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A meta-analysis of public compliance to boil water advisories

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ABSTRACT

Water utilities that generally provide continuous and reliable service to their customers may sometimes issue an advisory notification when service is interrupted or water quality is compromised. When the contamination is biological, utilities or the local public health agencies issue a 'boil water advisory' (BWA). The public health effectiveness of a BWA depends strongly on an implicit public understanding and compliance. In this study, a meta-analysis of 11 articles that investigated public compliance to BWA notifications was conducted. Awareness of BWA was moderately high, except in situations involving extreme weather. Reported rates of compliance were generally high, but when rate of awareness and non-compliant behavior such as brushing teeth were factored in, the median effective compliance rate was found to be around 68 percent. This does not include situations where people forgot to boil water for some part of the duration, or ingested contaminated water after the BWA was issued but before they became aware of the notification. The two-thirds compliance rate is thus an over-estimate. Results further suggest that timeliness of receipt, content of the advisory, and number of sources reporting the advisory have a significant impact on public response and compliance. This analysis points to improvements in the phrasing and content of BWA notices that could result in greater compliance, and recommends the use of a standard protocol to limit recall bias and capture the public response accurately.

1. Introduction

On May 27, 2010, residents of the U.S. city of Boston, Massachusetts and nearby areas were advised to boil their tap water before drinking and other ingestion activities such as washing and brushing. The advisory was issued due to a break in the water main tunnel that carried water to the city from a reservoir located about 150 km away, and lasted three days (Galarce and Viswanath, 2012). More than 2 million residents were affected by this incident. In 1998, nearly 4 million residents of metropolitan Sydney, Australia faced multiple boil water advisories over the course of nine weeks due to high levels of *Cryptosporidium* and *Giardia* in the source water (Stein, 2000).[1] Both of these incidents were newsworthy due to the scale of the event. However, the practice of issuing an advisory and requesting residents to boil tap water is not very uncommon. A search for 'boil water advisory' on Google News brings up several thousands of search results.[2] It is less common to experience a 'Do Not Drink' advisory, such as the one issued in the U.S. city of Toledo, Ohio following the detection of harmful algal blooms in the city's water supply in early August, 2014 (Kozacek, 2014).

Regulations vary across and within countries regarding when and how boil water advisories are issued. In the U.S., a boil water advisory (BWA) or a boil water notice is a public notification issued by water utilities or the local health department that informs the public to boil their municipal supply water before consumption (New York State Department of Health, 2014). Even though an advisory sounds more precautionary than a notice, both are interchangeable terms with no difference between the two. A boil water order, however, is a directive issued by the health department to the public water supplier instructing the utility to distribute a BWA to its customers. Health Canada (2015), however, does not distinguish between a "boil water advisory" and a "boil water order."

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[1] Others have disputed the source and extent of Sydney's water quality problems (Clancy, 2000).

[2] An analysis of media coverage of water infrastructure issues in the U.S. documented increasing rates of water main breaks, which often result in BWAs (Vedachalam et al., 2015).

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There are a variety of situations in which BWAs are issued, but health agencies in Australia (NHMRC/NMMRC, 2011), Canada (Health Canada, 2015) and the U.S. (CDC, 2013), and the World Health Organization (WHO, 2011) provide guidelines for issuing an advisory. A BWA may be issued when routine tests of the water find microbial concentrations exceeding the maximum contaminant levels for total coliform or *Escherichia coli* in tap water. Additionally, an outbreak of water-related gastroenteritis or the detection of low levels of pathogens such as *Cryptosporidium*, or *Giardia* may warrant the issuance of a BWA. Other situations that can result in a BWA include water main breaks, interruption in treatment or distribution, depressurization or low pressure in the line, power failures, etc. Extreme weather events such as heavy precipitation present scenarios where two or more of these causes exist simultaneously. Power failure and water main breaks can disrupt supply, in addition to the potential for contamination of water supply reservoirs through surface runoff. Canadian agencies are required to characterize BWAs as either emergency or precautionary. Detection of *E. coli* in drinking water or a water-related outbreak would result in an emergency BWA, whereas changes in source quality, water main breaks or persistent presence of total coliforms would trigger a precautionary BWA (Health Canada, 2015). Evidence from Canada suggests that BWAs are issued more often due to failures in the treatment and distribution process as compared to detection of *E. coli* or other microbial contaminants (Environment and Climate Change Canada, 2015).

BWAs vary in the information they provide to the public and can be conveyed through a multitude of modes (media, phone, door-to-door notice, etc.). Often included in BWAs is a description or explanation of the event that prompted the advisory, possible health effects of drinking unboiled tap water, contact information of the utility and the local health department, a description of corrective efforts underway, and instructions to properly boil and store water. According to the Centers for Disease Control guidelines, in the event of a BWA, water should be brought to a rolling boil and should continue to boil for 1 min (CDC, 2013). Other health agencies such as the World Health Organization and Australia's National Health and Medical Research Council recommend simply bringing water to a rolling boil (NHMRC/NRMMC, 2011; WHO, 2011). Health effects of drinking unboiled contaminated tap water vary based on the situation, but often include diarrhea, nausea, vomiting, and bloody stool (Kent et al., 1988).

From the water utility's perspective, cost is an important factor when deciding *whether* and *when* to issue a BWA.[3] Not only is it critical to gauge the risk-benefit potential of issuing an advisory, it is also important to consider the costs to the consumers, both in time and money. Issue too many precautionary BWAs and the public may lose trust in the utility or not give the notices adequate attention. Wait too long to issue the notice and it could lead to adverse public health impacts. Wagner et al. (2005, p776) modeled the decision to issue a BWA (or wait 72 h for microbial test results) in response to a hypothetical outbreak of diarrhea by assuming that the "cost of a BWA is the cost of bottled water consumed." The authors concluded that if the cost of BWA was lower than 14 cents (2005 value) per person per day, then the benefits of issuing a BWA would outweigh the cost of waiting for definitive microbial test results.

