially remove covariates that had the smallest impact on the parameter estimate of the water quality term. Beginning with n covariates, n models each containing $n-1$ covariates, each missing a different term, were run. The change in the parameter estimate of the water quality term was evaluated relative to the water quality parameter estimate obtained in the full model. The covariate that, when dropped from the model had the smallest impact on the water quality-AGI association was removed from subsequent iterations. This process was repeated until a covariate, when removed, resulted in a 5% change in the parameter estimate of the water quality term. Final models were fitted for each water group (effluent dominated and general use) and preferred models were identified based on Hosmer–Lemeshow goodness of fit testing. Because some of the covariates selected by the CIE process might be on the causal pathway between water quality and illness (such as water exposure metrics), models were run with and without such terms. In addition to associations between water quality and illness, we sought to characterize the associations between other covariates and illness. For each water location group a set of common covariates was identified based on their presence in the various location-group by water quality models. Some covariates were selected for inclusion by the CIE process for nearly all models, while specific exposure terms (swallowed any water, face got wet, face got drenched, etc.) and recreation terms (rowing vs. other, fishing vs. other) varied. Exposure and activity variables that were found in the largest number of models were included in the common set of covariates for modeling illness occurrence in each location group.

2.4. Human research subject protections

This research was approved by the UIC Institutional Review Board and included a written documentation of informed consent/assent.

3. Results

3.1. Study participants

7710 water recreators enrolled in the study and participated in telephone follow-up. Of these, 342 (4.4%) had at least one GI symptom at baseline and were excluded from analysis. Of the 7368 water recreators at risk for developing AGI, complete coliphage, parasite, and turbidity data were available for 4929 (67%) participants (due to the period of inconsistent commercial laboratory performance noted under "Methods," *E. coli* and enterococci data were only available for 3833 and 3755 participants respectively). The distributions of demographic, water recreation and health risk data of the remaining 4929 participants are summarized in Table 1. The distribution of all characteristics were nearly identical for participants whose data were used in analyses of water quality and health, and for the 7368 water recreators, including those for whom complete data on all variables was not available (Supplemental Information 1). Boating, rowing, and kayaking were more common among users of effluent dominated waters, while fishing and canoeing were more common among general use waters recreators.

Table 1
Demographic and exposure characteristics of study participants.

		Effluent-dominated waters n = 2321		General use waters n = 2608		All n = 4929	
		N	Pct.	N	Pct.	N	Pct.
Sex	Female	1107	47.7	1045	40.1	2152	43.7
	Male	1214	52.3	1563	59.9	2777	56.3
Age group	≤10	2139	92.2	2320	89.0	4459	90.5
	11–64	113	4.9	182	7.0	295	6.0
	≥65	69	3.0	106	4.1	175	3.6
Race/ethnicity	White	1854	79.9	2159	82.9	4013	81.5
	Black	96	4.1	96	3.7	192	3.9
	Hispanic	112	4.8	167	6.4	279	5.7
	Other	258	11.1	182	7.0	440	8.9
Chronic GI condition	No	2234	96.3	2495	95.7	4729	96.0
	Yes	86	3.7	113	4.3	199	4.0
Water activity	Boat	500	21.5	171	6.6	671	13.6
	Canoe	489	21.1	902	34.6	1391	28.2
	Kayak	830	35.8	739	28.3	1569	31.8
	Row	319	13.7	171	6.6	490	9.9
	Fish	183	7.9	625	24.0	808	16.4
Head/face wet	None	1224	52.7	1744	66.9	2968	60.2
	Drops	808	34.8	517	19.8	1325	26.9
	Splash	269	11.6	263	10.1	532	10.8
	Drenched	11	0.5	17	0.7	28	0.6
	Submerged	9	0.4	67	2.6	76	1.5
Swallowed water	None	2231	96.1	2519	96.6	4750	96.4
	Drops	64	2.8	59	2.3	123	2.5
	Teaspoon	20	0.9	19	0.7	39	0.8
	Mouthful	6	0.3	11	0.4	17	0.3

All participants have completed data regarding AGI (and were free of baseline GI symptoms), and day-location data for *Giardia*, *Cryptosporidium*, somatic coliphage, F+ coliphage, and turbidity.

3.2. Water quality

The seven measures of water quality are summarized by water location group (Table 2), with and without weighting by the number of participants who enrolled in the study on a given day-location. The weighted measures are somewhat higher than the un-weighted values, indicating that water quality tended to be worse on days (or during seasons) that participant enrollment was greater. Median un-weighted *E. coli* and enterococci densities at effluent-dominated locations were more than double the US EPA Recreational Water Quality beach action values of 235 and 75 CFU/100 mL, respectively (expected to limit the rate of gastrointestinal illness among swimmers to 36 cases/1000 users) (USEPA, 2012). At effluent-dominated waters the median densities of coliphages and *E. coli* were 10–30 times greater than at general use waters. Within the general use water locations, water quality differed by location subgroups, with microbe densities highest at rivers; lower at inland lakes, ponds, and lagoons; and lowest at Lake Michigan locations. This pattern was more apparent for the indicator bacteria than for other measures of quality. Enterococci densities in particular were quite high with median densities in general use rivers that were more than 20 times EPA criteria values for beaches (Supplemental Information 2).

