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# The impact of water consumption, point-of-use filtration and exposure categorization on exposure misclassification of ingested drinking water contaminants

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## Abstract

The use of population-level indices to estimate individual exposures is an important limitation of previous epidemiologic studies of disinfection by-products (DBPs). We examined exposure misclassification resulting from the use of system average DBP concentrations to estimate individual-level exposures. Data were simulated ($n=1000$ iterations) for 100 subjects across 10 water systems based on the following assumptions: DBP concentrations ranged from 0–99 μg/L with limited intra-system variability; water intake ranged from 0.5–2.5 L/day; 20% of subjects used bottled water exclusively; 20% of subjects used filtered tap water exclusively; DBP concentrations were reduced by 50% or 90% following filtration. DBP exposure percentiles were used to classify subjects into different exposure levels (e.g., low, intermediate, high and very high) for four classification approaches. Compared to estimates of DBP ingestion that considered daily consumption, source type (i.e., unfiltered tap, filtered tap, and bottled water), and filter efficiency (with 90% DBP removal), 48–62% of subjects were misclassified across one category based on system average concentrations. Average misclassification across at least two exposure categories (e.g., from high to low) ranged from 4–14%. The median classification strategy resulted in the least misclassification, and volume of water intake was the most influential modifier of ingestion exposures. These data illustrate the importance of individual water use information in minimizing exposure misclassification in epidemiologic studies of drinking water contaminants.


*Keywords:* Disinfection by-products; Trihalomethanes; Haloacetic acids; Exposure misclassification; Water consumption; Water intake

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## 1. Introduction

In a recent editorial, Steenland and Moe (2003) question whether epidemiologic studies of drinking water exposures had run their course due to exposure assessment limitations. The authors identify several research needs including prospective epidemiologic studies, uncertainty analyses and the development of new exposure assessment approaches. Arbuckle and colleagues (2002) highlight exposure assessment limitations from previous reproductive and developmental epidemiologic studies of disinfection by-products (DBPs), including reliance on indirect population-level measures (e.g., water type, disinfection type, or distribution system average concentration) to estimate exposure. The use of population-level surrogates results in measurement error that can lead to bias and imprecision in relative risk estimates (Rothman and Greenland, 1998). It is important to understand the potential for exposure misclassification and the direction and magnitude of the bias that could influence risk estimates in epidemiologic studies of DBPs, since these data are an important component of the scientific information used in support of the U.S Environmental Protection Agency's Stage 1 and 2 Microbial/DBP rulemaking process.

Since previous DBP studies primarily focus on the ingestion route of exposure for trihalomethanes (Bove et al., 1995; Dodds et al., 1999; Gallagher et al., 1998; Klotz and Pyrch, 1999; Savitz et al., 1995; Waller et al., 1998; Wright et al., 2004; Toledano et al., 2005), we have examined several factors that can impact ingestion exposure estimates including volume of water intake, bottled and filtered water consumption, and effectiveness of point-of-use filtration in the home. We incorporated data on water consumption habits among U.S. women of reproductive age along with information on DBP filtration removal for volatile THMs and non-volatile haloacetic acids (HAAs) to estimate individual exposure levels. We compared various exposure measures to demonstrate the potential impact of inter-individual variability in water consumption practices on misclassification of simulated DBP exposures. Exposure classification (i.e., low, intermediate, high, and very high) based on system-level average exposures were compared to exposure scores incorporating individual water consumption information. These DBP ingestion simulations are most relevant for HAA exposures, since inhalation and dermal contact are of minimal importance for non-volatile DBPs.

### 1.1. Tap water intake

Population-based estimates of tap water consumption among pregnant women in the U.S. are limited to United States Department of Agriculture surveys in the late 1970s and the mid 1990s. Average tap water intake was 0.9 L/day among women of childbearing age (i.e., 15–44 years) in the 1994–1996 Continuing Survey of Food Intakes by Individuals (U.S. EPA, 2000) and 1.2 L/day among pregnant women in the 1977–1978 National Food Consumption Survey (Ershow et al., 1991). Home tap water intake averaged 0.8 L/day in a convenience sample of pregnant women attending North Carolina obstetric clinics from 1994–1995, with 53% of the respondents reporting unfiltered tap water as their primary source of drinking water (Shimokura et al., 1998). Higher home consumption rates (2.9 L/day) were reported among women attending Well Infant and Children programs in Colorado during 1996–1997 (Zender et al., 2001). Three-quarters of the pregnant women in this convenience sample reported tap water as their primary water source, which may reflect the lower socioeconomic status of participants in this population. An ongoing prospective cohort study (Right from the Start) of early pregnancy is examining water consumption practices among women in three U.S. cities (Promislow et al., 2004). Preliminary data suggest that current estimates of average tap water intake among pregnant women range from 1.3–2.1 L/day across the three study sites (unpublished data).