A more comprehensive assessment was conducted following a *Giardia lamblia* outbreak in Milesburg, Pennsylvania, USA in 1989. Laughland et al. (1993) estimated that the time lost in boiling, hauling, or purchasing water to avert infections cost an average household $0.19–$1.12 per household in 1989 dollars ($0.35–$2.06 in 2012 dollars). Assuming an average household contains 2.3 persons, the cost per person per day is $0.15–$0.90. A more recent analysis of a water contamination incident reported the estimated cost of a 24-day Salmonella outbreak in a city of nearly 9000 residents to be $1.5–$2.6 million (Ailes et al., 2013). The approximate cost of per person per day comes out to be substantially higher at $7.15–$12.39 (2008 dollars). A broader analysis of disruptions in water service found the average cost per incident per household to be $94 or $7 per person per day (Heflin et al., 2014),[4] which matches the Ailes et al. (2013) estimates. Water utilities should factor in comprehensive estimates of economic loss due to water disruption and contamination when deciding whether or not to issue a BWA.

Several studies, mostly conducted in Canada (Hrudey et al., 2003; Wallis et al., 2001) and Northern Europe (Kargiannis et al., 2009; Rimhanen-Finne et al., 2010; Robertson et al., 2009), but also in Australia (Clancy, 2000; Stein, 2000) and the U.S. (Swerdlow et al., 1992), have documented and analyzed individual BWAs issued by a city or municipality – lead-up to the situation, the process of issuing BWA and corrective actions taken thereafter. Hrudey and Hrudey (2004, 2014) summarize many of these incidents in two books written for water industry professionals. A much more limited set of studies, one each in Canada and the U.S., have investigated characteristics of water utilities that issued BWA over a large spatial scale (Edwards et al., 2012; Vedachalam et al., 2014). Water Research Foundation (2014) published a synthesis report identifying the gaps in understanding the costs and benefits of BWAs in North America. A distinctly separate field of inquiry on this topic has studied the behavioral response of the customers affected by these advisories. Because the effectiveness of issuing a BWA is contingent on an implicit public understanding of the process, we find this line of inquiry particularly important to understanding the role of BWA in protecting public health. The implementation of Safe Drinking Water Act of 1974 in the U.S. resulted in consumers being notified of water quality issues. A series of articles published during the 1980s evaluated consumer response to such notifications, which yield insights for how BWA notices are received and understood by consumers (Bruvold et al., 1985; Wardlaw and Gaston, 1989). In this study, we conduct a meta-analysis of BWA compliance studies to quantify and draw broader conclusions on public compliance to BWA and the effectiveness of BWA in safeguarding public health during emergencies.

2. Methods

2.1. Literature search

After several trials with different search terms, two searches were conducted on each of the three online scholarly databases: PubMed, Web of Science and ProQuest Water Resources Abstracts (WRA). No time restriction was placed for inclusion in search results. However, only studies in English were included. The first search (referred to as Search 1) used the keywords: **TOPIC:** ("drinking water" OR "water supply" OR "water source" OR "potable water" OR "tap water") *AND* **TOPIC:** (advisory OR warning OR "boil water" OR notice OR order) *AND* **TOPIC:** (compliance OR adherence OR response OR "public response" OR "drinking water choices" OR perceptions OR choice). The second search (referred to as Search 2)

[3] This precludes situations where BWAs are issued at the direction of regulatory agencies or triggered because water quality tests exceed certain regulatory standards.

[4] Using the data provided in the article, the average length of the incident was calculated to be 6 days, and the average size of the household was taken to be 2.3 persons.

used the keywords: “boil water”. The two searches were conducted on June 16 and June 17, 2014, respectively. After removal of duplicates, all the abstracts were read to determine if the keywords attracted relevant articles. Only those studies that presented results from a survey of the public in response to a boil water advisory issued in the respondents' neighborhood or city were considered relevant for the purposes of this study.

2.2. Data extraction

Although the study is primarily concerned with awareness and compliance of boil water advisories, the study characteristics are integral to understanding how the public response is moderated by the site-specific conditions. Study location, date of issue, duration and cause of BWA were identified from each study. Wherever possible, survey questions were assessed to identify the method used to obtain responses (phone, mailed, door-to-door, etc.), number of questions asked, response rate, sample size and composition. The survey questions were further analyzed to identify which topics and themes are consistently covered in most of the studies. Information sources used by respondents were assessed to identify successful communication channels during emergencies. Finally, fraction of respondents reporting they were aware or complied with the BWA notice was extracted from each study. Many studies reported compliance rate as a fraction of those respondents that were aware of the BWA notice, hence an effective compliance rate was computed.

2.3. Heterogeneity

To test for heterogeneity of awareness and compliance rates across the studies, we computed Cochran's Q and I^2 statistics. A significant Q value suggests that the studies are heterogeneous and not reporting similar outcomes. The I^2 statistics describes the variation across studies that is attributed to heterogeneity rather than chance (Higgins and Thompson, 2002).

2.4. Bias

Bias in publishing significant results would suggest that of the studies that report effect sizes, the ones reporting higher effect sizes are more likely to be published than those with smaller effect sizes. As a result, any meta-analysis is likely to over-estimate the effect size. Our meta-analysis does not aggregate effect size. We extract a percentage numeric from each study, which are equally likely to be reported whether they are small or large. It is possible that researchers may believe that higher awareness and compliance rates are less worthy of investigation as public health issues, and thus may not report those results in published studies. However, because the constituent studies only report a percentage (and not effect size and standard error), we are unable to use standard techniques like the funnel plot and Egger's regression test to detect the possibility and the extent of significant bias in the reported results (Sterne et al., 2005; Egger et al., 1997).