3.3. Crude models of AGI occurrence

Covariate data were missing from 241 participants (4.7%) who were excluded from analyses. The variables that contained missing data were the frequency with which participants recreated at the location of enrollment over the past year ($n = 235$), race ($n = 5$), and pre-existing GI conditions ($n = 1$). As previously reported, AGI occurred among 4.30% of recreators on effluent-dominated waters and 4.25% at general use waters (as well as 3.43% of non-water recreators) (Dorevitch et al., 2012b). However, in the subset reported here (with complete covariate data, including water quality), 4.28% of recreators on effluent-dominated waters and 3.92% of those who used general use waters developed AGI.

In unadjusted models, daily location-specific measures (on a log10 scale) of the indicator bacteria, indicator viruses, and *Giardia* cysts were not associated with AGI (Table 3). This was true for water recreators overall and, in stratified analyses, for subgroups defined by location group and by water exposure. Among water recreators who reported getting their head or face wet during recreation, inverse associations between AGI incidence and *Cryptosporidium* oocysts were observed for water recreators overall and for general use recreators. Inverse associations between AGI incidence and turbidity were observed for water recreators overall, for each water location group, and for both exposure (face wet) categories, though not all of these associations reached statistical significance at a $p < 0.05$ level (Table 3).

3.4. Adjusted models of AGI occurrence following recreation at effluent dominated waters

Of the potential modifiers of water quality-AGI associations for water recreation on effluent-dominated waters, one, perceived health risk of recreation on the Chicago River system, met criteria for inclusion as a modifier of water quality-AGI associations based on the interaction term p-value <0.3. Participants reported perceived health risk of water recreation on the Chicago River system on a 0–10 scale. The strongest association between perceived risk and AGI was observed (post-hoc) with the 0–10 scale dichotomized at a score of 7, (odds ratio; 95% confidence interval 1.47; 0.97, 2.24). However, in multivariate models of AGI stratified by perceived risk category (high vs. low), the microbe-AGI

Table 2
Daily mean values of water quality, by water group and by weighting (by the number of participants enrolled at each location on the day of water sample collection).

Variable	Weighting	Effluent-dominated waters				General use waters				All			
		N	5th	50th	95th	N	5th	50th	95th	N	5th	50th	95th
E. coli/100 mL	None	71	40.8	581.4	6986.5	80	2.5	45.1	1598.9	151	4.2	174.3	5144.1
	Weighted	1704	41.1	834.7	18,250.0	2129	4.8	118.9	1572.8	3833	9.0	240.5	6437.5
Enterococci/100 mL	None	68	27.4	199.8	1111.5	74	2.5	71.0	3337.9	142	5.3	126.6	2065.0
	Weighted	1558	38.4	257.9	2550.0	2197	5.2	82.8	2948.0	3755	7.2	122.5	2550.0
Somatic coliphage/100 mL	None	112	10.0	344.2	3912.6	114	10.0	10.0	304.0	226	10.0	31.7	2613.3
	Weighted	2321	10.0	494.2	4674.0	2608	10.0	11.3	304.0	4929	10.0	63.3	3105.0
F+ coliphage/100 mL	None	112	1.0	13.0	265.5	114	1.0	1.0	17.3	226	1.0	1.7	166.8
	Weighted	2321	1.0	18.0	265.5	2608	1.0	1.0	26.3	4929	1.0	2.0	143.6
Giardia cysts/10 L	None	112	–	5.9	154.3	114	–	–	6.5	226	–	0.8	127.5
	Weighted	2321	–	12.0	159.9	2608	–	0.1	7.0	4929	–	1.5	130.5
Cryptosporidium oocysts/10 L	None	112	–	0.3	23.5	114	–	–	1.0	226	–	–	10.0
	Weighted	2321	–	0.5	25.0	2608	–	–	1.8	4929	–	–	11.5
Turbidity NTU	None	112	6.0	16.3	36.9	114	1.1	14.0	36.0	226	1.5	15.0	36.0
	Weighted	2321	7.5	16.2	37.0	2608	2.9	20.9	33.6	4929	3.7	17.1	33.6

E. coli and enterococci from the period of acceptable data quality only.

associations had wide confidence intervals and did not approach statistical significance in either the high or low category of perceived risk. For that reason, strata were collapsed. Based on prior work of Fleisher and Kay (2006), perceived risk was evaluated for inclusion in subsequent models as a potential confounder using the CIE approach.

