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Benefits of Water Safety Plans: Microbiology, Compliance, and Public Health

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Supporting Information

ABSTRACT: The Water Safety Plan (WSP) methodology, which aims to enhance safety of drinking water supplies, has been recommended by the World Health Organization since 2004. WSPs are now used worldwide and are legally required in several countries. However, there is limited systematic evidence available demonstrating the effectiveness of WSPs on water quality and health. Iceland was one of the first countries to legislate the use of WSPs, enabling the analysis of more than a decade of data on impact of WSP. The objective was to determine the impact of WSP implementation on regulatory compliance, microbiological water quality, and incidence of clinical cases of diarrhea. Surveillance data on water quality and diarrhea were collected and analyzed. The results show that HPC (heterotrophic plate counts), representing microbiological growth in the water supply system, decreased statistically significant with fewer incidents of HPC exceeding 10 cfu per mL in samples following WSP implementation and noncompliance was also significantly reduced ($p < 0.001$ in both cases). A significant decrease in incidence of diarrhea was detected where a WSP was implemented, and, furthermore, the results indicate that population where WSP has been implemented is 14% less likely to develop clinical cases of diarrhea.

INTRODUCTION

The Water Safety Plan (WSP) methodology for ensuring the safety of drinking water supplies, with its approach to systematic preventive management and risk assessment, has been recommended by the World Health Organization (WHO) since its incorporation in the third edition of the WHO Guidelines for Drinking Water Quality in 2004 and again in the fourth edition in 2011.[1,2] WSPs have become widely used and are incorporated into legal requirements for water utilities in several countries. However, systematic evidence for the effectiveness of WSPs in improving water quality and health is lacking and stakeholders recognize the need for research to strengthen the evidence base.[3] In Iceland, the use of the WSPs by drinking water utilities was legislated in 1995.[4] Implementation has progressed steadily and by 2008 over 80% of the population was served by a water utility with a WSP.[5] The staggered implementation and long duration of WSP use in Iceland, as well as availability of water quality data and surveillance data on diarrhea in humans, provide a unique opportunity to evaluate systematically the impacts of WSPs on water quality and public health.

The WSP methodology is more comprehensive than conventional approaches to drinking water safety, addressing the whole water system from catchment to consumer with the goal of preventing contamination at each stage.[6] This is in contrast to conventional approaches to drinking water quality that focus primarily on ensuring that drinking water meets government standards for biological and chemical parameters with end-point testing. The WSP approach includes, for example, improved maintenance policies and procedures, systematic repair of pipes, a cleaning plan (e.g., regular flushing of fire hydrants and cleaning of reservoir tanks), and improvements in the system (e.g., backflow prevention). Such interventions are expected to reduce microbial growth in the system, prevent infiltration of contaminants, and result in safer water.

Iceland is a developed country with a population of 320 000 inhabitants with well-run municipal water utilities and 100% piped drinking water supply.[7] Iceland is also one of the freshwater-richest countries in the world, estimated at around 600 thousand m^3 per person per year,[8] with good access to

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quality groundwater. About 95% of the country's piped drinking water supply originates from groundwater. Groundwater is typically not treated prior to distribution unless there is a danger of surface water intrusion. Surface water (used by less than 5% of the population), and groundwater under direct influence of surface water, are typically treated by filtration followed by UV disinfection.[9] Residual disinfection with chlorine or other disinfectants is not practiced in Iceland.[5] Local Competent Authority (LCA) is responsible for surveillance of drinking water protection and compliance. Legal requirements on protecting the sources of drinking water have been included in the Icelandic Drinking Water Regulation (IDWR) since 2001, obligating the LCA to define protection around water intakes. The Primary Health Care Centers (PHCCs) are required to collect and report data on diarrheal diseases to the Chief Epidemiologist at the Directorate of Health.

In 1995, Iceland became one of the first countries to legislate the use of WSPs;[4] implementation began with Reykjavik Energy in the spring of 1997.[5] Five years later, eleven utilities serving 63% of the population had implemented a WSP and by the end of 2008 thirty-one utilities serving 81% had WSP in place.[5,10] Preliminary evidence indicates that WSP implementation in Iceland has resulted in increased compliance with IDWR. A preliminary evaluation carried out in 2008 at two water utilities, City of Reykjavik and Akureyri town, showed compliance increasing following WSP implementation, from 94% to 99% at Reykjavik and from 88% to 99% at Akureyri, respectively.[10] Research at sixteen water utilities in 2009 and development of a scoring system to evaluate performance of WSP showed that nine out of sixteen utilities got a satisfactory score, however the range in scoring was great.[5] Results from that research also indicated that the process of implementing a systematic preventive approach to water safety improved the utility culture regarding drinking water as a public health issue. But the question of whether there are measurable benefits from having a WSP was unanswered.