2.5. Awareness and compliance predictors

In addition to the awareness and compliance rates, this meta-analysis also examined the effect of sample and study characteristics on awareness and compliance. The characteristics included in the meta-regression were percentage of women respondents, number of information sources used by the water utility, study location, duration of BWA in weeks, time elapsed since BWA in weeks, and whether the BWA issuance was related to an extreme weather event. Study location and extreme weather were coded as binary variables; the rest were continuous. The effect of predictor variables on awareness and compliance rates was measured by random-effects univariate meta-regression. The analysis was conducted in STATA (StataCorp, 2011).

3. Results

3.1. Study selection

Search 1 and search 2 yielded 1948 and 63 studies, respectively. Removal of duplicates resulted in an initial list of 1633 studies. The protocol defined by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method was followed to narrow the results further (Fig. 1). All 1633 abstracts were read to determine if the article focused on boil water advisory, and/or public response to a water-related emergency. From this list, 87 were selected for retrieving full-length text. The references listed within these 87 articles were scanned to identify additional articles that did not appear in the search results. This search yielded nine articles. In total, 96 full-text articles were read to determine if public awareness and compliance to boil water advisories were assessed and quantitatively reported. Studies that analyzed water contamination incident in a particular city, including details of the when and how the boil water advisory was instituted and communicated, but did not assess public response were not included. Using these criteria, 11 studies were eligible for meta-analysis. Two additional studies, one of which was hypothetical, assessed risk perception following BWAs, and were not included in the meta-analysis. Even though the inclusion criteria did not discriminate on the basis of publication status, all the 11 studies were published in peer-reviewed journals. An additional 43 articles were classified under qualitative synthesis.

3.2. BWA characteristics

3.2.1. Location and duration

Of the 11 studies, seven were from the United States, three from United Kingdom and one from the Netherlands (Table 1). Three articles surveyed a “control” community, in addition to the affected community (Angulo et al., 1997; Harding and Anadu, 2000; Kargiannis et al., 2009). Two articles conducted studies in multiple communities and reported individual as well as aggregate statistics. Details on the control communities and breakdown on individual communities are presented in Supplemental Information, Table S1. Ram et al. (2007) surveyed eight communities in Mississippi, USA after Hurricane Rita, while Harding and Anadu (2000) surveyed four towns in Oregon, USA, two of which were “control” and the other two reported BWAs of different nature and cause. The sample also includes two studies following the Boston Water Crisis of 2010 (Galarce and Viswanath, 2012; Wang et al., 2011). A median BWA lasted 14 days, with a range of three days to three years. Most BWAs were issued due to short-term issues, which included pathogen outbreak, water main break, and excessive precipitation and flooding. Only one of the BWAs was attributed to a long-term filtration problem. Studies in our sample were conducted between one week and 3 years after the BWA was issued, with a median of 1 month.

3.2.2. Population affected

Population affected by the BWA was reported in various studies either as individuals or in terms of households. To ensure consistency, number of households was converted to persons using a conversion factor that was most appropriate to that country and the closest year (see Supplemental Information, Table S2). The median population affected by a BWA was 368,000 persons, with a range of

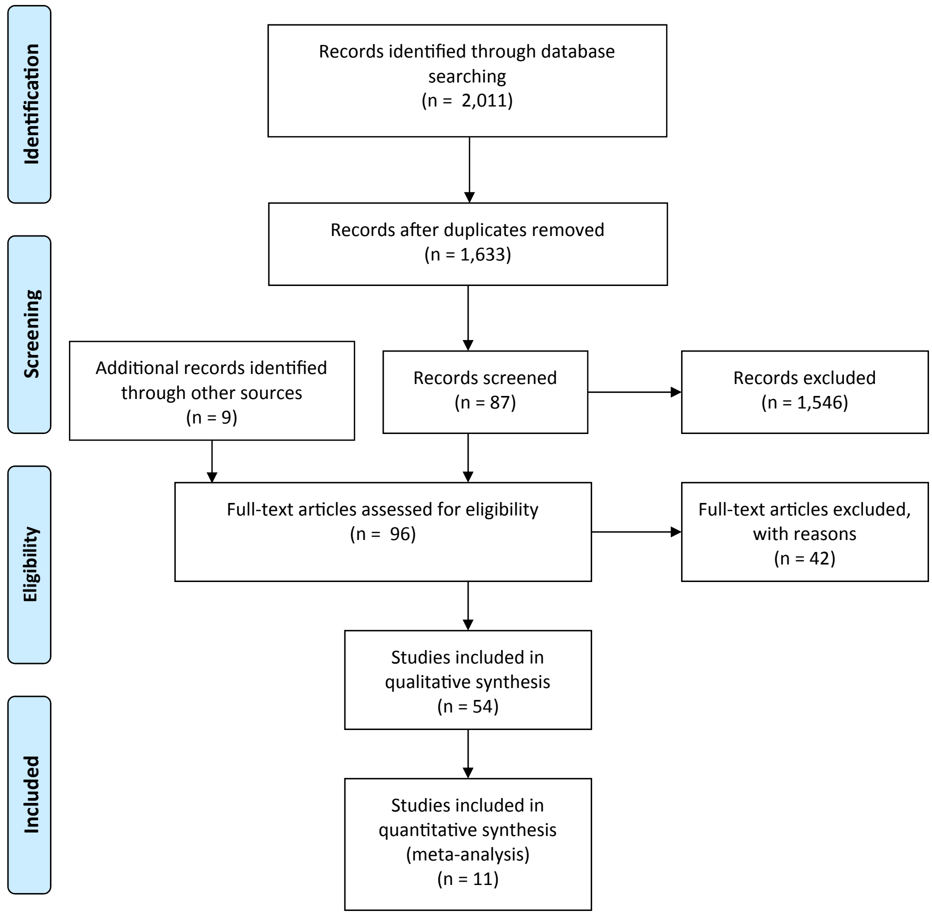

Fig. 1. Modified Preferred Reporting Items for Systematic Review and Meta-Analyses (PRIMA) flow diagram to select studies for the meta-analysis. *From*: Moher D, Liberati A, Tetzlaff J, Altman DG, The PRISMA Group (2009). *Preferred Reporting Items for Systematic Reviews and Meta-Analyses*: The PRISMA Statement. PLoS Med 6(6): e1000097. http://dx.doi.org/10.1371/journal.pmed1000097.

