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Exposure Path Perceptions and Protective Actions in Biological Water Contamination Emergencies

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ABSTRACT: This study extends the Protective Action Decision Model, developed to address disaster warning responses in the context of natural hazards, to "boil water" advisories. The study examined 110 Boston residents' and 203 Texas students' expectations of getting sick through different exposure paths for contact with contaminated water. In addition, the study assessed respondents' actual implementation (for residents) or behavioral expectations (for students) of three different protective actions – bottled water, boiled water, and personally chlorinated water – as well as their demographic characteristics and previous experience with water contamination. The results indicate that people distinguish among the exposure paths, but the differences are small (one-third to one-half of the response scale). Nonetheless, the perceived risk from the exposure paths helps to explain why people are expected to consume (or actually consumed) bottled water rather than boiled or personally chlorinated water. Overall, these results indicate that local authorities should take care to communicate the relative risks of different exposure paths and should expect that people will respond to a boil water order primarily by consuming bottled water. Thus, they should make special efforts to increase supplies of bottled water in their communities during water contamination emergencies.

KEYWORDS: water contamination, exposure paths, risk perception, protective action

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Introduction

In normal circumstances, Americans can reasonably assume that their tap water is safe to use. Occasionally, however, water distribution systems become contaminated by unusually high levels of biological contaminants.[1] When local authorities believe that such contamination exists, they need to warn those at risk to take precautions, but such efforts often achieve only partial success. Recent research on water consumption advisories provides some insight into the magnitude of the warning noncompliance problem, as well as preliminary explanations why noncompliance occurs. Examination of a broader research literature on disaster risk communication, especially evacuation warnings, provides a more complete picture of this problem.[2–6] The decision processes involved in responses to evacuation warnings are likely to be similar to those involved in responses to "boil water" advisories, but they cannot be assumed to be identical. Thus, research is needed to test the applicability of research on evacuation warnings to boil water advisories.

The following sections address this issue by reviewing research on water consumption advisories and natural hazard warnings and concluding with a set of specific research needs that are characterized by four research hypotheses and two research questions. The "Method" section describes two student surveys that examined the possible antecedents of compliance with boil water advisories after a fictitious hurricane and a resident survey that examined responses to the May 2010 Boston boil water order. The "Results" section compares respondents' perceptions of seven exposure paths and examines the correlations of their water contamination experience, demographic characteristics, and risk perceptions with their expected (for students) and actual (for residents) consumption of bottled, boiled, and chlorinated water. Finally, the "Discussion" and "Conclusions" sections identify the study's theoretical and practical implications, methodological limitations, and research recommendations.

Research on Water Consumption Advisories

Many publications provide recommendations about boil water advisories, but few report the range and levels of compliance during water system emergencies.[7–10] Angulo et al found that in response to a salmonellosis outbreak, only 10% of the households at risk heard about the event within 10 days and, among those who were aware, 31% did not comply.[11] In two counties stricken by Hurricane Rita, only 39% of their respondents were aware of a boil water order.[1] Many of those who received a warning did boil water (46%), but almost as many who were able to boil water did not (39%) and 15% reported being unable to boil water because of interrupted electric and gas utilities. Even though the leaflet announcing the water consumption advisory stated that water should be brought to a rolling boil for one full minute, only 7% could give the correct answer. In a town that experienced *Escherichia coli* contamination in its water system after a flood, only 57% of those who received a warning boiled tap water as advised, while 77% drank bottled water and 10% took no protective action.[12]

Research on Natural Hazard Warnings

There is a much more extensive literature on disaster warning response that has led to the development of the Protective Action Decision Model (PADM).[3,4] The PADM, which is based on six decades of disaster research, describes a sequence of stages in the warning response process and the progression of events that can prevent people from taking appropriate protective actions. As indicated in Figure 1, people receive warnings from a variety of social (news media, authorities, and peers) and environmental (sights, sounds, and smells) sources. The social sources include authorities (professional/public utilities, civil servants, and elected officials), the news media, and peers (friends, relatives, neighbors, and coworkers). Sources communicate their warnings by means of a number of different channels including face-to-face conversations, telephones, loudspeakers, and the print and electronic (television, radio, and internet) media (Refer Lindell and Perry[13]; pp. 103–113). Authorities can control the timing of warning dissemination over some information channels (eg, face-to-face, telephone, and loudspeaker warnings), but population segments vary in the frequency with which they are accessible by other channels, especially radio, television, and newspapers.