Although waterborne disease is a much greater burden in developing countries, it is essential that the causes of both endemic and epidemic diarrheal disease from drinking water supply be addressed in wealthy countries like Iceland. There were 12 confirmed waterborne disease outbreaks in Iceland between 1984 and 2011. Six were due to *Campylobacter* and six were due to norovirus.[11] The last confirmed outbreak was in 2004 and at least one contamination event has been confirmed since 2004 but was not associated with adverse health impacts.[12] All of these outbreaks were at small water utilities. However, absence of detected outbreaks of disease is not a reason for complacency[1,13,14] as endemic and sporadic cases of gastrointestinal illness and small waterborne outbreaks can be undetected by surveillance systems.[15] Research also indicates increased risk for gastrointestinal illness during pressure loss in a distribution system. A cohort-study among recipients of water from seven larger water utilities in urban areas in Norway during the years 2003−04 showed that breaks and maintenance work in the distribution systems were associated with an increased risk for gastrointestinal illness among water recipients;[16] and a similar study in England and Wales showed a strong association between self-reported diarrhea and reported low water pressure at the faucet.[17] These examples indicate that addressing health risk from drinking water in developed countries requires an approach like WSPs that can address risk at all stages of supply, particularly in the distribution system, and establish appropriate procedures for maintenance and operation.

The aim of this study was to determine the impact of WSP implementation on (a) regulatory compliance, (b) microbiological water quality, and (c) incidence of clinical cases of diarrhea, using comprehensive surveillance data.

■ MATERIALS AND METHODS

Design of Study. The design of this study is an observational retrospective cohort study. The uptake areas without WSP were considered risk exposed (nonintervention) and the uptake areas with WSP were nonrisk exposed (intervention). The following indicators were compared in water utilities before and after implementing WSP: (1) percentage of annual compliance with drinking water regulation in heterotrophic plate counts (HPC), total coliform, and *E. coli* bacteria; (2) the number of colony forming units (cfu) by HPC in water; and (3) incidence of diarrhea per 1000 inhabitants per month.

For (1) and (2) five utilities were chosen for analysis of water quality and compliance data based on the following criteria: (a) available data for water quality and compliance; (b) at least two full years of data with and two full years of data without WSP; and (c) at least 100 regular water quality compliance samples reported during the study period.

For (3) the inclusion criteria for the PHCCs were the following: (a) data availability of reported monthly number of cases of diarrhea during the study period (defined below); (b) that the entire population in the uptake area for the PHCC had received piped drinking water from a single water utility; and (c) the geographic boundary of service for the PHCC was stable over the period of study (e.g., two community clinics were not consolidated into one during the study period). These criteria eliminated 42 of the 60 PHCCs, leaving 18 for inclusion in the study, whereof 7 could be tested for before and after WSP.

Data Collection for Water Quality. Regular monitoring of microbiological and chemical parameters is carried out according to Icelandic Drinking Water Regulation (IDWR)[18] and the European drinking water directive[19] at all water utilities over a certain size (>50 users) with frequency of sampling according to population. To be in compliance with IDWR the HPC in a water sample must contain less than 100 cfu per mL at 22 °C and zero value for both total coliform and *E. coli* in 100 mL.

Data for compliance of HPC, total coliform, and *E. coli* were collected from five water utilities, either from the LCA or from the utility, where sufficient data and period before and after WSP implementation were available. Results from 1562 regular monitoring samples were included. Repeated monitoring that was carried out because of deviation incidence, real or suspected, and monitoring after complaints from users were excluded to increase conformity between cases and avoid bias. The five water utilities serve around 24% of the population of Iceland. WSP were implemented in the five water utilities between 1998 and 2007 and data on water quality extended from 8 up to 13 years before implementation and 3 to 10 years after. Time of implementation was based on the month when the WSP was certified by the LCA. In some of the water utilities the frequency of sampling was reduced as regulatory compliance improved, as permitted in the IDWR since 2001. Scope of data available for the five water utilities as well as the periods before and after WSP implementation is shown in

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Table 1. Results from Binary Logistic Regression Test for Water Quality (n = 1562)

	B	S.E.	Wald	df	sign.	odds ratio	95% C.I.	
							lower	upper
noncompliance	1.315	0.280	22.056	1	0.000	3.725	2.152	6.448
HPC > 10 cfu per mL	0.789	0.127	38.340	1	0.000	2.202	1.715	2.827

Supporting Information (SI) Tables S1 and S5. In no case were electronic data available. In subsequent analysis the water utilities are labeled with V followed by a number for simplification and in order to keep them anonymous.

Data Collection on Diarrhea in Humans. The Chief Epidemiologist for Iceland at the Directorate of Health is responsible for maintaining a register of communicable diseases according to Act no. 19/1997 on Health Security and Communicable Diseases. Diarrhea is a notifiable disease with monthly reporting of number of cases from the PHCCs to the Chief Epidemiologist. The reporting is based on the International Classification of Diseases (ICD-10)[20] for standard diagnostic classification of diseases, which is used almost for the entire health care system in Iceland. For every patient seeking health care one or more ICD-10 codes are selected by the physician and entered into each patient record. For this study data from the monthly reporting for the two following ICD-10 codes representing diarrhea were selected and collected from the Chief Epidemiologists register on communicable diseases:

- A09 - Diarrhea and gastroenteritis of presumed infectious origin.
- A05 - Other bacterial food-borne intoxications, not elsewhere classified.