CIE-based selection substantially reduced the number of covariates in models of AGI for users of effluent-dominated waters. Age category and gender had minimal impacts on the water quality-AGI association, while, depending on the microbe and the way it was parameterized (linear, log10, dichotomous, or dose), others variables impacted the water quality-AGI association and were therefore included as confounders in final models. A set of variables common to most microbe-specific models were: fishing, frequent use of the same water recreation location group (effluent-dominated vs. general use), head/face having gotten wet, recent precipitation, hand washing following water recreation, perceived risk of water recreation on the Chicago River system, and the presence of chronic gastrointestinal condition (Table 4).

In adjusted models, among users of effluent-dominated waters, measures of water quality were not associated with AGI whether or not covariates that might be on the causal pathway were excluded. Table 4 summarizes associations between AGI, water quality, and covariates in the best-fitting models for each measure of water quality (results of other models is provided in Supplemental Information 4). Removal of covariates that might be on the causal pathway linking water quality and illness had little impact on measures of association with one exception: the log10 enterococci–AGI association achieved borderline significance($p = 0.09$) in the reduced model (Table 4). The variables that were consistently associated with an increased odds of AGI were the presence of a chronic GI condition and high perceived risk of water recreation on the Chicago River system. Odds of AGI were decreased among those whose face remained dry during water recreation. Fit of models in

Table 3
Odds ratio for unadjusted associations between water quality (on a log10 scale) and AGI, by location group, overall and among the subset with self-reported water exposure to the face. OR: Odds ratio; CI: confidence interval; n: number of observations.

	Effluent-dominated waters		General use waters		All water recreators	
	All	Face wet	All	Face wet	All	Face wet
	OR (95% CI) n	OR (95% CI) n	OR (95% CI) n	OR (95% CI) n	OR (95% CI) n	OR (95% CI) n
E. coli	0.88 (0.62, 1.26) 1329	0.86 (0.55, 1.34) 603	1.28 (0.90, 1.81) 1673	1.27 (0.75, 2.13) 592	1.10 (0.89, 1.35) 3002	1.07 (0.8, 1.41) 1195
Enterococci	0.82 (0.46, 1.45) 1206	0.75 (0.35, 1.58) 536	1.20 (0.89, 1.60) 1611	1.20 (0.75, 1.91) 561	1.10 (0.86, 1.42) 2817	1.05 (0.72, 1.54) 1047
Somatic coliphage	0.91 (0.71, 1.16) 2321	0.89 (0.63, 1.26) 1097	1.05 (0.74, 1.48) 2608	0.83 (0.46, 1.49) 864	1.00 (0.86, 1.16) 4929	0.98 (0.79, 1.21) 1961
F+ coliphage	0.80 (0.61, 1.05) 2321	0.74 (0.52, 1.07) 1097	1.15 (0.80, 1.66) 2608	1.00 (0.57, 1.75) 864	0.96 (0.80, 1.15) 4929	0.91 (0.71, 1.17) 1961
Giardia cysts	0.87 (0.71, 1.06) 2321	0.81 (0.61, 1.08) 1097	1.05 (0.81, 1.36) 2608	0.77 (0.51, 1.17) 864	0.97 (0.85, 1.11) 4929	0.89 (0.74, 1.08) 1961
Cryptosporidium oocysts	0.92 (0.72, 1.18) 2321	0.76 (0.54, 1.06) 1097	1.06 (0.69, 1.64) 2608	0.36* (0.14, 0.93) 864	0.98 (0.8, 1.2) 4929	0.74* (0.55, 0.99) 1961
Turbidity	0.33* (0.13, 0.87) 2321	0.54 (0.11, 2.73) 1097	0.71 (0.43, 1.17) 2608	0.38** (0.2, 0.72) 864	0.61* (0.4, 0.94) 4929	0.42** (0.24, 0.76) 1961

*$p < 0.05$ **$p < 0.001$.

Table 4
Results of models of AGI, participants at effluent-dominated waters.