Information from environmental cues and social warnings, together with prior beliefs about the hazard agent, produces a situational perception of personal risk that is characterized by beliefs about the ways in which environmental conditions will produce specific personal consequences. In hurricanes, for example, risk perceptions can be characterized by people's beliefs about the degree to which storm surge, inland flooding, and storm wind will cause their death or injury, kill or injure their loved ones, destroy their property, or disrupt their jobs or basic services such as electric power and water.[14–17]

There is some evidence that risk perception and protective action are related to people's demographic characteristics, especially gender.[18] This appears to be partially attributable to women's tendency to differ from men in their perceptions of stakeholders.[19,20] Moreover, ethnic minorities have been found to differ in their risk perceptions.[21] In addition, there is some evidence that past experience (previous warnings and previous illnesses) will be positively correlated with risk perception[22,23] and that facilitating conditions (availability of bottled water and chlorine bleach) will be positively correlated with protective action.[3,4]

Research Needs

Although the research on which the PADM is based does not include boil water advisories, this model seems to be compatible with the findings of behavioral studies in this area.[1,11,12,24–26] However, more research is needed to determine how the PADM applies to water contamination threats. Specifically, the risk of getting sick from biological contaminants is more

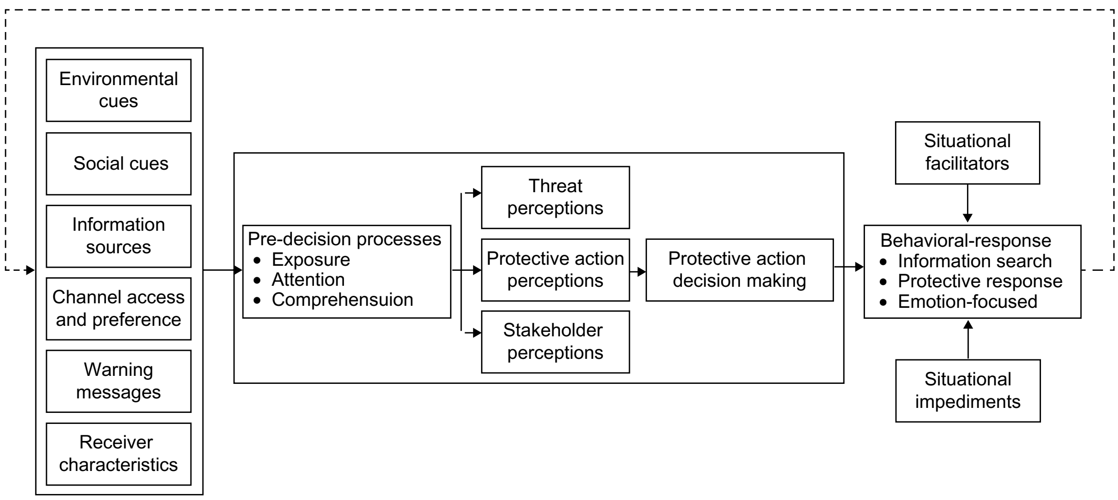

Figure 1. Information flow in the PADM.
Source: Ref. 4.

likely to arise from some exposure paths, such as drinking contaminated tap water, than others, such as using contaminated water to wash clothes.[27] However, it has not been documented whether people do, in fact, believe that there are significant differences in the likelihood of becoming sick from these exposure paths. In addition, although risk perception of exposure to contaminated water is likely to influence protective actions, it is unclear if risk perception from different exposure paths will be equally correlated with consumption of bottled, boiled, or personally chlorinated water rather than untreated tap water.

The literature reviewed above leads to the following hypotheses and research questions.

RQ1: Do respondents differentiate among exposure paths, as indicated by significant differences in their mean ratings of getting sick?

H1: Respondents are more likely to consume bottled water than boiled or personally chlorinated water.

H2: Female gender will be positively correlated with risk perception from different exposure paths and protective actions.

RQ2: Are ethnicity and education significantly related to risk perception from different exposure paths and protective actions?

H3: Past experience (eg, previous warnings and previous illnesses) and facilitating conditions (eg, availability of bottled water and chlorine) will be positively correlated with risk perception from different exposure paths and protective actions.

H4: Risk perception from the different exposure paths will be positively correlated with protective actions.