These codes are notifiable without personal identification. All data available from individual PHCCs on the above ICD-10 codes were collected from January 1997 to the end of 2009. Over the 13-year (156-month) period of the study, the total number of clinic-months of data available was 2408 (see SI Table S2). Delivery of data for these eighteen PHCCs was approximately 90%. Nonconformity and missing data were observed at each PHCC and rectified with the help of Chief Epidemiologist and regional or local PHCC if possible. Adequate data on diarrhea in humans were available for PHCCs with uptake areas served by seven water utilities before and after the implementation of WSP; of these, two also provided adequate water quality data. The seven water utilities are sufficiently localized so minimal commuting exists between the service areas. Additionally, data for eleven PHCCs were collected; four had an uptake area served by water utilities with a WSP during the entire study period and seven had uptake areas that were served by water utilities without a WSP at any time during the study period. The uptake areas for these eighteen PHCCs covered approximately 38% of the population of Iceland. Scope of data and population for the PHCCs where data on diarrhea were obtained is shown in SI Tables S2 and S5.

Data on population in the uptake areas for the PHCCs were obtained from the Web site of Statistics Iceland[21] and from the Administration Office of PHCC in the capital area. The populations served by the PHCCs are generally connected to postal codes in the uptake areas; one exception is in the capital area where people can more easily choose among PHCCs. There are nineteen PHCCs in the greater capital area, five of which were included in this study.

Testing for Confounders and Strength of the Data. Correlation tests between diarrhea and pneumonia were conducted at three PHCCs (V1, V16, and V17). The three PHCCs selected had significant difference in incidence of diarrhea before and after WSP implementation and sufficient months of data that coincided. The correlation test examines factors other than WSP that could affect these diseases simultaneously, such as changes in definitions or methods for reporting/registering. Pneumonia was selected as it is a common disease, which is notifiable to the Chief Epidemiologist and reported in the same way as diarrhea using the ICD-10 codes J12−J18, with subcodes for pneumonia. While associated with water supply through the impact of water availability on hygiene there is no evidence to suggest an association of pneumonia with water quality.

In addition the correlation between interventions in water utilities and diarrhea incidence was investigated. This was assessed by testing the correlation between the WSP scoring of sixteen water utilities, and the diarrheal incidence in the PHCCs uptake areas that the water utilities were serving. Ten of the water utilities had implemented a WSP and were rated according to the WSP scoring system reported in a previous study[5] and six were without WSP and were given a score of zero. Surveillance data on diarrhea from the Chief Epidemiologists register were available for all PHCCs uptake areas served by these sixteen water utilities. Data availability is given in SI Table S3.

Statistical Analysis. Statistical analysis was conducted with SPSS 19. For all data sets, mean, median, 5th and 95th percentiles and range were calculated before and after WSP implementation. Statistical significance was set as two tail and at 5% (p = 0.05).

The binary logistic regression test was used when analyzing the relative frequency of two possible outcomes (e.g., compliance vs noncompliance). It tests whether noncompliance to drinking water regulation in the parameters HPC, total coliform, and *E. coli* was significantly more frequent before than after WSP implementation. The binary logistic regression test was also used to examine if there was difference in HPC before and after the WSP implementation; this comparison was based on an HPC concentration of 10 cfu per mL.

When analyzing the difference in numerical values (e.g., bacterial concentration or diarrheal incidence), two tests were used: the t test was used for parametric analysis and the Mann−Whitney U test was used for nonparametric analysis.

Univariate two-way ANOVA test was used to compare diarrheal incidence before and after WSP implementation in all seven PHCCs. The difference in mean before and after WSP implementation at each of the seven PHCCs was then tested with a posthoc t test. To adjust for multiple comparisons, the Bonferroni correction was used; accordingly, the significance level was divided by number of tests conducted (n = 7) p = 0.00714 (0.05/7). For the supporting evidence of correlation between diarrhea and pneumonia a nonparametric Kendall's tau test was used, and Persons correlation was used for WSP scoring and incidence of diarrhea.

■ RESULTS

Compliance with Icelandic Drinking Water Regulation (IDWR). Surveillance data for drinking water showed a decrease in noncompliance with IDWR requirements following WSP implementation ($p < 0.001$) as shown in Table 1. Mean annual noncompliance declined following implementation of a WSP at four of the five water utilities investigated, as shown in Figure 1. Mean noncompliance across all five utilities declined approximately 80% (from 7.7% of samples to 1.5%).

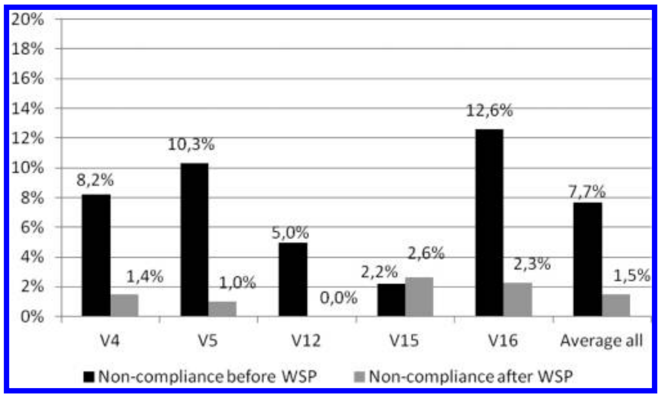

Figure 1. Mean annual noncompliance with IDWR at five water utilities before and after WSP.