1104 (Gideon, Missouri, USA) to 2 million persons (Greater Boston, Massachusetts, USA).

3.2.3. Survey details

Key characteristics of the surveys presented in the articles are highlighted in Table 2. In-person interviews were the most common, followed by phone interviews and mailed questionnaires. The median response rate was 68 percent, with a low of 20 percent and a high of 94 percent. Sample size of the surveys ranged from 50 to 675 persons, with a median of 226. Women respondents comprised between 50 and 80 percent of the sample population, with a median of 60 percent. Overall, women had higher response rates than men. All studies drew samples from the affected population. However, two of those samples can be categorized as convenience samples since they targeted a select group of respondents – visitors accompanying patients to a hospital one week after a BWA (WLH; Wang et al., 2011) and hospital employees in a BWA affected region (WSW; Willocks et al., 2000). As a result, both studies yielded significantly higher proportion of female respondents.

3.2.4. Survey content

Details about the survey content are presented in Table 3. Ten of the 11 studies questioned respondents on their awareness of the BWA and the mode of receipt of the BWA notice. More than half the studies asked further questions on the BWA notice including its clarity and time and/or date of its receipt. All of the studies asked respondents about actions taken in response to the BWA. Specifically, all except one asked whether the respondents had boiled water for drinking purposes. Less frequently asked questions focused on other water uses such as food preparation, brushing teeth, making ice and feeding pets. Bottled water consumption and reasons for non-compliance with BWA notices were additional questions included in many studies to understand consumer behavior. On the whole, though, very little consistency was observed in the content of the questionnaires across the 11 studies. Among the most relevant, only one question was uniformly asked across all studies, while three questions were asked in 10 studies. Even when respondents were asked a particular question, the inconsistent wording or response options made it difficult to compare the response rates. Except in a few instances, breakdown by demographic groups was not provided and no statistical analysis conducted. Though some of the surveys asked respondents to list ways to improve the communication of BWAs from the water authorities, there was no consistent assessment of the wording of the notices or the instructions provided therein, for us to make a quantitative conclusion.

3.3. Survey results

3.3.1. Sources of information

All studies, except two, asked the respondents about the sources of information by which they became aware of the BWA notice (Table 4). Radio was the most commonly cited source of information used in receiving the BWA notice, followed by leaflet/flyer,

Table 1
Summary of BWA incidences and studies.

Author(s)[a]	Location	BWA issue date	Duration	Date of study[b]	Time between BWA issue and study	Cause of BWA	Population[c]
Angulo et al. (1997) [ATS]	Gideon, Missouri, USA	Dec 18, 1993		Dec 31, 1993–Jan 6, 1994	13 days	Salmonella Typhimurium	1104
Bruvold and Gaston (1980) [BG]	San Bernardino, California, USA	1977		Jun–Aug 1977	1 month	Bacteria	
Galarce and Viswanath (2012) [GV]	Boston, Massachusetts, USA	May 1, 2010	3 days	May 27, 2010–Jun 14, 2010	27 days	Water Tunnel Break	2,000,000
Harding and Anadu (2000) [HA]	A, Oregon, USA	1993	3+ yrs	Jun–Oct 1996	3+ years		Undisclosed
	C, Oregon, USA	Undated	2–3 weeks	Jun–Oct 1996		*E.coli*, total coliform, flooding	Undisclosed
Kargiannis et al. (2009) [KSD]	North Holland, Netherlands	May 15, 2007	8 days	Jun 2007	15 days	*E.coli* detection; runoff contaminated with animal feces	414,000
Laughland et al. (1993) [LMM]	Milesburg, Pennsylvania, USA	Jan 1989		Apr 1989	3 months	Giardia	2104
O'Donnell et al. (2000) [OPA]	Wigan and Bolton, UK	Nov 19, 1998	6 days	Dec 1998	13 days	Water main damage; sewage contamination	2107
Ram et al. (2007) [RBK]	Louisiana, USA[d]	Sep 24, 2005	14–43 days	Nov 2005	6 weeks	Hurricane; loss of electricity or pressure in distribution system	
Rundblad et al. (2010) [ROP]	Gloucestershire, UK	Jul 27, 2007	11 days	Jan–Feb 2009	18 months	Flooding	322,000
Wang et al. (2011) [WLH]	Boston, Massachusetts, USA	May 1, 2010	3 days	May 7–11, 2010	1 week	Water Tunnel Break	2,000,000
Willocks et al. (2000) [WSW]	North Thames, UK	Mar 2, 1997	16 days	Apr 10, 1997	1 month	Cryptosporidiosis	720,000

Notes:
[a] Studies will be referred to by shorthand abbreviations (eg. Bruvold and Gaston (1980) = BG) in all subsequent tables.
[b] Dates of Study refer to when the surveys were conducted, not the date of publication.
[c] Population data obtained from the census information in the cases of Karagiannis et al., Willocks et al., Rundblad et al., and Laughland et al.
[d] This entry refers to the overall compiled data and findings from the eight mobile home communities surveyed.

Table 2
Survey characteristics.