### 1.2. Bottled and filtered water consumption

Water consumption patterns can vary between individuals and groups and are influenced by source water quality perception and various socio-demographic factors. Fifteen percent of the pregnant women from the North Carolina study reported primarily using filtered water, while 24% reported bottled water as their main source (Shimokura et al., 1998). Filtered water was the main source of water at home for 11% of the pregnant women in the Colorado study, while another 14% primarily drank bottled water (Zender et al., 2001). Geographic differences in self-reported water use are evident in preliminary findings from the Right from the Start study. Bottled water was the primary water source (i.e., all or nearly all of home water use) for 18% (range across 3 sites: 10–42%) of participants, while another 30% (range: 17–43%) reported using home filtration devices. Among those using filtration devices, 11–29% reported filtering all or nearly all of their tap water consumed at home (unpublished data).

### *1.3. Filtration removal efficiency*

Frequency of point-of-use filtration devices in the home is an important determinant of overall DBP ingestion exposure, since filtration has been shown to effectively reduce DBP concentrations from tap water. Average chloroform removal efficiency of 92% was reported for a Brita™ pitcher filter following 100 L of use (Egorov et al., 2003). Eslinger and Weinberg (2003) reported an 87% average reduction for total THMs over the 40 gal capacity for two commercially available pitcher filters. Similar findings were found for commercially available faucet-mounted pitchers, with more than 95% of THMs initially removed.

The effectiveness of point-of-use filtration HAA concentrations can vary over the life of a filter. Egorov and colleagues (2003) reported dichloroacetic acid (DCAA) and trichloroacetic acid (TCAA) reductions ranging from 39–95% in 1 to 100 L of Brita™ filtered water. Increased TCAA concentrations were reported upon filtering water at the manufacturer recommended capacity (i.e., 150 L) suggesting possible elution of HAAs. Kim (1997) reported an average removal efficiency of 74% for DCAA and 71% TCAA for paired samples from six homes, but did not examine removal efficiency over the life of the filters.

## 2. Materials and methods

SAS, Version 9.1 (2003) was used to simulate system average DBP exposures and exposure measures incorporating water intake volume, point-of-use filtration, and bottled water consumption. We generated data for 100 subjects equally distributed across 10 different water systems ($n=1000$ iterations). Each water system had different average DBP concentrations (range 0–99 μg/L) with concentrations increasing by 10 μg/L per system. Limited intra-system variability was assumed, so all subjects using the same water system had average concentrations within 9 μg/L of each other. For example, exposures for subjects from Water System 1 ranged from 0–9 μg/L, while exposures ranged from 10–19 μg/L in Water System 2. Twenty percent of the subjects were randomly assigned as exclusive bottled water users assuming that DBPs were not present in bottled water. An additional 20% of the subjects were randomly assigned as exclusive users of filtered water for all water-based beverages. We examined average DBP removal of 50% and 90% following point-of-use filtration of home tap water. We further incorporated inter-individual variability in water consumption by randomly assigning intake rates of 0.5–2.5 L/day for each subject. Ten percent of the subjects were assumed to each drink 0.5 and 2.5 L/day. Twenty percent of subjects were assigned an intake rate of 2.0 L/day, while 30% of the subjects were each assigned 1.0 and 1.5 L/day. Using these data, we calculated average DBP intake from ingestion of tap water by multiplying system average concentrations by individual water intake levels. Pearson correlation coefficients were used to describe the relationship between individual intake measures and system average exposure concentrations.