Noncompliance can result from a violation in any or all of the three following parameters: HPC, total coliform, or *E. coli* bacteria (as described in Materials and Methods). The total number of incidents of noncompliance decreased from 85 (out of 955 samples) before WSP implementation down to 16 (out of 607 samples) after WSP in all five water utilities combined. HPC violations were the most common cause of noncompliance, both before and after WSP implementation; see SI Table S6 for details.

According to IDWR water samples should be obtained at both the source (e.g., at the borehole or a well from which groundwater is pumped) and from the piped distribution system. For the 1562 samples 33% were taken at the source and 67% were taken from the distribution network. Samples from the source were in compliance more often than those from the distribution network. Noncompliance at the source reduced from 4.8% to 2.3% following WSP implementation while the reduction was from 10.7% to 2.8% in the distribution network.

Heterotrophic Plate Count (HPC) in Drinking Water. In Figure 2 HPC is plotted for the five utilities before and after WSP implementation. The figure shows that number of HPC that were above the upper cutoff level 10 cfu per mL at all five utilities decreased following a WSP implementation. A binary logistic regression test showed that the decrease was significant ($p < 0.001$) as shown in Table 1.

Table 2 provides detailed information on HPC bacteria in samples taken before and after WSP implementation at the five water utilities. It shows that the median is higher before than after WSP implementation at all water utilities except at V15, although at V15 there were only 2 noncompliances before WSP (during 8 years) and 2 after WSP (during 7 years) and low HPC both before and after WSP, yielding unreliable results. However the difference in the median is only significant for two of the five utilities, V5 and V16, according to nonparametric test. Table 2 shows also that when all sample results were combined, and also when samples at the source and in the distribution system were compared separately, the median HPC

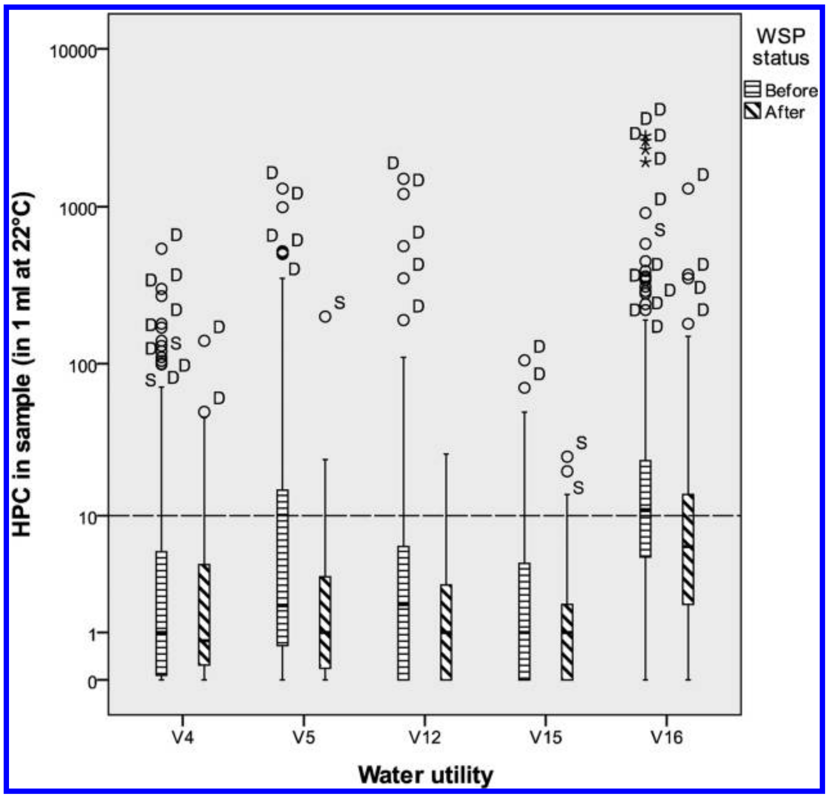

Figure 2. Boxplot of HPC before and after WSP implementation at five water utilities showing sampling site of outliers (S = water source, D = distribution network). The broken line shows 10 HPC in samples.

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Table 2. Statistical Summary of HPC in Water Samples at Five Water Utilities Before and After WSP

water utility	status	no. of water samples	mean[a]	median[a]	percentiles[a] (5th, 95th)	range[a] (min, max)	$P_{nonparam}$ (2 tail)
V4	before WSP	159	19.7	1	0, 121.5	0, 540	0.617
	after WSP	96	5.4	0.8	0, 21.0	0, 140	
V5	before WSP	250	33.0	2	0, 146.7	0, 1300	0.001
	after WSP	103	5.1	1	0, 18.8	0, 200	
V12	before WSP	100	45.0	2	0, 206.0	0, 1500	0.104
	after WSP	35	3.7	1	0, 21.3	0, 26	
V15	before WSP	51	7.5	1	0, 57.4	0, 105	0.082
	after WSP	78	2.2	1	0, 13.1	0, 25	
V16	before WSP	395	61.2	11	1, 182	0, 2800	<0.001
	after WSP	295	21.4	6	1, 84.6	0, 1300	
all samples	before WSP	955	42.3	5	0, 144.0	0, 2800	<0.001
	after WSP	607	12.6	3	0, 45.0	0, 1300	
all samples at source	before WSP	294	16.0	2	0, 74,4	0, 580	<0.001
	after WSP	218	6.7	1	0, 21.0	0, 200	
all samples in distribution network	before WSP	657	54.0	6	0, 181.0	0, 2800	<0.001
	after WSP	393	15.9	4	0, 54.3	0, 1300	

[a]cfu/mL: HPC colony forming units per milliliter in water sample.