Method

Participants. This study began with a preliminary survey in December 2009 of 48 Texas A&M University introductory psychology students who completed a questionnaire as part of a course requirement. The participants in this sample were 52% female, with an average age of 18.7 (ranging from 18 to 21), and all were single. Most identified themselves as Caucasian (68.8%), but there also were African Americans (4.2%), Asian/Pacific Islanders (2.1%), Hispanics (8.3%), Native Americans (2.1%), and mixed ethnicity (14.6%). Although undergraduates are not representative of the population as a whole, many of them live in apartments where they have facilities for boiling or disinfecting water and have enough disposable income to purchase bottled water if there were a water contamination incident in their community. Moreover, findings from a preliminary study of college students' perceptions of seismic hazard, hazard adjustments, and stakeholders[28] were substantially replicated in a later study of households in six cities.[19,29,30]

Later, a water contamination incident in the Boston area (including Boston, Brookline, and Somerville) during May 1–4, 2010 provided an opportunity to examine residents' actual responses to a boil water order. Six months after the event, the Texas A&M University Hazard Reduction & Recovery Center (HRRC) conducted a mail survey that comprised 600 households inside the impact area. The survey was mailed following Dillman's four-step procedure.[31] In a total of 117 responses, 110 households returned valid questionnaires for a response rate of 22.4%, which is somewhat lower than other HRRC surveys that had response rates of 25%–50%. Participants in the Boston sample were 61% female, with an average age of 47.5, and 38.2% were married. Households identified themselves as African American (0.9%), Asian/Pacific Islander (10.0%), Caucasian (73.6%), and Hispanic (5.5%). They reported an average of 2.20 household members (including 0.32 children and 0.40 elders) and 45% identified themselves as homeowners having an average of 16.0 years of education and averaging an annual income of $67,604. Compared with the 2010 Boston Census data, this survey overrepresented females (census = 52%), Caucasians (census = 54%), homeowners (census = 34%), and college graduates (census = 43% with a bachelor's degree or higher), and they were slightly younger (census = 42 years) and poorer (census median = $40,225).

To increase the small size of the original student sample, data were collected in December 2014 from another 155 undergraduates in the Texas A&M University Psychology subject pool. Participants in the second student sample were 52% female, with an average age of 18.6 (ranging 17–22), and all were single. This sample was also predominantly Caucasian (65.2%), but participants were also African Americans (3.9%), Asian/Pacific Islanders (5.8%), Hispanics (21.3%), and mixed ethnicity (3.9%). All data collection protocols were reviewed by the Texas A&M University Institutional Review Board and complied with the principles of the Declaration of Helsinki. Consistent with IRB requirements, all survey participants were provided with a cover letter describing the study's risks and benefits; returning the questionnaire after reading the letter was considered to provide adequate documentation of informed consent to take part in the research.

Instrument

Perception of risk from different exposure paths was measured by asking respondents to judge on a scale of Not at all likely (= 1) to Almost certain (= 5), the likelihood that they could get sick by using untreated tap water to have a glass to drink, rinse fresh vegetables such as lettuce, cook spaghetti noodles, brew a pot of coffee, rinse their mouths after brushing their teeth, take a shower, and wash clothes. Respondents' overall risk perception was measured by calculating the mean of their ratings for these seven exposure paths.

Students' expected protective action was measured by the likelihood (from Extremely unlikely = 1 to Extremely likely = 5) that they would consume bottled, boiled, or personally chlorinated water in a hypothetical water contamination emergency. Residents' actual protective action was measured by the extent (from Not at all = 1 to Very great extent = 5) that they did consume bottled, boiled, or personally chlorinated water during the May 2010 water contamination emergency.

Resource access was measured by asking respondents to report how many quarts of bottled water they had in their homes (ranging 0–10 or more) and whether they had at least one cup of chlorine bleach (No = 0, Yes = 1). Previous warning experience was measured by whether respondents had ever been told by public officials not to drink tap water in their homes (No = 0, Yes = 1), and previous illness experience was measured by whether they or a family member had ever gotten sick from drinking tap water in their homes (No = 0, Yes = 1).

Finally, there were three demographic variables – gender (male = 0, female = 1), education (Some high school = 1, High school graduate/GED = 2, Some college/vocational school = 3, College graduate = 4, and Graduate school = 5), and ethnicity (African American, Asian/Pacific Islander, Caucasian, Hispanic, Native American, Mixed, or Other – recoded to Minority = 0, White = 1).