Author(s)	Survey method[a]	Number of questions[b]	Response rate (percent)	Sample size	Women (percent)	Median age
ATS	1, 2	15	94	246		
BG	2	15		50	50	
GV	3	12	73	267	52	
HA	1	22	69[c]	193	59	
KSD	4	19	66	99	58	47.7[d]
LMM	1	22	61	226	62	49.3[d]
OPA	4	16	69	241		
RBK	2	24		196	64	46
ROP	4	28	20	159	60	
WLH	2	15		533	69[e]	
WSW	2	13	34	675	80[e]	33
Mean		18	61	262	62	44
Median	2	18	68	226	60	47

[a] Survey method: 1: phone interview, 2: in-person interview, 3: online questionnaire, 4: mailed questionnaire.
[b] Some of the studies did not give the exact number of questions asked in the survey, so a best estimate was made given the methods and descriptions provided.
[c] The response rate is for the entire study, including the control locations.
[d] Average age as reported in the study.
[e] The higher proportion of women respondents is attributed to sampling a highly specific population group – visitors accompanying patients to a hospital (WLH) and employees of a hospital (WSW).

Table 3
Survey questions.

Questions/topics	N	Questions/topics	N
Demographics	9	Boiled water for:	
		Drinking	10
Awareness of BWA	10	Food preparation	5
BWA notice:			
Clarity	6	Brush teeth	5
Time/day of receipt	7	Make ice	3
Mode of receipt	10	Feed pets	3
Actions taken	11	Use bottled water	8
Changes in drinking habits	5	Reasons for noncompliance	8

newspaper, television, internet and family/friends. Information received via phone and word-of-mouth was less frequently cited as information sources by the respondents. Across all studies, a median of 30 percent or more of the respondents received BWA notices through television, radio, phone, leaflet/flyer, and family/friends.

3.3.2. Public awareness

Of the nine studies that reported results on this topic, awareness of BWA ranged from 40 to 100 percent, with a median rate of 97 percent (Table 5). Five of the nine studies reported awareness rates of 97 percent or more, suggesting successful communication by

Table 4
Information sources.

Author(s)	Newspaper (%)	TV (%)	Radio (%)	Phone (%)	Internet (%)	Leaflet/flyer (%)	Family/friends/neighbors (%)	Word of mouth (%)	Number of sources used
ATS			90			10			2
BG	–	–	–	–	–	–	–	–	–
GV	6	77	22	18	18		28		6
HA	74		35	43		58	57		5
KSD	20	50	24		7		23		5
LMM	–	–	–	–	–	–	–	–	–
OPA	5					85		10	3
RBK	5	21	15		1	32		23	6
ROP	28	17	57		7	38	10		6
WLH	1	25	2	36	2	1	80	33	8
WSW		39	37			87			3
Median Source Utilization (%)	6	32	30	36	7	36.5	34.5	23	

Note: The percentages across all information sources may add up to more than 100, since they were not presented as exclusive options in the surveys.

Table 5
Awareness and compliance.

Author(s)	Awareness of BWA (%)	Compliance rate (%)	Boiled drinking water (%)	Bottled water or other source (%)	Effective compliance rate (%)
ATS	99	69+	69		68 (69 × 0.99)
BG	82	41[a]			34 (41 × 0.82)
GV	100	88			88
HA	75	85+	49	72	54 (72 × 0.75)
KSD	100	82*	71	43	82
LMM			53	45	98
OPA	100	36	80		36
RBK	40	87	47	69	87
ROP	71	52+	71	36	37 (52 × 0.71)
WLH	97	98	57[b]	88[b]	95 (98 × 0.97)
WSW		43	85	72	43
Mean	85	68	65	61	66
Median	97	76	69	69	68

^ In the absence of any mention in the article, awareness was assumed to be 100 percent.
+ compliance rate is measured only among those respondents who were aware of the BWA.
*compliance rate includes those residents who either boiled water or drank bottled water.
[a] BG asked a set of questions, and depending on the number of positive responses, the awareness was presented in a likert-type scale. The figure presented here is a mean of two ends of the spectrum that signify the respondents understood the notifications either fully (4 percent) or partially (78 percent).
[b] WLH presented three options to the respondents: exclusive use of boiled water (10%), exclusive use of bottled water (41%), either boiled or bottled water (47%). In the absence of more information, figures from the third category were applied to the first categories to provide a liberal estimate of users relying on boiled water and bottled water, respectively.

public utilities. At the other end of the spectrum, the lowest awareness rate was recorded in the RBK study conducted in Louisiana, USA after Hurricane Rita had disrupted water supply in the region.

3.3.3. *Public compliance*

Except one, all studies provided some measure of BWA compliance. The lone exception was the LMM study, which was designed to assess the cost of averting public health consequences due to a BWA, and was not intended to assess public compliance (Laughland et al., 1993).[5] Among the communities affected by a BWA, compliance rates ranged from 36 to 98 percent, with a median rate of 76 percent. The highest compliance rate was observed in WLH where the surveys were conducted in the waiting rooms of medical clinics and the emergency department at a large city hospital, which potentially made the sample less representative and more homogeneous. Additionally, the WLH study did not discuss the use of boiled or bottled water for purposes other than drinking (e.g., brushing teeth and washing food), so it is possible that this statistic is misleadingly high. A breakdown of compliance rates by individual activities, as reported in OPA, is a good example of this. Eighty percent of the respondents reported boiling tap water for drinking purposes, but 54 percent continued to brush their teeth with unboiled tap water during the advisory period. In most studies, the authors provided the compliance rate based on the proportion of respondents who either boiled water or used bottled water, two most prominent ways of taking action. However, a few studies had a question in the survey that asked respondents if they had complied or taken action since the advisory. The discrepancy is evident in HA and RBK, where a higher proportion of respondents claimed to have taken action than those who either boiled water or purchased bottled water. Commonly attributed reasons for non-compliance included forgetting (Angulo et al., 1997; Laughland et al., 1993; O'Donnell et al., 2000), not believing the notice (Angulo et al., 1997) and choosing not to boil the water (O'Donnell et al., 2000; Ram et al., 2007).