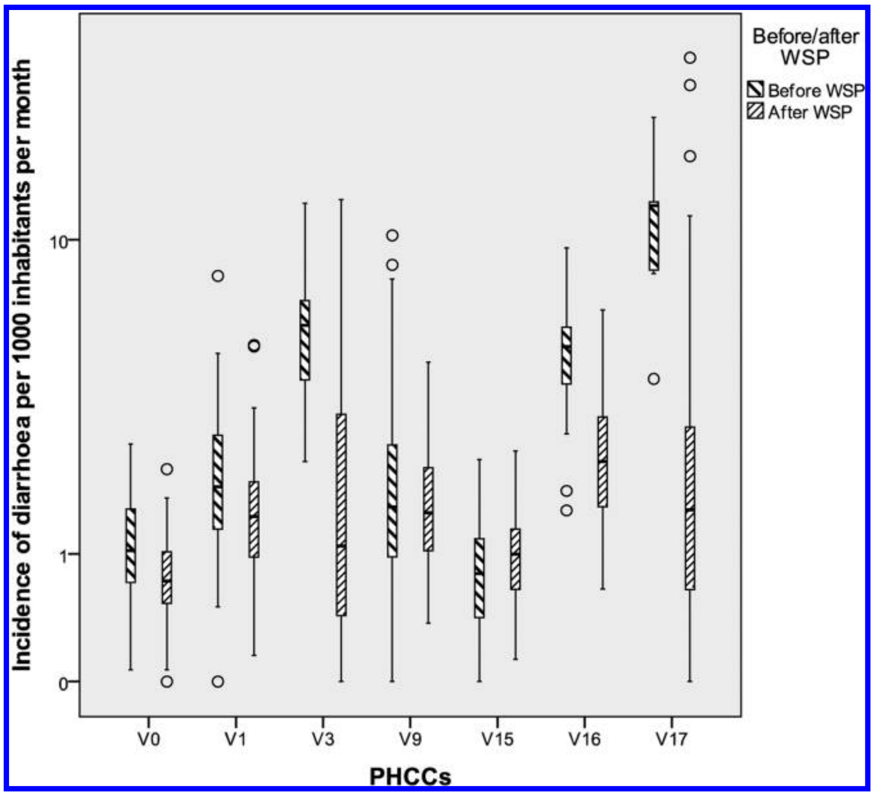

Figure 3. Incidence of diarrhea before and after WSP at seven PHCCs.

was significantly lower after WSP implementation ($p < 0.001$ for all three comparisons).

Additionally, HPC concentrations were more consistent following WSP implementation, with a decreased range and a decrease of the 95th percentile value as can be seen in Table 2. Most outliers were recorded before WSP implementation and more often in the distribution network than at the source as can be seen in Figure 2.

Incidence of Diarrhea. Figure 3 and Table 3 show the difference in diarrheal incidence before and after WSP implementation. The mean incidence of diarrhea for all the surveillance data set studied here, which covers about 38% of the population of Iceland, is 1.7 per 1000 inhabitants per month or 0.02 per person year as shown in SI Table S4. When data from all seven PHCCs were combined, univariate two-way ANOVA indicated an overall significant reduction of diarrheal incidence (F (1982) = 232, $p < 0.001$, $\eta_p^2 = 0.19$); this test also indicated that there was a significant interaction between PHCC and WSP status (e.g., that the difference in diarrheal incidence varied between PHCCs) (F (6982) = 53, $p < 0.001$, $\eta_p^2 = 0.24$). Diarrheal incidence was significantly reduced at five out of seven PHCCs (Table 3); this finding was confirmed using the Bonferroni correction to account for the problem of multiple comparisons (tested at significance level α/n of $p <$ 0.00714).

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Table 3. Statistical Summary of Incidence of Diarrhea Per Month Per 1000 Inhabitants at Seven PHCCs Before and After WSP

PHCCs	status	no. of months with data	mean[a]	median[a]	percentiles[a] (5th, 95th)	range[a]	$p_{posthoc}$
V0	before WSP	68	1.12	1.04	0.30, 2.13	2.56	<0.001
	after WSP	87	0.84	0.73	0.25, 1.66	2.17	
V1	before WSP	48	2.16	1.88	0.50, 4.76	8.04	0.005
	after WSP	93	1.59	1.45	0.49, 2.78	5.06	
V3	before WSP	17	6.01	5.91	2.30, 10.99	10.11	<0.001
	after WSP	103	2.15	1.09	0, 7.27	12.67	
V9	before WSP	117	2.07	1.58	0.29, 5.95	10.26	0.362
	after WSP	32	1.76	1.50	0.46, 4.55	4.29	
V15	before WSP	53	0.84	0.80	0.10, 2.12	2.34	0.056
	after WSP	80	1.02	1.00	0.27, 2.05	2.37	
V16	before WSP	34	5.22	5.16	1.74, 9.40	7.99	<0.001
	after WSP	116	2.48	2.30	1.06, 4.50	5.86	
V17	before WSP	21	11.19	12.22	4.57, 20.00	16.21	<0.001
	after WSP	127	2.59	1.54	0, 7.61	28.52	
all	before WSP	358	2.74	1.60	0.30,9.37	20.37	<0.001
	after WSP	638	1.88	1.37	0, 4.90	28.52	
sum		996					

[a]Monthly incidence of diarrhea per 1000 inhabitants served by the PHCC.