	Water quality metric	Chronic GI condition	Activity: fishing	CSO in past 72 h	Season: summer	Rain in past 48 h	Face dry	Wash hands	Perceived risk: high	Frequent water use	H-L p-value
	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)	
E. coli, log10	1.10 (0.84, 1.44)	2.81* (1.23, 6.46)	1.30 (0.38, 4.4)	0.65 (0.32, 1.35)	1.17 (0.6, 2.26)	0.90 (0.51, 1.59)	0.55* (0.34, 0.88)	0.71 (0.45, 1.13)	1.49 (0.93, 2.38)	0.84 (0.32, 2.17)	0.81
Reduced	1.15 (0.90, 1.48)	2.59* (1.14, 5.89)		0.65 (0.32, 1.03)	1.29 (0.70, 2.37)	0.85 (0.49, 1.46)					
Enterococci log10	1.21 (0.93, 1.57)	3.53* (1.51, 8.24)	2.36 (0.79, 7.1)	0.55 (0.23, 1.35)	1.10 (0.50, 2.4)	1.17 (0.62, 2.23)	0.51* (0.3, 0.87)	0.71 (0.43, 1.18)	1.41 (0.84, 2.36)	0.67 (0.24, 1.84)	0.92
Reduced	1.24 (0.97, 1.60)	3.19* (1.39, 7.34)		0.54 (0.23, 1.26)	1.26 (0.62, 2.56)	1.10 (0.59, 2.04)					
Somatic phage, 75th	1 0.00 (0.63, 1.57)	3.14* (1.49, 6.62)	1.48 (0.51, 4.33)	0.67 (0.36, 1.25)	1.08 (0.60, 1.96)	1.00 (0.59, 1.71)	0.45* (0.28, 0.71)	0.73 (0.47, 1.12)	1.63* (1.05, 2.52)	0.58 (0.25, 1.36)	0.73
Reduced	1.10 (0.71, 1.71)	2.82* (1.36, 5.85)		0.63 (0.34, 1.15)	1.29 (0.75, 2.22)	0.92 (0.55, 1.54)					
F+ phage log10	0.82 (0.59, 1.14)	3.13* (1.49, 6.6)	1.41 (0.49, 4.1)	0.72 (0.38, 1.35)	1.01 (0.56, 1.84)	1.07 (0.62, 1.85)	0.44* (0.28, 0.69)	0.72 (0.47, 1.11)	1.62* (1.05, 2.51)	0.55 (0.23, 1.29)	0.51
Reduced	0.92 (0.67, 1.25)	2.77* (1.34,5.76)		0.64 (0.35, 1.18)	1.24 (0.72, 2.14)	0.96 (0.57, 1.62)					
Giardia, 75th	0.97 (0.57, 1.63)	3.15* (1.49, 6.64)	1.48 (0.51, 4.29)	0.68 (0.36, 1.28)	1.10 (0.60, 1.99)	1.0 (0.59, 1.7)	0.45* (0.28, 0.71)	0.72 (0.47, 1.12)	1.62* (1.05, 2.52)	0.59 (0.25, 1.37)	0.99
Reduced	1.0 (0.61, 1.66)	2.80* (1.35, 5.81)		0.63 (0.34, 1.17)	1.27 (0.74, 2.19)	0.94 (0.56, 1.56)					
Crypto, 75th	0.81 (0.49, 1.32)	3.13* (1.48, 6.6)	1.46 (0.5, 4.21)	0.67 (0.36, 1.25)	1.10 (0.61, 1.97)	1.06 (0.61, 1.83)	0.44* (0.28, 0.7)	0.73 (0.47, 1.13)	1.62* (1.04, 2.5)	0.59 (0.26, 1.38)	0.71
Reduced	0.83 (0.52, 1.35)	2.79* (1.35, 5.79)		0.63 (0.34, 1.14)	1.27 (0.74, 2.19)	0.98 (0.58, 1.65)					
Turbidity log10	0.39 (0.10, 1.52)	3.26* (1.54, 6.9)	1.48 (0.51, 4.29)	0.67 (0.36, 1.25)	1.11 (0.62, 1.98)	1.01 (0.6, 1.7)	0.46* (0.29, 0.72)	0.74 (0.48, 1.14)	1.67* (1.08, 2.59)	0.56 (0.24, 1.3)	0.29
Reduced	0.42 (0.11, 1.57)	2.89* (1.39, 6.01)		0.62 (0.34, 1.13)	1.3 (0.76, 2.22)	0.94 (0.57, 1.56)					

Reduced: models without covariates that may be on the causal pathway linking recreation and illness.
N = 1888 for *E. coli*, 1765 for enterococci, and 2187 for other microbes.
75th indicates a variable dichotomized at the 75th percentile for CAWS locations.
75th percentile values at CAWS locations were: for somatic coliphage, 946.3 PFU100/mL; Giardia, 60 cysts/10 L, and for Cryptosporidium, 2 cycsts/10 L.
H–L: Hosmer–Lemeshow goodness of fit p-value (low values indicate poor model fit).
*$p < 0.05$.

which water quality was parameterized as dose (on a linear or log10 scale) were generally poorer than models that included separate terms for water quality and water exposure (data not presented). Stratified analyses by face exposure did not change (the lack of) associations between water quality and AGI.

3.5. Adjusted models of AGI occurrence following recreation at general use waters

In adjusted models of incidental contact recreation at general use waters, one variable, precipitation in the preceding 48 h, met criteria for inclusion in models as a modifier of water quality-GI illness occurrence associations. Table 5 summarizes associations between AGI, water quality, and covariates in the best-fitting models for each measure of water quality (results of other models is provided in Supplemental Information 5a and 5b). In models with acceptable fit, no measure of water quality was associated with AGI. This was also the case after removing covariates that are potentially on the causal pathway (Supplemental Information 6). With the general use water data stratified into the wet weather and dry weather strata, associations between AGI and chronic GI conditions or face exposure to water (which were significant in models of AGI among users of effluent-dominated waters) did not approach statistical significance. As was the case with models of AGI among users of effluent dominated waters, in models of AGI among users of general use waters terms for microbe dose (rather than microbe concentration) were not significant.