Exposure misclassification was determined from comparisons of exposure groupings derived from system average surrogates in relation to groupings based on more accurate water intake exposures. Subjects were initially classified into low, intermediate, high, and very high exposure groups based on the system average concentration percentiles. Following incorporation of water intake and exposure modifying data, individual-level exposures were calculated. Subjects were re-classified into groups based on the distribution of the exposure scores and compared to their previous system average concentration classifications. Total misclassification, including the proportion of subjects misclassified across one category and at least two exposure categories, was quantified using four exposure classification strategies based on the percentage of the population comprising the reference population. For the median classification strategy, exposures were assigned as ≤50%, 51–90%, and >90%. The tertile approach was based on exposures

≤34%, 35–67%, and >67%. For the third classification strategy, exposures were assigned as ≤40%, 41–70%, and >70%. The fourth approach had the following exposure groups: ≤40%, 41–70%, 71–90%, and >90%.

The simulations were based on the following assumptions:

- Ingestion was the only exposure route of interest examined (e.g., non-volatile DBPs)
- Temporal variability in DBP concentrations during the critical period of exposure was captured by the average system values
- Spatial variability in DBP formation was limited, so women residing in the same service area were exposed to similar average DBP concentration via residential tap water
- Hot water intake was similar across all subjects, and any changes in DBP concentration upon heating or boiling were reflected in the average DBP concentrations
- All DBP exposures occurring outside the home were similar to that received by subjects inside their homes
- 20% of women in each water system used filter tap water for all water-based beverages (i.e., no unfiltered tap or bottled water exposures)
- 20% of women in each water system used bottled water for all water-based beverages (i.e., no tap water exposures)
- Bottled water contained no DBPs
- Incorporation of additional water use information represented actual exposure which were misclassified when less accurate measures were used.

## 3. Results

The simulated exposure data were based on system average concentrations of 0–99 μg/L, with a mean exposure of 50 μg/L (Table 1). DBP intake based on system average DBP concentrations and randomly assigned consumption rates was highly correlated with DBP concentration ($r=0.79$). System average surrogate exposures were correlated with exposure measures incorporating water intake data and bottled water or filtered water use ($r=0.61$–$0.74$), but were less correlated when both bottled and filtered water use was considered ($r=0.49$–$0.57$). Despite being correlated with more accurate exposure estimates, using system average concentrations as a surrogate for individual-level exposures resulted in considerable exposure misclassification. Average misclassification for DBP intake or intake modified by bottled or filtered water use ranged from 29–51% across the four classification strategies (Table 2). When these factors were considered simultaneously, average misclassification ranged from 38–51% for 50% DBP removal efficiency and 48–62% for 90% removal. Misclassification was most pronounced in the fourth exposure classification strategy (51–62%) upon consideration of all of the modifying factors, while the median approach resulted in the least amount of misclassification (38–48%).

As shown in Table 3, most misclassification occurred across one exposure group (e.g., from high to intermediate) when more accurate intake measures were compared with system average surrogates. The use of system average exposures resulted in average misclassification of 28–36% compared to exposure

Table 1
Average exposure levels based on different exposure modifier adjustments to original water system concentration estimates

| | DBP Conc (μg/L) | DBP intake[a] (μg) | DBP intake[a] (μg) modified for exclusive filtered[b] or bottled[c] water use | | | DBP intake[a] (μg) modified for exclusive filtered[b] and bottled[c] water use | |
|---|---|---|---|---|---|---|---|
| | Conc | Intake | Intake and 50% filter | Intake and 90% filter | Intake and BW | Intake and BW and 50% filter | Intake and BW and 90% filter |
| Mean | 49.5 | 71.8 | 64.6 | 58.9 | 57.5 | 50.3 | 44.6 |
| $r^d$ | – | 0.79 | 0.74 | 0.63 | 0.61 | 0.57 | 0.49 |

Abbreviations: Conc, system average concentration; Filter, point-of-use filtration of tap water; BW, bottled water.

[a] DBP Intake (μg) based on randomly assigned water consumption rates of 0.5, 1.0, 1.5, 2.0, 2.5 L/day for each subject multiplied by average system DBP concentration.

[b] 20% of subjects were assumed to be exclusive filtered tap water users for all water based beverages.

[c] 20% of subjects were assumed to be exclusive bottled water users for all water based beverages.

[d] Pearson correlation coefficients for system average concentration and individual exposure measures.