Five studies questioned respondents on the use of boiled water for various non-drinking purposes. Certain practices such as preparing food, and brushing teeth with unboiled water constitute noncompliant behavior and increase the chances of contracting illness. Other uses such as taking bath, washing dishes and washing

[5] Even though boiling water and consuming bottled water are effective compliance strategies and are measured in this study, LMM failed to self-report the compliance rate.

hands also constitute risk, but the probability of contracting illness is low. Keeping this in mind, we computed the effective compliance rate for each of the studies, as shown in Table 5. Only two-thirds of the respondents complied with the BWA notice, bringing the effectiveness of such notices into question. In cases where the questionnaires probed respondents about non-compliant behavior, uses that did not involving direct consumption of water such as brushing teeth were prominently cited. ROP reported some respondents using unboiled water for food preparation.

3.4. Heterogeneity tests

Cochran's Q statistic was significant for both awareness (42.45, $p < 0.05$) and compliance (101.60, $p < 0.05$) rates, indicating that there were differences in the survey response that cannot be attributed to sampling error alone. I^2 values for awareness (76.44 percent) and compliance (90.16 percent) rates were also high, which shows high degree of variability across the studies. Due to the high degree of heterogeneity, we used a meta-regression to test between-study factors or predictors to isolate the effect of each of the predictors on the awareness and compliance rates.

3.5. Predictors

We tested the association between six variables of interest and the rates of BWA awareness and compliance to identify patterns. The low number of regressors prevented a multivariate analysis, so a univariate analysis was conducted (Table 6). Proportion of women respondents, number of information sources and location of the study had no association with awareness rates. However, awareness was negatively associated with BWA duration ($p = 0.10$), time since the BWA was issued ($p = 0.012$) and an extreme weather condition causing the BWA ($p = 0.012$). Compliance was significantly lower in UK studies ($p = 0.002$) and negatively associated with time since BWA ($p = 0.032$). A weak association between number of information sources and compliance rate was also observed ($p = 0.092$).

4. Discussion

In the event of crises that prompt the issuance of a BWA, effective communication is of the utmost importance. This has been stressed both by the data and the conclusions of the articles studied in this meta-analysis. Crucial in crisis communication are timeliness, wording and nature of the advisory, sources used to relay the advisory, and instructions on how to respond to the advisory. Even though the best efforts will fail to guarantee complete public compliance, improvements can be made to facilitate effective communication and yield better compliance.

Table 6
Predictors of awareness and compliance rates.

Predictor	Awareness		Compliance	
	Estimate (S.E.)	*p*	Estimate (S.E.)	*p*
Women (percent)	0.228 (0.522)	0.675	0.055 (1.210)	0.965
Sources (number)	−3.742 (3.433)	0.312	6.942 (3.561)	0.092*
UK	3.708 (11.656)	0.758	−37.083 (8.362)	0.002***
BWA duration (weeks)	−0.308 (0.158)	0.100*	−0.262 (0.225)	0.288
Time since BWA (weeks)	−0.298 (0.096)	0.012**	−0.378 (0.151)	0.033**
Extreme weather	−39.278 (12.552)	0.012**	−4.444 (21.459)	0.841

Parameter estimates are linear coefficients (standard errors robust to heteroskedasticity in parenthesis). *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.
Estimating compliance rate with USA as the binary variable is not significant ($p = 0.103$).

Except two, all studies presented information on BWA awareness (Table 5). However, these figures likely do not capture those respondents who were unaware of the advisory for the first few days. For example, 10 percent of the Gideon, Missouri (USA) residents was not aware of the BWA until 10 days after its issuance (ATS). As a result, these residents continued to drink *Salmonella*-contaminated water. Further, not only did the initial notification fail to reach all residents, but it also did not clearly inform residents of the nature of the problem, its potential health effects, or the protocol to be followed. Consequently, “many of the people who heard the initial boil order did not appreciate the severity of the situation” (Angulo et al., 1997, p584). The authors go on to state that BWA compliance improved only after information sheets that explained the rationale for the advisory and boiling procedure were delivered to all residents. GV examined this dynamic in detail, and reported that respondents who learned about the crisis the day the pipe broke were significantly more likely ($p < 0.01$–0.1, depending on the question) to comply with instructions. An evaluation of public notifications issued under the Safe Drinking Water Act in California, USA by BG also reported strong association between knowledge of the contaminants of concern and awareness of the problem (Bruvold et al., 1985).

OPA reported that 56 percent of the respondents consumed unboiled water after the notice was issued, but before they received it (a period of roughly 1.5 days). WLH noted a similar effect in their study of the 2010 Boston Water Crisis. The authors generated a conservative estimate of “exposed” respondents (34 percent) by categorizing those who were either unaware of the notice, received the message several hours after it was issued, or took no action upon receive the notice.

Thus, depending on the communication channels employed by the water utility, a significant proportion of the residents could be exposed to pathogens in the initial period of the advisory. Effective compliance is further reduced when residents stop boiling water or forget to boil at some point during the advisory period (Laughland et al., 1993). Researchers have proposed guidelines for water utilities in deciding whether, when and how to issue a boil water advisory (Baird, 2011; Pontius, 1996). These include setting up a task force to anticipate and plan for infrastructure failures and post-failure response, coordinating with local agencies for immediate relief, and focusing on emergency communication to alert the public. The Centers for Disease Control (USA) provides a list of suggested best management practices in case of boil water advisories (CDC, 2013).

4.1. Clarity and compliance

The results of several of the studies suggest that the content and clarity of the BWA may have some impact on compliance with the advice. In their study, HA found higher rates of Town C residents (57 percent) boiled their water in comparison to residents of Town A (35 percent). The residents in Town C, which experienced a flood, received a detailed notice that specified the exact nature of the problem and actions to be undertaken. Town A, on the other hand, experienced long-term water filtration problem lasting more than 3 years and provided quarterly notices to its residents. However, the notices did not recommend any specific remedial action or “risk-reduction behavior appropriate for the situation, nor does it warn customers about actions that would not be beneficial” (Harding and Anadu, 2000, p38). The authors further argued that the low compliance rate in Town A could be attributed to the ambiguity of the public notice. However, in doing so, the authors missed the fundamental difference in the nature and length of the advisories. A short BWA with intense media attention keeps the public engaged, whereas a long-term advisory with quarterly updates fades into the background resulting in a new normal where occasional non-compliance does not result in dramatic adverse impacts. This assessment is corroborated by statistical analysis (Table 6), where BWA duration is negatively associated with rate of awareness.