3.6. Adjusted models of AGI occurrence following recreation, combined location groups

Analyses of the set of all water users was performed because interaction terms for location group (effluent dominated vs. general use) were either non-significant or in cases in which interaction terms were significant, water quality terms were not significant in either stratum of location group. The all water recreator analyses (Table 6) showed that in best fitting models measures of water quality did not predict AGI (fit of other models with varying ways of parameterizing water quality is summarized in Supplemental Information 7). Compared to models that included a water quality term, those that did not generated similar measures of association between illness occurrence and other covariates. The odds of AGI were approximately twice as high among those who had a chronic gastrointestinal condition (such as peptic ulcer disease, gastroesophageal reflux, irritable bowel syndrome, or inflammatory bowel disease) compared to those who did not, even though all participants included in the analyses indicated that they were free of GI symptoms at the time of water recreation. Frequent use of the water at the location at which participants were enrolled decreased the risk of AGI by a factor of approximately half. Compared to those who engaged in other limited contact water recreation activities, those who fished appear to be at significantly greater risk of developing AGI than those who engaged in other limited contact water recreation activities. Hand washing between the time of water recreation and eating or drinking (but before the post-recreation field interview) appears to be associated with a lower odds of AGI based on point estimates of the odds ratio of 0.7–0.8, though this did not reach statistical significance at a $p < 0.05$ level.

4. Discussion

In the largest cohort study of incidental contact recreation to date, despite the wide range of water quality and the fairly common occurrence of AGI (approximately 4% of study participants), measures of water quality were not useful as predictors the occurrence

Table 5
Results of models of AGI, participants at general use water location, stratified by the presence or absence of rain the 48 h prior to water recreation.

	Water quality metric	Chronic GI condition	Activity: fishing	Season: Summer	Face dry	Wash hands	Frequent water use	H-L p-value
	Or (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)	
NO RAIN								
E. coli, 75th	0.79 (0.26, 2.45)	1.70 (0.38, 7.55)	1.59 (0.73, 3.46)	1.63 (0.78, 3.41)	0.61 (0.28, 1.33)	0.88 (0.43, 1.80)	0.56 (0.13, 2.43)	0.35
Enterococci, log10	1.23 (0.68, 2.22)	1.83 (0.41, 8.18)	1.84 (0.84, 4.03)	1.42 (0.67, 3.00)	0.63 (0.28, 1.42)	0.88 (0.42, 1.85)	0.65 (0.15, 2.86)	0.90
Somatic coliphage, linear	1.01 (1.00, 1.02)	1.54 (0.34, 6.93)	1.59 (0.75, 3.40)	1.49 (0.73, 3.04)	0.60 (0.28, 1.29)	0.77 (0.38, 1.57)	0.52 (0.12, 2.29)	0.95
F+ phage, linear	1.05 (0.96, 1.14)	1.59 (0.36, 7.13)	1.51 (0.71, 3.22)	1.47 (0.71, 3.03)	0.58 (0.27, 1.25)	0.79 (0.39,1.60)	0.48 (0.11, 2.07)	0.63
Giardia, linear	1.05 (0.82, 1.34)	1.66 (0.37, 7.41)	1.58 (0.74, 3.37)	1.53 (0.75, 3.14)	0.58 (0.27, 1.24)	0.80 (0.39, 1.64)	0.49 (0.11, 2.12)	0.42
Crypto, log10	3.02 (0.22, 41.2)	Unstable	3.41 (0.19, 61.68)	0.56 (0.02, 21.51)	Unstable	0.62 (0.07,5.37)	Unstable	0.68
Turbidity, log10	0.53 (0.16,1.78)	1.75 (0.39, 7.78)	1.64 (0.76, 3.55)	1.74 (0.82, 3.69)	0.69 (0.28, 1.3)	0.84 (0.41, 1.70)	0.40 (0.09, 1.83)	0.50
RAIN								
E. coli, 75th	1.25 (0.62, 2.49)	1.30 (0.39, 4.33)	1.32 (0.62, 2.83)	1.01 (0.52, 1.95)	0.62 (0.33, 1.16)	0.70 (0.38, 1.29)	0.25 (0.03, 1.88)	0.09
Enterococci 75th	0.92 (0.64, 1.34)	1.53 (0.46, 5.14)	1.32 (0.62, 2.84)	1.47 (0.74, 2.95)	0.57 (0.3, 1.1)	0.74 (0.39, 1.38)	0.27 (0.04, 2.02)	0.25
Somatic coliphage, linear	1.0 (1.0, 1.0)	1.42 (0.5, 4.04)	1.11 (0.53, 2.3)	1.02 (0.59, 1.77)	0.64 (0.37, 1.1)	0.68 (0.4, 1.16)	0.18 (0.03, 1.32)	0.08
F+ coliphage, 75th	1.01 (0.59, 1.73)	1.42 (0.5, 4.04)	1.11 (0.53, 2.32)	1.02 (0.59, 1.76)	0.64 (0.37, 1.1)	0.68 (0.4, 1.16)	0.18 (0.03, 1.33)	0.26
Giardia, linear	1.01 (0.97, 1.06)	1.41 (0.5, 4.02)	1.15 (0.55, 2.38)	1.02 (0.6, 1.74)	0.64 (0.37, 1.1)	0.67 (0.39, 1.16)	0.19 (0.03, 1.36)	0.17
Cryptosporidium, log10	1.45 (0.53, 3.95)	1.56 (0.35, 6.91)	1.69 (0.2, 14.03)	0.72 (0.24, 2.11)	1.44 (0.63, 3.3)	0.66 (0.27, 1.65)	Unstable	0.59
Turbidity, linear	0.99 (0.96, 1.02)	1.42 (0.5, 4.03)	1.10 (0.54, 2.25)	0.98 (0.57, 1.69)	0.63 (0.37, 1.09)	0.70 (0.41, 1.21)	0.17 (0.02, 1.24)	0.16