Initial Analyses

The first step in analyzing the data was treatment of missing data. In the first student survey, over 44 of 48 students (91.7%) responded to all items, with the maximum missing data rate being one item (2.1%). Similarly, in the second student survey, 144 of 155 students (92.9%) responded to all items, with the missing data rates per item ranging 1–5 items (0.6%–3.2%). However, only 44 of 110 residents (40.0%) responded to all items, with the missing data rates per item ranging from 2–34 items (1.8%–30.9%). The nonsignificant χ^2 values of Little's missing completely at random (MCAR) test[32] ($\chi^2_{775} = 0.00$, $P = 1.00$ for the first student sample; $\chi^2_{1763} = 1533.72$, $P = 1.00$ for the second student sample; and $\chi^2_{7096} = 5510.63$, $P = 1.00$ for the resident sample) were consistent with the MCAR assumption. That is, "missing responses to a particular variable are independent of the values of any other variable in the explanatory model and of the true value of the variable in question."[33] (p. 182) Consequently, the Expectation–Maximization algorithm was used to replace missing values for all three samples.

The second step in analyzing the data was assessing the homogeneity of the samples. The correlation matrices were tested to determine if the inter-item correlations were equal in the three samples. The homogeneity test for the two student samples (Box's $M = 2024.74$, $F_{990,\ 24,335} = 1.27$, $P < 0.001$) was highly significant, indicating that the two matrices had unequal correlations among all of the variables. However, the extremely large number of degrees of freedom gives this test the statistical power to detect trivial levels of heterogeneity so Gnanadesikan's graphical homogeneity test was performed.[34] The cross-plot showed the obtained value of each correlation for respondents from the first student dataset plotted against the corresponding value of that correlation for respondents from the second student dataset. The cross-plot of $136 - k(k - 1)/2 = 17(16)/2$ – inter-item correlations from the two student samples was approximately linear ($r = 0.67$) and had no obvious outliers, so the two student samples were pooled. There was a similar result for the cross-plot of the combined student samples with the resident sample (Box's $M = 2885.17$, $F_{990,\ 158520} = 2.43$, $P < 0.001$; $r = 0.70$).

Next, the similarity of the two student samples with respect to their mean ratings was assessed by creating a dummy variable, in which the first student sample was coded 1, the second student sample was coded 2, and this dummy variable was correlated with each item in the questionnaire. This analysis revealed that the correlations between the dummy variable and the other items were negligible ($|\bar{r}| = 0.04$). Since there were no meaningful differences between the two student groups with respect to either their inter-item correlations or their mean ratings, they were pooled in subsequent analyses. However, a similar dummy variable analysis comparing the student and resident samples showed that 11 of 17 (64.7%) correlations between the combined student sample and the resident sample were significant at $P < 0.05$ with an average $|\bar{r}| = 0.20$ including 4 of 17 (23.5%) $r > 0.30$. These results indicate that students and residents had significantly different mean ratings on the questionnaire items, so the student and resident samples were analyzed as separate groups in subsequent analyses of mean differences.

The third step in analyzing the data was testing for pseudo-attitudes. Asking people to rate the likelihood of getting sick through different exposure paths will not necessarily yield reliable data because such responses might reflect only pseudo-attitudes that people construct when they are asked for their opinions about issues for which they have no prior information.[35,36] Although test–retest procedures can sometimes be used to test for the presence of pseudo-attitudes,[37] cross-sectional surveys have used other procedures.[38] Thus, it is appropriate to rule out the possibility that respondents' ratings can be attributed to central tendency, as indicated by items means that are significantly different from their scale midpoints[39] and to confirm that response distributions are significantly different from a uniform distribution, as indicated by values of r_{WG} – an index that ranges $-1 \leq r_{WG} \leq +1$ – that are significantly different from zero.[40] It is also useful to conduct a factor analysis to verify that the data are not characterized by halo error, the tendency for ratings of separate dimensions to be consistent with a global evaluation or judgment,[41] as indicated by highly correlated ratings among the exposure path ratings and, in the extreme, a single factor.

Single sample *t*-tests revealed that 6/7 (85.7%) of the exposure path ratings in the student sample and 5/7 (71.4%) of the exposure path ratings in the resident sample were significantly different from their scale midpoints (3 on a scale of 1–5), thereby suggesting that the ratings lacked central tendency. In addition, the levels of inter-rater agreement were tested using r_{WG} tables.[42] The tests of $r_{WG} \neq 0$ were statistically significant for 29/31 (93.5%) of the students' exposure path items and 20/31 (64.5%) of the residents' exposure path items, suggesting the responses were not random. Finally, factor analysis of the exposure path ratings yielded three factors having eigenvalues >1, suggesting that these ratings were not determined by halo.