Awareness of and compliance with BWA notice assume greater significance in situations involving extreme weather, where residents' daily life may be disrupted enough that they may not be able to receive messages via traditional sources like newspaper and TV. Indeed, the lowest awareness rates in this meta-analysis were reported from Louisiana, USA (RBK) and Gloucestershire, UK (ROP) where extreme weather resulted in BWAs. RBK found low risk perception among respondents in Louisiana, USA and attributed it to poor awareness of the health consequences of drinking contaminated water. The authors stressed the necessity of improving public knowledge of the health effects of consuming contaminated water. Perhaps ironically, the most effective way to do this is through a boil water advisory notice that contains the necessary information. It is possible that the public may assume that compliance with a BWA notice will cost them time and money. To combat this assumption, the public should be made aware of inexpensive water treatment practices such as chlorination via the BWA notice.[6] Chlorination using household bleach is an effective form of treatment when boiling is not an option due to lack of electricity or other fuel sources. Despite the low awareness, RBK reported a very high compliance rate. This could be attributed to the use of bottled water, which was the primary source of many residents even before the advisory. As a result, very few residents consumed contaminated water.

The BWA issued in Gloucestershire, UK was the most unique among those studied in this meta-analysis. This is because initially a 'Do Not Drink' notice was issued, which was later rescinded and replaced by a 'Boil Water Advisory.' There was a lot of public confusion as to which particular notice was in place at the time. Survey results (RBK) found that correct recall of which advisory was in place varied from 23.2% to 26.7% (Rundblad et al., 2010). Often the public does not receive notifications with information that an advisory has been rescinded, which can lead to additional confusion. In fact, while the Do Not Drink notice was in place, the majority of respondents reported believing two notices were in place at the same time. The RBK study also found consumers' actions regarding tap water in response to the notifications both risky and over-cautious, which the authors attributed to consumers being unaware or unsure of what actions were unsafe. When considering non-drinking uses such as brushing teeth and washing food, the RBK study found high non-compliance rates. In addition to the content of the notifications, the titles could also be construed as ambiguous. "The title of the notice 'Do Not Drink' is highly misleading as it fails to highlight all ingestion actions listed on the notice" (Rundblad et al., 2010, p10). This suggests that the titles and the content presented in the notifications should be reconsidered and public health education should be improved to better educate consumers on the potential effects of consuming contaminated water and the precautionary measures they should take in the event of a water crisis.

Based on the studies analyzed, however, failure to adhere to BWA instructions is not associated with adverse health outcomes. Most of the studies in the sample did not report any illness or morbidity either among the respondents or in the general population affected by the BWA. Although this assertion is partly based on lack of clear evidence – nearly half the studies did not ask respondents any questions pertaining to illness or morbidity (Bruvold and Gaston, 1980; Kargiannis et al., 2009; Laughland et al., 1993; Ram et al., 2007; Rundblad et al., 2010), others reported evidence from state or local health agencies that either certified the water provided during the BWA period was not contaminated with pathogens (Galarce and Viswanath, 2012) or reported no documented cases of waterborne diseases attributed to the BWA (Laughland et al., 1993; Harding and Anadu, 2000; Wang et al., 2011). O'Donnell et al. (2000) reported that only one of the 71 water samples collected and tested were confirmed positive, but even that sample had a low concentration of pathogens – 1 colony forming unit (cfu)/100 ml of total coliforms. The incidence of illness could have been diminished because the affected residents left the area to friends/relatives' houses that were outside the affected area (Ram et al., 2007; Rundblad et al., 2010). Two percent of the respondents in one study reported someone in the household receiving a scald or burn as a result of boiling water during the BWA period (Willocks et al., 2000).

Perhaps the most adverse impacts of BWA caused by contaminated water were reported in Gideon, Missouri, USA (ATS). Nearly 40 percent of the respondents displayed symptoms consistent with diarrhea (Angulo et al., 1997). Twelve of the 14 respondents who developed diarrhea after the BWA did not boil their water. Overall, 650 residents in the town were likely to have been affected by diarrhea, resulting in 15 hospitalizations and 7 deaths. The deceased were likely to be old and/or severely immunocompromised since all of them resided in nursing homes, where 28 of the 68 residents had diarrhea. The outcomes reported in ATS are similar to the ones recorded after a massive outbreak of cryptosporidium in Milwaukee, Wisconsin, USA in 1993 (study not part of the meta-analysis). More than 400,000 residents in the greater Milwaukee area (population 1.6 million at that time) had watery diarrhea, an attack rate of 26 percent (McKenzie et al., 1994).

4.2. Limitations

This analysis is not without limitations, the primary being the small number of studies ($n = 11$) that originate from a few countries. The U.S., U.K., and the Netherlands are the only countries represented in this meta-analysis of articles that investigate public compliance to boil water advisories. Therefore, though this meta-analysis summarizes all the literature on this topic, it is restricted to observations from three countries which together represent less than one-third the population of Organisation for Economic Development and Cooperation (OECD), a group of countries that is most likely to provide uninterrupted water supply and thus be subject to public health notifications such as the one discussed in this article (OECD, 2015).