Dry weather n = 811 for *E. coli*, 795 for enterococci 839 for other microbes. Wet weather (precipitation of at least 0.01 inches in prior 48 h) n = 1242 for *E. coli*, 1195 for enterococci, and 1562 for other microbes.
75th indicates a variable dichotomized at the 75th percentile for general use water locations.
75th percentile values at these locations were: E. coli, 203 CFU/100 mL. F+ coliphage: 1.25 PFU/100 mL.
H–L: Hosmer–Lemeshow goodness of fit p-value (low values indicate poor model fit).
*$p < 0.05$.

of AGI.

Water quality in the effluent-dominated waters was poor, and median densities of FIB were an order of magnitude or more higher than those observed in epidemiologic studies of swimming at beaches (Arnold et al., 2013; Colford et al., 2007; Wade et al., 2010). While fecal indicator concentrations at Lake Michigan beaches were generally below EPA Beach Action Values (USEPA, 2012), at the other general use waters – rivers and inland lakes – FIB densities were considerably higher (Supplemental Information 2). Nevertheless, the frequency of illness among incidental contact recreators in the two water location groups was comparable. The risk of AGI was higher among those who reported a chronic gastrointestinal condition. Fishing (relative to other incidental contact recreation activities) appears to be associated with a higher risk of AGI. A decreased incidence of AGI was associated with frequent use of a water recreation location and completing recreation without exposure of the face to water.

The absence of associations between measures of water quality and GI illness during incidental contact recreation in the settings we studied is in contrast with findings of studies of swimmers at freshwater beaches impacted by publically-owned wastewater treatment works (POTW). In those studies the risk of AGI increased with higher densities of enterococci measured by culture (USEPA, 1984) or qPCR (Wade et al., 2008). Likewise in a study of swimmers at a freshwater reservoir in Ohio, *E. coli* measured by culture was associated with gastrointestinal illness despite relatively low *E. coli* densities (Marion et al., 2010). Approximately 95% of the flow in the Chicago River system is wastewater effluent that had been treated with activated sludge but without disinfection (Rijal et al., 2011). Aerobic digestion of wastewater results in greater reductions of indicator bacteria than pathogens (Harwood et al., 2005), which might explain a lack of association between indicators and GI illness incidence. However, positive associations have been observed between indicators and protozoan pathogens in surface waters used in CHEERS (Yavuz et al., 2014). Thus, although positive associations between indicator bacteria and illness might be expected, this was not observed. Perhaps this is due to the smaller volumes of water swallowed during incidental contact water recreation than swimming. We have previously estimated using tracer methods the volume of water ingested using questionnaire and chemical tracer methods during a variety of activities in a swimming pool, including swimming, canoeing, kayaking, wading, and simulated fishing. That work suggests that the self-reported volume of water ingested in a pool or on surface waters during limited contact recreation is perhaps half the volume of water ingested than while swimming laps (Dorevitch et al., 2011b). A 50% lower rate of water ingestion seems unlikely to account for the lack of association between FIB and AGI occurrence among users of the waters that are predominantly wastewater effluent. We did not observe differences in associations between AGI and precipitation. Precipitation was defined as any precipitation in the past 48 h, and days with 0.01 inches of precipitation were fairly common. Future analyses of effect modification of microbe-AGI associations using other definitions of precipitation (such as exceedances of a higher threshold value or looking at shorter time frames, such as the 24 h prior to recreation) may be useful.

Two studies of incidental contact water recreation have been have been conducted at a whitewater slalom course fed by a mix of treated and untreated wastewater in the United Kingdom (Fewtrell et al., 1992; Lee et al., 1997). Despite much smaller sample sizes (hundreds, rather than thousands of participants enrolled as was the case in CHEERS), gastrointestinal symptom occurrence among canoeists and rafters at the white water course was associated with F+ coliphages. A potential explanation for the discordant findings (risk increased with increasing F+ coliphages in the UK study but not in CHEERS) is that water quality was poorer in the UK study, where enterovirus was present in five of the nine sampling study dates; in CHEERS 20% of surface water samples contained enterovirus RNA (and not necessarily infectious enterovirus) (Aslan et al., 2011). Second, water ingestion was likely greater in the UK whitewater slalom course compared to the low-velocity Chicago River system. “Unintentional swimming” (following capsize) occurred with some frequency on the UK slalom course, and occurred more

Table 6
Results of models of AGI, participants at all locations.