Results

Exposure paths. In the examination of RQ1 (Do respondents differentiate among exposure paths, as indicated by significant differences in their mean ratings of getting sick?), multivariate analysis of variance revealed a significant effect for exposure path (Students: Wilks $\Lambda = 0.05$, $F_{7,196} = 546.84$, $P < 0.001$, Residents: Wilks $\Lambda = 0.08$, $F_{7,103} = 179.29$, $P < 0.001$); both students and residents discriminated significantly among the exposure paths. Table 1 shows the students and residents gave the same rank ordering to the exposure paths, with drinking water from a glass having the highest rating, washing clothes having the lowest rating, and other exposure paths having intermediate ratings. However, residents' ratings had more differentiation between the highest and lowest rated exposure paths (range = 1.83 or 45.8% of the 5-point scale) than the students' ratings (range = 1.46 or 36.5% of the scale). This is largely due to the fact that students had higher expectations of getting sick by taking a shower and washing clothes. The most noticeable pattern in the results is that the exposure paths involving direct ingestion of contaminated tap water (eg, drinking from a glass, rinsing fresh vegetables, and rinsing mouths) were significantly different from the next four exposure paths ($t_{1419} = 13.07$, $P < 0.001$ for students and $t_{768} = 12.16$, $P < 0.001$ for residents).

Table 1. Means (*M*) and standard deviations (SD) for students' and residents' data.

VARIABLE	STUDENTS (*N* = 203)		RESIDENTS (*N* = 110)	
	M	*SD*	*M*	*SD*
Background variables				
1. Gender	0.52	0.50	0.61	0.49
2. White	0.66	0.47	0.74	0.44
3. Education	13.45	1.09	16.00	2.76
4. ExperWarn	0.24	0.43	0.20	0.40
5. ExperSick	0.04	0.20	0.02	0.13
6. WatBottles	5.04	3.16	3.22	3.06
7. ChlorBlch	0.65	0.48	0.60	0.49
Risk perception variables				
8. DrinkTap	3.91	1.03	3.48	1.06
9. RinseVegs	3.18	1.02	3.08	1.20
10. CookPasta	2.56	1.17	2.27	1.24
11. BrewCoffee	2.64	1.22	2.55	1.29
12. RinseMouth	3.36	1.17	2.96	1.29
13. TakeShower	3.03	1.18	1.91	1.14
14. WashClothes	2.45	1.12	1.65	1.07
15. AvgRisk	3.02	0.78	2.56	0.89
Protective action variables				
16. BottWater	4.30	0.96	3.74	1.34
17. BoilWater	3.83	1.04	3.14	1.62
18. BlchWater	2.09	1.06	1.25	0.77
19. AvgProtAct	3.41	0.72	2.71	0.75

Abbreviations: Gender, respondent gender; White, respondent ethnicity; Education, respondent education level; ExperWarn, previous warning experience; ExperSick, previous sick experience; WatBottles, gallons of bottled water in storage; ChlorBlch, bleach in storage; DrinkTap, drink tap water; RinseVegs, rinse vegetables; CookPasta, cook pasta; BrewCoffee, brew coffee; RinseMouth, rinse mouth; TakeShower, take shower; WashClothes, wash clothes; AvgRisk, average perception on exposure paths; BottWater, tendency to use bottled water; BoilWater, tendency to use boiled water; BlchWater, tendency to use chlorinated water; AvgProtAct, average tendency to adopt protective actions.

Relative prevalence of expectations/behaviors. Consistent with H1 (respondents are more likely to consume bottled water than boiled or personally chlorinated water), Table 1 shows students reported higher ratings on using bottled water ($M = 4.30$) than boiled water ($M = 3.83$) or chlorinated water ($M = 2.09$) with similarly high levels of agreement on all three ($r_{WG} = 0.43$–0.54). Residents reported the same rank order ($M_{\text{bottled water}} = 3.74$, $M_{\text{boiled water}} = 3.14$, and $M_{\text{chlorinated water}} = 1.25$) but had much lower levels of agreement ($r_{WG\text{bottled water}} = 0.10$, $r_{WG\text{boiled water}} = -0.32$, and $r_{WG\text{chlorinated water}} = 0.70$).

Prediction of protective action expectations/behaviors. The results are only partially consistent with H2 (female gender will be positively correlated with risk perception from different exposure paths and protective actions). As Table 2 indicates, female gender was not significantly correlated with perceived risk from the exposure paths ($r = 0.08$), although there was also a significant correlation with risk from brewing coffee ($r = 0.13$). Female gender also had a nonsignificant correlation with overall protective action ($r = 0.09$) but was significantly correlated with consumption of bottled water ($r = 0.14$).