Supporting Information Table S4 shows diarrheal incidence for both those groups of PHCCs that experienced a change in WSP status during the study and those with and without WSP for the entire study period; both the mean and the median rate of diarrhea were lower when WSPs were in use and 95% percentile was reduced by half.

Confounders and Strength of the Data. It was hypothesized that decreases in diarrheal incidence over time could possibly be attributable to changes in the Iceland health care system or broader improvements in population health. To test whether the decline in diarrhea was not attributable to these factors, but rather to WSP implementation, data for pneumonia for three PHCCs were collected as a control variable. A nonparametric correlation test between pneumonia and diarrhea for these three PHCCs did not show significant relation between the rate of the two diseases (V1: $r = 0.094$, $p = 0.119$, $n = 129$; V16: $r = 0.053$, $p = 0.363$, $n = 135$; V17: $r = -0.053$, $p = 0.377$, $n = 144$), providing further evidence that the reduction in diarrheal incidence was attributable to WSP implementation.

Figure 4 shows the incidence of diarrhea as a function of WSP scoring for sixteen water utilities for 2009.[5] The figure shows a trend suggesting a lower incidence for water utilities with high WSP score, but the trend is not significant according to parametric test ($r = -0.443$, $p = 0.086$, $n = 16$).

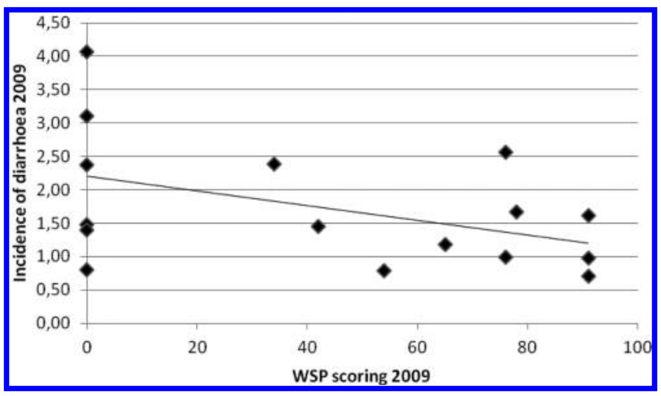

Figure 4. Incidence of diarrhea per 1000 inhabitant per month versus WSP scoring at 16 water utilities, Iceland, 2009.

DISCUSSION

This study provides systematic evidence of the positive impacts of WSPs on drinking water quality and health. These data indicate that WSP implementation in Iceland resulted in substantial and measurable reductions in drinking water noncompliance, amount of HPC in water (both at the source and in the distribution system), and incidence of diarrhea in communities served by utilities implementing WSP.

The strength of the study is that it covers a large proportion of a national population: well over one-third of the population for diarrhea incidence and nearly one-fourth for water quality. Therefore, there is a substantial amount of data behind the results. The uniformity of the Icelandic society, both socially and culturally is a further strength. Additionally, both consumers and health workers were unaware of the WSP implementation and were therefore effectively blinded to the intervention. These results are further supported by the fact that there is no correlation between incidence of diarrhea and pneumonia, indicating that the findings on diarrheal disease incidence were not influenced by broader trends in the Icelandic health care system. Using a previous analysis that scored the strength of WSP implementation at various utilities in Iceland revealed a possible correlation between better functioning WSP and lower diarrheal incidence; however, limited data were available and the trend was not statistically significant.

There were some limitations that could have influenced the results obtained. There was some nonconformity in delivering and recording data from the PHCCs into the national surveillance system. There was a variation in how the physicians used the ICD-10 codes, as different physicians used different ICD-10 codes for the same diseases and symptoms. Additionally physicians change frequently in some areas while in others there was greater staffing stability. To control for this potential bias, data from all PHCCs were reviewed in detail and additional data were pursued if there were abnormal or large gaps. If these gaps could not be rectified, the associated PHCC was left out of the analysis. In addition to this, the usual disadvantages of an ecological study apply, such as lack of control for confounding factors (partly addressed with the comparison with pneumonia in Results section), and the study addresses population, as data on individuals was not available.