	Water quality metric	Chronic GI condition	Activity: fishing	Season: Summer	Face dry	Wash hands	Frequent water use	Rain past 48 h	H-L p-value
	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)	OR (95% CI)	
E. coli, 75th	1.01 (0.72, 1.41)	1.94* (1.05, 3.58)	1.54* (1.01, 2.35)	1.25 (0.88, 1.79)	0.59* (0.42, 0.82)	0.77 (0.56, 1.06)	0.55 (0.27, 1.09)	0.88 (0.63, 1.23)	0.92
Reduced	1.07 (0.76, 1.49)	1.92* (1.04, 3.53)	1.37 (0.93, 2.04)	1.31 (0.94, 1.85)					0.91
Enterococci, linear	1.00 (1.00, 1.00)	2.32*(1.25, 4.30)	1.90* (1.24, 2.91)	1.44 (0.97, 2.14)	0.58* (0.40, 0.83)	0.79 (0.57, 1.11)	0.54 (0.26, 1.14)	1.04 (0.72, 1.51)	0.98
Reduced	1 (1, 1)	2.33* (1.26, 4.32)	1.64* (1.11, 2.43)	1.63* (1.12, 2.37)					0.93
Somatic coliphage, 75th	0.89 (0.64, 1.26)	2.13*(1.23, 3.70)	1.44 (0.93, 2.21)	1.20 (0.87, 1.65)	0.53* (0.39, 0.73)	0.77 (0.57, 1.04)	0.43* (0.22, 0.82)	0.95 (0.69, 1.29)	0.21
Reduced	0.97 (0.69, 1.35)	2.09* (1.21, 3.62)	1.28 (0.85, 1.92)	1.32 (0.97, 1.78)					0.78
F+ coliphage, 75th	1.24 (0.87, 1.75)	2.15* (1.24, 3.74)	1.63* (1.08, 2.49)	1.14 (0.82, 1.56)	0.55* (0.40, 0.75)	0.77 (0.57, 1.04)	0.43* (0.23, 0.84)	0.93 (0.68, 1.27)	0.90
Reduced	1.34 (0.95, 1.88)	2.11* (1.22, 3.65)	1.46 (0.98, 2.16)	1.24 (0.91, 1.68)					0.89
Giardia, 75th	1.07 (0.74, 1.55)	2.14* (1.23, 3.72)	1.57* (1.00, 2.46)	1.18 (0.86, 1.62)	0.54* (0.40, 0.74)	0.77 (0.57, 1.04)	0.43* (0.22, 0.82)	0.93 (0.68, 1.28)	0.23
Reduced	1.16 (0.81,1.67)	2.10* (1.21,3.63)	1.42 (0.92,2.18)	1.32 (0.98,1.78)					0.47
Cryptosporidium, log10	1.1 (0.78, 1.56)	2.86* (1.32, 6.16)	1.64 (0.62, 4.29)	0.98 (0.62, 1.53)	0.81* (0.53, 1.26)	0.70 (0.45, 1.08)	0.47 (0.18, 1.20)	0.65 (0.4, 1.03)	0.99
Reduced	1.06 (0.76, 1.47)	2.62* (1.22, 5.61)	1.84 (0.72, 4.69)	1.07 (0.69, 1.65)					0.23
Turbidity, linear	0.99 (0.97, 1.00)	2.18* (1.25, 3.79)	1.47 (0.98, 2.20)	1.13 (0.82, 1.56)	0.54* (0.40, 0.74)	0.79 (0.59, 1.07)	0.40*(0.20, 0.77)	0.98 (0.71, 1.34)	0.54
Reduced	0.99 (0.97, 1.00)	2.13* (1.23, 3.69)	1.26 (0.87, 1.83)	1.28 (0.95, 1.73)					0.45
No water quality term		2.14* (1.23, 3.71)	1.51* (1.01, 2.26)	1.18 (0.86, 1.61)	0.54*(0.4, 0.73)	0.77 (0.57, 1.04)	0.43* (0.22, 0.82)	0.94 (0.69, 1.29)	0.30
Reduced		2.09* (1.21, 3.62)	1.3 (0.89, 1.88)	1.31 (0.97, 1.76)					0.88

N = 4046 for analyses of *E. coli* and enterococci; for all others n = 4694.
Reduced: models without covariates that may be on the causal pathway linking recreation and illness.
75th indicates a variable dichotomized at the 75th percentile for (based on general use water locations).
75th percentile values at these locations were: *E. coli*, 203 CFU/100 mL. F+ coliphage: 1.25 PFU/100 mL.
H–L: Hosmer–Lemeshow goodness of fit p-value ($p < 0.05$ indicates inadequate model fit).
*$p < 0.05$.

than twice per study day for some participants. Although the frequency of these exposures was not reported, it may have been greater than the 2% frequency of head/face submersion occurred among CHEERS participants (Table 1). Thus, with less water ingestion and lower densities of pathogens in water ingested, participants at the effluent-dominated Chicago River system locations may have ingested lower doses of viable pathogens, resulting in associations between microbe densities and gastrointestinal illness risk that could not be detected.