There are consistent results regarding RQ2 (Are ethnicity and education significantly related to risk perception and protective actions?). Specifically, Whites ($r = -0.20$) and those with higher levels of education ($r = -0.22$) tended to have lower perceptions of risk – especially from rinsing their mouths, taking a shower, and washing clothes. Similarly, Whites ($r = -0.13$) and those with higher levels of education ($r = -0.25$) tended to be less likely to take protective actions. In particular, those with higher education levels tended to be less likely to boil ($r = -0.18$) or personally chlorinate ($r = -0.29$) water.

Partially consistent with H3 (Past experience and facilitating conditions will be positively correlated with risk perception from different exposure paths and protective actions), only a minority of respondents reported having been previously told by public officials not to drink tap water in their homes (24%), and almost none of them had gotten sick from drinking tap water in their homes (4%). Table 2 shows that neither warning experience nor illness experience was significantly correlated with perceptions of exposure paths ($r = -0.01$ and $r = 0.07$, respectively) or protective actions ($r = 0.05$ and $r = 0.11$, respectively).

Table 2. Intercorrelations among variables.

VARIABLE	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1. Gender	1.00																	
2. White	0.01	1.00																
3. Education	0.04	0.26	1.00															
4. ExperWarn	0.03	−0.01	−0.07	1.00														
5. ExperSick	−0.06	−0.19	−0.03	0.16	1.00													
6. WatBottles	−0.09	−0.23	−0.29	0.04	0.17	1.00												
7. ChlorBlch	−0.07	−0.01	−0.08	0.12	0.06	0.18	1.00											
8. DrinkTap	0.09	−0.08	−0.11	−0.01	−0.03	0.08	−0.07	1.00										
9. RinseVegs	0.09	−0.10	−0.09	−0.05	0.06	0.10	−0.05	0.66	1.00									
10. CookPasta	0.08	−0.13	−0.08	0.02	0.07	0.11	0.02	0.33	0.48	1.00								
11. BrewCoffee	0.13	−0.10	−0.06	0.02	0.01	0.09	0.07	0.34	0.45	0.75	1.00							
12. RinseMouth	0.09	−0.17	−0.23	−0.04	0.10	0.09	−0.06	0.53	0.62	0.40	0.40	1.00						
13. TakeShwr	−0.04	−0.26	−0.31	−0.01	0.09	0.16	−0.02	0.30	0.30	0.32	0.35	0.60	1.00					
14. Expclothes	−0.02	−0.14	−0.23	0.00	0.07	0.11	−0.04	0.13	0.27	0.32	0.35	0.47	0.71	1.00				
15. AvgRisk	0.08	−0.20	−0.22	−0.01	0.07	0.15	−0.03	0.64	0.74	0.72	0.73	0.80	0.73	0.66	1.00			
16. BottWater	0.14	−0.10	−0.06	−0.05	0.13	0.09	0.12	0.21	0.20	0.13	0.05	0.23	0.15	0.08	0.21	1.00		
17. BoilWater	0.08	−0.07	−0.18	0.08	0.02	0.04	−0.00	0.09	0.09	0.04	0.07	0.16	0.16	0.15	0.15	0.09	1.00	
18. BlchWater	−0.05	−0.11	−0.29	0.06	0.09	0.07	0.11	0.06	−0.03	0.01	0.00	0.07	0.24	0.16	0.11	0.17	0.34	1.00
19. AvgProtAct	0.09	−0.13	−0.25	0.05	0.11	0.10	0.10	0.18	0.13	0.09	0.06	0.22	0.26	0.19	0.22	0.60	0.74	0.71

Note: $N = 313$, $r_{ij} > 0.10$ is statistically significant at $P < 0.05$, 2 tailed.

Respondents were generally able to implement the two protective actions requiring special resources (having bottled water and bleach at home). Students reported a median of five quarts of bottled water and 65% had at least one cup of chlorine bleach, whereas residents reported substantially less bottled water at home (Md = 1.50 quarts) but a similar percentage (60%) had at least one cup of chlorine bleach. Bottled water in storage was significantly correlated with perceptions of exposure paths (r = 0.15) but not having bleach at home (r = −0.03). Both resources were significantly correlated with protective action (r = 0.10 for both), but the correlations of this magnitude are considered "small".[43]

Consistent with H4 (Risk perception from the exposure paths will be positively correlated with protective actions), Table 2 shows that overall risk perception was significantly correlated with overall protective action (r = 0.22), especially bottled water and boiled water consumption (r = 0.21 and r = 0.15, respectively). More specifically, overall protective action was significantly correlated with five of the seven exposure paths.