Table 2
Percentage of subjects misclassified compared to original system average exposure categorization

| Classification strategy | DBP intake[a] | DBP intake[a] modified for exclusive filtered[b] or bottled[c] water use | | | DBP intake[a] modified for exclusive filtered[b] and bottled[c] water use | |
|---|---|---|---|---|---|---|
| | Intake | Intake and 50% filter | Intake and 90% filter | Intake and BW | Intake, BW and 50% filter | Intake, BW and 90% filter |
| 50–40–10%[d] | 29 | 30 | 36 | 36 | 38 | 48 |
| 34–33–33%[e] | 31 | 34 | 43 | 43 | 45 | 55 |
| 40–30–30%[f] | 33 | 35 | 43 | 43 | 44 | 54 |
| 40–30–20–10%[g] | 42 | 44 | 51 | 51 | 51 | 62 |

Abbreviations: Filter, point-of-use filtration of tap water; BW, bottled water.
[a] DBP Intake (μg) based on randomly assigned water consumption rates of 0.5, 1.0, 1.5, 2.0, 2.5 L/day for each subject multiplied by average system DBP concentration.
[b] 20% of subjects were assumed to be exclusive filtered tap water users for all water based beverages.
[c] 20% of subjects were assumed to be exclusive bottled water users for all water based beverages.
[d] Exposures ≤50th percentile comprised the low exposure group; exposures between the 50th and 90th percentile comprised the intermediate exposure group; exposures ≥90th percentile comprised the high exposure group.
[e] Exposures ≤34th percentile comprised the low exposure group; exposures between the 34th and 68th percentile comprised the intermediate exposure group; exposures ≥68th percentile comprised the high exposure group.
[f] Exposures ≤40th percentile comprised the low exposure group; exposures between the 40th and 70th percentile comprised the intermediate exposure group; exposures ≥70th percentile comprised the high exposure group.
[g] Exposures ≤40th percentile comprised the low exposure group; exposures between the 40th and 70th percentile comprised the intermediate group; exposures between the 70th and 90th percentile comprised the high group; exposures ≥90th percentile comprised the very high group.

metrics incorporating water intake volume and DBP concentrations. Misclassification across one category was similar in magnitude for system average concentrations compared to exposure scores incorporating water intake and 50% filtration removal efficiency (29–37%). When water intake was combined with

Table 3
Percentage of subjects misclassified across one category (and across at least two categories) compared to original system average exposure categorization

| Classification strategy | DBP intake[a] | DBP intake[a] modified for exclusive filtered[b] or bottled[c] water use | | | DBP intake[a] modified for exclusive filtered[b] and bottled[c] water use | |
|---|---|---|---|---|---|---|
| | Intake | Intake and 50% filter | Intake and 90% filter | Intake and BW | Intake, BW and 50% filter | Intake, BW and 90% filter |
| 50–40–10%[d] | 28 (1)[e] | 29 (1)[e] | 34 (2)[e] | 34 (2)[e] | 36 (2)[e] | 45 (4)[e] |
| 34–33–33%[f] | 30 (1)[e] | 33 (1)[e] | 37 (6)[e] | 36 (7)[e] | 38 (7)[e] | 46 (9)[e] |
| 40–30–30%[g] | 30 (3)[e] | 32 (3)[e] | 36 (6)[e] | 36 (7)[e] | 36 (8)[e] | 44 (10)[e] |
| 40–30–20–10%[h] | 36 (5)[e] | 37 (6)[e] | 42 (9)[e] | 42 (9)[e] | 40 (11)[e] | 47 (14)[e] |

Abbreviations: Filter, point-of-use filtration of tap water; BW, bottled water.
[a] DBP Intake (μg) based on randomly assigned water consumption rates of 0.5, 1.0, 1.5, 2.0, 2.5 L/day for each subject multiplied by average system DBP concentration.
[b] 20% of subjects were assumed to be exclusive filtered tap water users for all water based beverages.
[c] 20% of subjects were assumed to be exclusive bottled water users for all water based beverages.
[d] Exposures ≤50th percentile comprised the low exposure group; exposures between the 50th and 90th percentile comprised the intermediate exposure group; exposures ≥90th percentile comprised the high exposure group.
[e] Misclassification across at least two exposure categories.
[f] Exposures ≤34th percentile comprised the low exposure group; exposures between the 34th and 68th percentile comprised the intermediate exposure group; exposures ≥68th percentile comprised the high exposure group.
[g] Exposures ≤40th percentile comprised the low exposure group; exposures between the 40th and 70th percentile comprised the intermediate exposure group; exposures ≥70th percentile comprised the high exposure group.
[h] Exposures ≤40th percentile comprised the low exposure group; exposures between the 40th and 70th percentile comprised the intermediate group; exposures between the 70th and 90th percentile comprised the high group; exposures ≥90th percentile comprised the very high group.

either bottled water use or 90% filtration removal efficiency, 34–42% of the subjects were misclassified based on system average concentrations. Upon consideration of all modifying factors, misclassification across the exposure classification strategies ranged from 36–40% and 45–47% for 50% and 90% DBP removal efficiency, respectively.