Studies included in this meta-analysis were conducted over a span of 30 years, a time period during which methods of detection, communication channels and survey modes have evolved. Techniques to detect microorganisms and changes in water pressure have improved, allowing water utilities to identify and avoid BWAs. In cases where BWAs become necessary, rapid communication channels such as email and online social networks allow utilities to quickly inform their subscribers about the situation and the necessary precautions to take. The said, we do not find major differences across time in how the BWAs were communicated to the residents. In the five studies where Internet was presented as an information source, it was either the least- or the second-least selected source from a list that included traditional media such as

[6] Chlorination is an effective strategy in most circumstances, except in cases involving *Cryptosporidium* contamination (WHO, 2011).

newspaper, radio, and phone. Despite the availability of online surveys for several years now, only one study used an online questionnaire. Hence, despite the long temporal range of the included studies, we are confident in comparing data collected across these studies.

Due to the small number of independent observations, we were unable to conduct multivariate meta-regression to isolate the effect of predictor variables on the awareness and compliance rates in the sample. The small sample is attributable to a number of factors. One, there are very limited studies that have quantitatively assessed public response to notices such as BWA. Purposefully, we did not consider studies that evaluated other water quality notices like beach closures. We also did not include studies focusing on developing countries that evaluated public willingness to voluntarily boil water for drinking and other purposes. Although the latter set of studies would have been thematically closely aligned with our intended study, we were more interested in quantifying the public response to discrete events that last for a few days and except in a few cases, do not present life-threatening risks. By specifying a narrow set of inclusion criteria, we eliminated systematic sources of heterogeneity and improved the internal validity of the results. Another major limitation of this exercise is that the studies analyzed are not representative of most BWA incidents occurring in the United States and elsewhere (see Water Research Foundation (2014) for a detailed analysis of BWAs in the U.S., and the Drinking Water Inspectorate's (2015) annual reports for a comprehensive list of BWAs in the UK). The studies presented here are large-scale events that received wide media attention. In contrast, most BWAs have localized impacts due to water main breaks or lesser-intensity water quality violations and likely have lower rates of awareness and compliance.

As discussed earlier in the article, all of the studies did not report their results in a uniform manner, which prompted us to make ad-hoc approximations. The use of a standard protocol to sample and interview respondents after a BWA notice could eliminate the need for approximations. There exists a tradeoff between obtaining a representative sample and capturing the residents' perceptions and behavior soon after the outbreak/BWA. Researchers may consider fielding two surveys – one immediately after the BWA is issued that relies on a smaller sample size or is narrow in scope, and another that is fielded within a few weeks of the first one. Using the same protocol will allow comparison across the two samples, thereby revealing the extent of recall bias, if any. Although we have no hypothesis regarding the direction of the recall bias, we suspect that the respondents will be unlikely to remember specific actions taken weeks earlier or reveal non-compliant actions to the interviewer. We did not find any significant difference between the compliance rates reported in contact interviews (in-person or phone) as compared to remote interviews (mailed or online). However, the time between the issuance of BWA and fielding of the survey protocol was negatively associated with both awareness ($p < 0.05$) and compliance ($p < 0.05$) rates. Wang et al. (2011) minimized by the recall bias by fielding the survey protocol one week after the BWA, though it resulted in a convenience sample.

The recommendation to use a standard protocol extends beyond the recall bias issue. The studies included in the meta-analysis asked varying number of questions (Table 2) that were not consistent regarding the topics covered, except for a few items (Table 3). Even when they did, the options presented varied, making comparisons across studies difficult (Table 5). The use of a standard protocol, while not eliminating the consistency issue, will seek to reduce it and allow for modifications that may be needed for site-specific situations. Development of a standard protocol will also ensure that researchers can deploy the survey soon after a BWA is issued. The protocol should also attempt to ascertain any illnesses experienced by the respondents during the BWA that may not rise to the level of hospitalization or a doctor's visit.

5. Conclusions

Population growth and fiscal pressures have resulted in water utilities serving more customers than before, or sharing a large water source with nearby utilities. In either case, any disruption in the source water quality or the processing of such water downstream has the potential to affect many customers. While regular disruptions in water supply are uncommon in the developed countries, a single event can affect many people at once and erode public confidence in local utilities and governance structures. Disruptions caused by certain microbial contamination, gastrointestinal outbreaks, power outages and failure in production or the distribution process result in a public health advisory called boil water advisory (BWA). Since the effectiveness of BWAs depends on strong civic action, understanding public response to such advisories is a public health and policy issue.

In this article, we conducted a meta-analysis of 11 studies that investigated public response to a locally-issued BWA. Based on responses obtained from the 11 studies ($N = 2885$), the median rates of awareness and compliance were observed to be 97 percent and 76 percent, respectively. Using the awareness rate and compliance rate for non-drinking but ingestion activities, we designed a unique metric called the effective compliance rate, which was determined to be lower than reported compliance rate at 68 percent (median). Non-compliant behavior exhibited by one-third of the targeted public constitutes a significant public health risk. Non-compliance was attributed to forgetting, not believing the notice and choosing not to boil water. We suspect the real compliance rates to be even lower due to the inability of respondents to recall non-compliant actions, and the exposure to contaminants between the period of contaminant detection and the issuance of BWA.

Boil water advisories are an effective and long-standing regulatory process by which water utilities and health agencies communicate to the public regarding the state of water supply in the region and preventive action to be taken. Since public compliance is a strong component of BWA effectiveness, monitoring public response is a critical part of reviewing the success and failure of BWAs in protecting public health. Therefore, it is surprising that only 11 published studies spread over a period of 30 years have measured public awareness and compliance in response to a local BWA. This meta-analysis fills a much-needed gap in the literature by synthesizing the outcomes of these individual studies and making tentative assessments that can inform future actions and improve public policy. This analysis identifies a need for more monitoring and reporting of public response to BWAs to increase our understanding of and improve BWA compliance. The use of a standard protocol that is deployed soon after the BWA event will reduce the likelihood of recall bias among the respondents, capture the public response more accurately, and facilitate comparisons across geographical regions.

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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.2016.02.014.

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