Discussion

Implications of results. The test of RQ1 (Do respondents differentiate among exposure paths, as indicated by significant differences in their mean ratings of getting sick?) revealed statistically significant differences among the exposure paths. Moreover, Table 1 shows that the rank ordering of the exposure routes appears to be reasonable, with drinking tap water from a glass (a significant ingestion exposure) having the highest hazard rating, washing clothes (a minor external contact exposure) having the lowest hazard rating, and other exposure paths having intermediate ratings. Compared to residents, students had a much smaller differentiation between the highest and lowest rated exposure routes and were more concerned about getting sick via direct skin contact with contaminated water (eg, taking a shower). One possible explanation for this result is that many residents received multiple warning messages about water contamination that emphasized boiling water before drinking, whereas students were given a scenario that provided only a single message that tap water might be contaminated. Thus, students might have expected that any kind of contact with contaminated water could produce illness. Thus, it will be important for local authorities to clearly specify the nature of the exposures that are hazardous in any future contamination emergencies.

These results are consistent with other researches on warning message content that recommend describing the nature of the threat, geographic areas that are at risk (or those that are safe), personal consequences of exposure, recommended protective actions, and sources of additional information and assistance.[2–6,44] In the present study, respondents seemed to be heeding differences in the amount of water consumed (drinking a glass of tap water vs. rinsing one's mouth with tap water) as well as between ingestion (drinking a glass of tap water) and skin contact (taking a shower). However, one would expect the ratings of drinking tap water from a glass to be higher than they were because this activity involves direct ingestion of significant amounts of water. Conversely, one would expect that brewing coffee and cooking spaghetti would have lower ratings than they did because these actions involve boiled water (which, in the case of spaghetti, is not ingested). One would expect even lower ratings for taking showers and washing clothes because these activities involve only a very limited exposure even though the water is not boiled. These results emphasize the need to develop a more comprehensive understanding of people's interpretations of exposure because the data in Table 1 suggest that the respondents' intuitive toxicology could account for the differences in the ratings of risk associated with the different exposure paths.[45,46] Further research is needed to test these possible explanations for the observed differences.

The test of H1 (Respondents are more likely to consume bottled water than boiled or personally chlorinated water) confirms earlier findings by showing that people prefer bottled water to boiled or personally chlorinated water.[12] The reasons for this preference are likely to be the resource-related attributes identified in the PADM – the lower levels of time and effort, as well as knowledge and skill, in obtaining bottled water, compared to boiling or chlorinating water.[3,4,38,47] Moreover, if bottled water was also perceived to be more effective than boiled or chlorinated water in avoiding exposure to contamination, these attributes could all offset any perceptions that bottled water is more expensive than boiling or chlorinating water. However, further research is needed to test this explanation.

The lack of support for H2 (Female gender will be positively correlated with risk perception from different exposure paths and protective actions) and H3 (Past experience and facilitating conditions will be positively correlated with risk perception from different exposure paths and protective actions) is somewhat surprising, given that some previous research has found gender[18] and previous experience[23] to be significantly correlated with protective actions. One potential methodological explanation for the nonsignificant findings is variance restriction.[48] However, as noted earlier, 52% of the students were female and 34% were minorities. Similarly, 61% of the Boston respondents were female and 36% were minorities, so variance restriction on these two variables is not an explanation for the absence of significant correlations involving these variables. In addition, the respondents reported generally high but variable levels of facilitating conditions for implementing the protective actions. Specifically, students had a median of 5.0 quarts of bottled water in a distribution ranging from 1 to 10 quarts and 65% reported having at least one cup of chlorine bleach. Similarly, residents reported that they had a median of 1.5 quarts bottled water at home and 60% had at least one cup of chlorine bleach. Thus, there does not appear to be a significant amount of variance restriction for these variables either. However, only 24% of the students reported having previously been told by public officials not to drink tap water in their homes and only 4% had gotten sick from drinking tap water in their homes. Similarly, only 20% of residents reported previous experience with a water consumption advisory and only 2% had illness experience. In summary, with the exception of previous experience with water contamination advisories and water-related illness, there was little potential for variance restriction to reduce the correlations.