The mean incidence of diarrhea for the surveillance data set studied here is 1.7 per 1000 inhabitants per month with sample variance of mean 4.5 and range 28.52. This gives 0.02 per person per year, but the proportion seeking medical care and the true incidence of diarrhea in the community is not known in Iceland. Cross-sectional telephone surveys in Australia, Canada, Ireland, and the United States found that approximately one in five with diarrhea sought medical care.[22] A similar result is reported from a study in Norway, with 17% consulting a physician.[23] If the situation is similar in Iceland it could be concluded that incidence of diarrhea in Iceland is around 0.10 per person per year. This is low compared to other countries, for example in Norway the rate is 1.2 per person year;[23] in Ireland 0.44 per person year, in Australia 0.83, and in Canada and United States 0.99.[22] FoodNet in the U.S. has estimated a rate of 0.65 per person year of acute gastrointestinal illness based on 33 studies.[24] There is insufficient information to enable estimation of the global burden of water-borne disease, which has proven complex because of the complex relationships among sources of hazards and routes of transmission. Estimates suggest that 6.6% of the total global burden of disease (measured in disability-adjusted life years or DALYs) could be prevented through well-recognized interventions in drinking-water supply and quality, sanitation, and hygiene.[25,26] Hunter et al.[17] concluded that up to 15% of gastrointestinal illness in the United Kingdom could be associated with contamination of drinking water in the distribution system. Colford et al.[27] estimated attributable risk percent (AR%) of acute gastrointestinal illness to drinking water by reviewing five household drinking water intervention trials, two in Canada, two in the U.S., and one in Australia, with the median estimate of AR% of 12%. The U.S. Environmental Protection Agency (EPA) has estimated the mean incidence of acute gastrointestinal illness attributable to drinking water to be 8.5% of all cases in the population served by community water system.[28] The median value of incidence of diarrhea between the seven PHCCs before and after WSP (shown in SI Table S4) obtained in the present study, yields a conservative estimate of AR% of about 14% for Iceland, which can be attributed to drinking water and cause endemic or sporadic cases of diarrhea.

Residual disinfection is not used in Iceland, due to high availability of good quality groundwater, which provides insight into what happens in the distribution system. Noncompliance was higher in the network than at the source and the main decrease of HPC following WSP implementation was in the network. This indicates that it may be possible to keep water safe by preventing contamination and bacterial growth in the pipe network rather than with disinfection. In some countries in Northern Europe disinfection of drinking water with chlorine is not used or used in a limited way. These are countries, where the dominant source is groundwater as in Iceland, such as The Netherlands, where chlorine is not used at all, neither for primary disinfection or to maintain a residual disinfectant in the network,[29] and Denmark where most systems are not chlorinated.[30] The reason for higher noncompliance in the distribution network than at the source in this study could be the fact that water and sewage pipes are most often in the same ditch. In all pipe system there are some leaks and soil will become contaminated around sewage pipes. A common theory is that this contamination does not enter the water pipes if sufficient internal pressure is maintained in the water pipe system. But some pressure events may cause low or negative pressure that result in intrusion of pathogens.[31−33] These events can be because of pipe break, pump shutdown, or sudden increase in water demand. They can be short-lived and still cause many incidents and that risk is greater where there is no residual disinfection.

The results from this study show significant benefit from WSP implementation in the form of improved regulatory compliance with drinking water standard, water quality, and reduced disease risk. It indicates that there are measurable benefits from implementing water safety plans in water utilities. The general conclusion of the study is that a WSP is an important instrument in improving water quality and reducing the occurrence of waterborne illnesses and as such improves public health.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Tables showing scope of data for the research and some results. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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■ REFERENCES

(1) *Guidelines for Drinking-water Quality*, 3rd ed.; Vol. *1* Recommendations; World Health Organization: Geneva, 2004.

(2) *Guidelines for Drinking-water Quality*, 4th ed.; World Health Organization: Geneva, 2011.

(3) *A Conceptual Framework to Evaluate the Impacts of Water Safety Plans*; Centers for Disease Control and Prevention, U.S. Department of Health and Human Services: Atlanta, GA, 2011; http://cdc.gov/nceh/ehs/GWASH/Publications/WSP_Evaluation_-Framework.pdf.

(4) The Foodstuffs Act No.93/1995; http://eng.umhverfisraduneyti.is/legislation/nr/375. Article 4, 2 pgr.

(5) Gunnarsdottir, M. J.; Gardarsson, S. M.; Bartram, J. Icelandic Experience with Water Safety Plans. *Water Sci. Technol.* **2012**, *65* (2), 277−288.

(6) Bartram, J.; Corrales, I.;, Davison, A.; Deere, D.; Drury, D.; Gordon,B.; Howard, G.; Rinehold, A.; Stevens, M. *Water Safety Plan*