To the best of our knowledge, this is the first epidemiologic study of water recreation that evaluated measures of protozoan parasites as predictors of illness. We found no association between densities or presence of *Giardia* or *Cryptosporidium* (oo)cysts and the occurrence of AGI. This should not be surprising, given that no differences in the risk of water recreation were identified between users of the effluent-dominated and general use waters (Dorevitch et al., 2012b), despite the much higher densities of the parasites (as well as higher frequencies of detecting adenovirus (Aslan et al., 2011)) at effluent-dominated than at general use waters locations. CHEERS participants were followed by phone for onset of symptoms through day 21 post-recreation, which should have been sufficient to identify cases of cryptosporidiosis or giardiasis; however analyses of stool samples of 740 CHEERS participants who developed GI symptoms did not identify Giardia, *Cryptosporidium*, or any other pathogens as causes of symptoms (Dorevitch et al., 2012a). To predict illness we also used a novel estimate of exposure, the estimated dose of indicators and pathogens, which takes into account both volume of water ingested and density of microbes in water. While the estimated dose of protozoan pathogens did not predict illness occurrence in the settings studied, pathogen measurement – including viral pathogens – should be pursued in future studies, particularly studies of swimming, given that the loading, transport, and fate of protozoan parasites in our setting may not be representative of these and other pathogens in other settings. Similarly the estimated dose of microbes should be explored in future studies, particularly those set in locations in which water quality measures typically do predict illness (POTW-impacted freshwater swimming beaches).

CHEERS participants at general use waters who used the same water recreation site 15 or more time within the past year were about one third as likely to develop AGI than participants who engaged in water recreation at that site less frequently, after adjusting for water quality, water exposure, and other covariates. This is consistent with the observation of Lee et al., who noted that at the UK whitewater slalom course, canoeists and rafters who had used the course seven or more times previously were about 1/3 as likely to develop gastrointestinal symptoms as those who had not used the course before (Lee et al., 1997). Lee et al. proposed several potential explanations for this that are reasonable in our context as well. Frequent users may have a higher skill level and are able to avoid swallowing water; frequent use may result in clinical and/or subclinical infections that generate some degree of immunity, and self-selection may occur, with individuals who develop illness choosing to avoid future exposures, while those who stay well return for repeated recreational events.

Final models of AGI (that included water quality, demographic, medical, and exposure covariates) found that participants who fished (from a boat or from shore) were 50% more likely to develop illness as participants who engaged in other incidental contact activities. This finding was robust to sensitivity analyses that eliminated from analysis specific dates and locations of enrollment (data not presented). We are not aware of other observational studies that have addressed short term illness risks of fishing. *Cryptosporidium* oocysts have been detected in samples of fish caught by urban anglers in Baltimore, MD, and on hands of the anglers (Roberts et al., 2007). In that study, a probability of *Cryptosporidium* infection among anglers was estimated to be approximately 1–8 per 10 anglers. While none of the 740 stool samples collected from symptomatic CHEERS participants contained *Cryptosporidium* (Dorevitch et al., 2012a) the presence of this pathogen may indicate the presence of others, including one (or more) responsible for illness. The hand-to-mouth and hand-to-object-to-mouth activities of fishermen, particularly those who eat, drink, and/or smoke during fishing, may provide additional pathways of exposure to pathogens which would be less available to competitive rowers (who do not eat or smoke during training or races). In a setting similar to the one we studied, fisherman in a polluted catchment area of New York City perceived a low degree of risk of eating fish that they caught despite the presence of warnings and advisories, in part because they believed that they could differentiate safe from unsafe fish (Burger et al., 1993). We propose that while water recreators in general are exposed to surface water and its contaminants, the elevated risk of AGI among fishers is due to their additional exposure to microbes present on bait and on fish.

5. Conclusions

Gastrointestinal illness following incidental contact water recreation was not readily predicted by measures of water quality in the settings studied. Protozoan pathogens, while frequently detected, were not useful as predictors of illness. Based on our findings, the risk of gastrointestinal illness following incidental contact water recreation might be reduced by efforts to decrease exposure among at risk groups, such as those who have limited prior experience on the water, those with underlying gastrointestinal conditions, and those who fish. Such efforts may include education about the hazards of capsizing and swallowing water and promoting frequent hand washing.

Conflict of interest

In the past three years Dr. Dorevitch has received grant support from the US EPA, US CDC, and the National Science Foundation. He has served as a consultant to the Eastern Research Group. No other potential completing interests are declared.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.watres.2015.06.028.

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