The nonsignificance of these variables is not completely surprising because reviews of the correlations of demographic characteristics and previous experience with protective actions have concluded that the effects are weak and inconsistent.[14,16,49] This is probably because these variables exert their influence early in a causal chain from hazard exposure through hazard experience and risk perception to protective action.[22] If future research replicates the nonsignificant correlations of demographic variables with perceived risk and perceptions of stakeholders, then local officials will have little need for audience segmentation strategies during water contamination incidents.

The results of the analyses for RQ2 (Are ethnicity and education significantly related to risk perception from different exposure paths and protective actions?) revealed that Whites and those with higher education levels tended to have lower risk perceptions and were less likely to take protective actions. However, it is unclear how to explain these correlations, especially since the more consistent correlation of gender with risk perception was not found. Additional studies on water contamination risk perception and protective action are needed to determine if these results will replicate and, if so, how they can be explained.

Finally, the significant support for H4 (Risk perception from different exposure paths will be positively correlated with protective actions) confirms other research showing that risk perception can be, although it not always is, a significant predictor of protective action for a variety of hazards.[49,50] In particular, this finding supports an important prediction of the PADM – threat perception is an important motivation to search for, and implement, protective action.

Study Limitations

It is important to acknowledge that this study has its limitations. First, the response rate for the resident sample was only 22%, which raises questions about how representative respondents may be of all Boston residents. However, comparison of the sample's demographic characteristics to the corresponding census data indicates that the sample is not significantly different from the population averages. Moreover, overrepresentation of some demographic categories will produce bias in other variables such as risk perceptions only to the degree the latter variables are correlated with demographic variables, but such correlations are low in this sample – as well as more generally.[16,49,50] Moreover, other reports indicate low response rates do not appear to bias central tendency estimates such as means and proportions[51,52] and Newman's[53] method of analyzing the effect of response rates on correlations suggests there might be little bias with respect to those statistics.

Second, the cross-sectional design limits the ability to draw conclusive causal inferences because it is not possible to determine the direction of causal effect. For example, it is not possible to determine if perceptions of the exposure paths caused protective actions or vice versa. Thus, longitudinal studies are needed to assess the causal paths among variables, as well as the test–retest reliability (stability) of respondents' perceptions. If such studies show high stability in the perceptions of exposure paths and protective actions, local officials could have greater confidence in the usefulness of these results for water contamination warnings.

Conclusions

The PADM was developed to address disaster warning responses in the context of natural hazards. This model describes a sequence of stages in the warning response process and the progression of events that can prevent people from taking appropriate protective actions. This study demonstrates that the PADM can be successfully extended to the study of responses to boil water advisories, especially confirmation of one of the PADM's most important predictions – the perceived threat from different exposure paths is an important motivation to search for, and implement, protective action.

This study documents that people distinguish among different paths of exposure to contaminated tap water but might do so insufficiently. Of the proposed predictor variables, only minority ethnicity, lower education, and access to bottled water were significantly related to higher levels of perceived risk from different exposure paths, and these correlations were strongest for rinsing one's mouth, taking a shower, and washing clothes. Moreover, only minority ethnicity and lower education were significantly related to protective actions – specifically consumption of boiled and personally chlorinated water. Personal experience with water contamination and access to resources such as bottled water and chlorine bleach generally had non-significant correlations with risk perceptions and protective actions. However, there were significant correlations between perceived risk and expected (for students) or actual (for residents) protective actions. The correlations of risk perception were generally highest for consumption of bottled water and weakest for chlorinated water – probably because respondents believed that bottled water would be much more effective in protecting their health.[54]

Overall, these results indicate that local authorities should take care to communicate the relative risks of different exposure paths to ensure that people do not expose themselves to excessive levels of contaminated water from important exposure paths (eg, untreated tap water) or unnecessarily avoid exposure from trivial paths (eg, washing clothes). Authorities need not be unduly concerned about differences in perceptions and responses due to people's demographic characteristics and prior experience. However, they should expect that people will respond to a boil water order primarily by consuming bottled water. This is particularly likely to be the case if interruption of electric and gas supplies limits people's ability to boil water. Thus, local authorities should encourage local stores to request additional stocks of bottled water and make special efforts to acquire their own stocks of bottled water to supplement commercially available supplies, if needed. Of course, boiling or chlorinating water will not be an appropriate protective action for all water contamination incidents, so further research should examine these other situations as well.

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Author Contributions

Conceived the study and developed the questionnaires: MKL, JLM, S-KH, HCW. Collected/analyzed data: MKL, S-KH, CDS, H-CW. Drafted and revised the manuscript: MKL, JLM, S-KH, CDS, H-CW. All the authors reviewed and approved the final manuscript.

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