Manual: Step-by-Step Risk Management for Drinking-Water Suppliers; World Health Organization: Geneva, 2009.
(7) *Progress on Sanitation and Drinking Water: 2010 Update*; WHO/UNICEF Joint Monitoring Programme for Water Supply and Sanitation, 2010.
(8) UNESCO-WWAP. *Water a Shared Responsibility; The United Nations World Water Development Report 2*; New York, 2006; p 132.
(9) European Environment Agency. *The European Environment – State and Outlook 2010 – Iceland*; 2010; http:// eea.europa.eu/soer/countries/is/soertopic_view?topic=freshwater (accessed 28 February 2012).
(10) Gunnarsdottir, M. J.; Gissurarson, L. R. HACCP and water safety plans in Icelandic water supply: Preliminary evaluation of experience. *J. Water Health* **2008**, *6* (3), 377–382.
(11) Geirsdottir, M. *Unofficial List of Waterborne Outbreaks from the Icelandic Food and Biotech R&D*, 2011.
(12) *Report on contamination of drinking water in Eskifjordur in July 2010*; Local Competent Authority for Eastern Iceland; http://fjardabyggd.is/media/PDF/2010_08_neylsuvatnsmengun_a_Eskifirdi.pdf.
(13) Payment, P.; Siemiatycki, J.; Richardson, L.; Renaud, G.; Franco, E.; Prévost, M. A prospective epidemiological study of gastrointestinal health effects due to the consumption of drinking water. *Int. J. Environ. Health Res.* **1997**, 5–31.
(14) Payment, P.; Hunter, P. Endemic and epidemic infectious intestinal disease and its relation to drinking water. In *Water Quality Guidelines. Standards & Health: Risk Assessment and Management for Water-related Infectious Diseases*; Fewtrell, L.. Bartram, J., Eds.; IWA Publishing: London, 2001; pp 61–88.
(15) Craun, G. F.; Calderon, R. L.; Wade, T. Assessing waterborne risks: an introduction. *J. Water Health* **2006**, *4* (suppl 2), 3–18.
(16) Nygaard, K.; Wahl, E.; Krogh, T.; Tveit, O. A.; Böhleng, E.; Tverdal, A.; Aavitsland, P. Breaks and maintenance work in the water distribution systems and gastrointestinal illness: A cohort study. *Int. J. Epidemiol.* **2007**, *39* (4), 873–880.
(17) Hunter, P. R.; Chalmers, R. M.; Huges, S.; Syed, Q. Self-Reported Diarrhoea in a Control Group: A Strong Association with Reporting of Low-Pressure Events in Tap Water. *Clin. Infect. Dis.* **2005**, *40*, 32–34.
(18) Icelandic Drinking Water Regulation no. 536/2001.
(19) Council Directive 98/83/EC of 3 November 1998 on the quality of water intended for human consumption.
(20) International Statistical Classification of Diseases and Related Health Problems, 10th Revision; Version for 2007; World Health Organization, 2007.
(21) Population According to Postcode; Statistics Iceland, 2011; http://www.statice.is/Statistics/Population/Urban-nuclei-and-zip-codes.
(22) Scallan, E.; Majowicz, S. E.; Hall, G.; Banerjee, A.; Bowman, C. L.; Daly, L.; Jones, T.; Kirk, M. D.; Fitzgerald, M.; Angulo, F. J. Prevalence of diarrhea in the community in Australia, Canada, Ireland, and the United States. *Int. J. Epidemiol.* **2005**, *34*, 454–460.
(23) Kuusi, M.; Aavitsland, P.; Gondrosen, B; Kapperud, G. Incidence of gastroenteritis in Norway – a population-based survey. *Epidemiol. Infect.* **2003**, *131*, 591–597.
(24) Roy, S. L.; Scallan, E.; Beach, M. J. The rate of acute gastrointestinal illness in developed countries. *J. Water Health* **2006**, *04* (suppl 2), 31–70.
(25) Bartram, J.; Cairncross, S. Hygiene, Sanitation, and Water: Forgotten Foundations of Health. *PLoS Med.* **2010**, *7* (11), e1000367 DOI: 10.1371/journal.pmed.1000367.
(26) Pruess-Ustun, A.; Bos, R.; Gore, F.; Bartram, J. *Safer Water, Better Health*; WHO: Geneva, 2008.
(27) Colford, J. M., Jr.; Roy, S.; Beach, M. J.; Hightower, A.; Shaw, S. E.; Wade, T. J. A review of household drinking water intervention trials and an approach to the estimation of endemic waterborne gastroenteritis in the United States. *J. Water Health* **2006**, *4* (suppl 2), 71–88.
(28) Messner, M.; Shaw, S.; Regli, S.; Robert, K.; Blank, V.; Soller, J. An approach for developing a national estimate of waterborne disease due to drinking water and a national estimate model application. *J. Water Health* **2006**, *04* (suppl 2), 201–240.
(29) Smeets, P. W. M. H.; Medema, G. J.; van Dijk, J. C. The Dutch secret: how to provide safe drinking water without chlorine in the Netherlands. *Drink. Water Eng. Sci.* **2009**, *2*, 1–4.
(30) Neimann, J.; Engberg, J.; Molbak, K.; Wegner, H. C. A case control study of risk factor for sporadic campylobacter infections in Denmark. *Epidemiol. Infect.* **2003**, *130*, 353–366.
(31) LeChevallier, M. W.; Gullick, R. W.; Karim, M. R.; Friedman, M.; Funk, J. E. The potential for health risks from intrusion of contaminants into the distribution system from pressure transients. *J. Water Health* **2003**, *1* (1), 3–14.
(32) Teunis, P. F. M.; Xu, M.; Fleming, K. K.; Yang, J.; Moe, L. C.; LeChevallier, M. W. Enteric virus Infection Risk from Intrusion of Sewage into a Drinking Water Distribution Network. *Environ. Sci. Technol.* **2010**, *44*, 8561–8566.
(33) Besner, M.-C.; Prévost, M.; Regli, S. Assessing the public health risk of microbial intrusion events in distribution systems: Conceptual model, available data, and challenges. *Water Res.* **2011**, *45*, 961–979.