Extreme misclassification occurring across at least two exposure categories (e.g., from high to low) was minimal (1–6%) for system average surrogates compared to DBP intake or intake modified by filtered water use assuming 50% removal efficiency (Table 3). Upon examination of all of the exposure modifying factors, average misclassification ranged from 2–11% and 4–14% assuming 50% and 90% filtration removal efficiency, respectively. Misclassification across at least two exposure categories was most pronounced in the four-category (i.e., 40–30–20–10%) classification strategy (5–14%), while the median approach resulted in the least amount of extreme misclassification (1–4%). The other two categorization approaches resulted in similar misclassification (1–10%) upon examination of the various exposure modifiers.

## 4. Discussion

Despite moderate to high correlations with more accurate estimates of exposure, considerable misclassification resulted from the use of system average concentrations to estimate individual DBP exposures. Compared to exposure estimates incorporating data on individual water consumption practices, 29% to 62% of the subjects would be misclassified based on system average concentration assignments alone. Water intake volume was the most influential exposure modifier (misclassification range: 29–42%), since it affected exposure scores for all of the subjects. Exclusive bottled water and filtered water use (assuming 90% removal efficiency) resulted in total misclassification similar in magnitude to the water intake data, despite only impacting exposure scores for 20% of the subjects. Failure to consider water intake volume primarily resulted in misclassification across one category, while not incorporating exclusive bottled and filtered water use data was more likely to lead to more misclassification across two or more categories.

Bottled and filtered water use resulted in considerably less DBP intake; therefore most of the misclassified subjects had system average concentrations larger than their true exposures. These adjustments to individual exposure scores, therefore, had less of an impact for classification approaches with more subjects in the lower exposure groups. For example, 90% of subjects were grouped into the low or intermediate exposure categories for the median approach compared to 67–70% in the other approaches. The narrow range for high and very high exposure levels found in the fourth exposure classification strategy also increased the likelihood of subjects being re-classified into lower exposure groups.

Most of the exposure misclassification occurred in adjacent exposure categories when water use information was not considered. Extreme misclassification across two exposure categories was predominantly due to individuals with low exposures being incorrectly classified into the high exposure group. The median classification strategy was the most robust categorization approach for minimizing misclassification across at least two exposure categories, again largely due to a minimum number of subjects in the higher exposure categories. Although the four-category classification approach had slightly more extreme misclassification, it was not directly comparable to the other three approaches. Only 60–70% of the subjects in the other three approaches could be misclassified across two exposure groups, while all of the subjects in the four-category approach were able to move across two exposure categories.

We assumed that 20% of subjects each were exclusive users of bottled water and filtered tap water and did not consider combinations of multiple water types (i.e., bottled, filtered, and unfiltered tap water). Based on the assumptions that DBPs were not present in bottled water and that point-of-use filtration removed 90% of DBPs, 40 different bottled and filtered water users were typically re-classified into the lowest exposure category. This yielded more representative exposure values for individuals who do not consume unfiltered tap water and enhanced the generalizability of our findings to other modifying factors that dramatically reduce DBP concentrations. The findings for exclusive bottled water use and 90% filtration removal efficiency (each based on 20% of subjects) were very similar with average misclassification ranging from 36% to 51%. Misclassification from the use of system average exposure surrogates should be similar in magnitude for other combinations of exclusive bottled and filtered water users equaling 40%.

Our simulated data were dependent on several assumptions and only considered a few individual-level exposure modifying factors that could impact misclassification rates. For example, more extreme misclassification would be expected to occur if water consumption practices (e.g., bottled and filtered water use) were non-random and related to high system average DBP levels. On the contrary, if exclusive filtered or bottled water use estimates were overestimated (e.g., if some users periodically used tap water) we would expect less misclassification to occur. Additional misclassification could occur if the system average exposures did not adequately capture the exposure period of interest or if DBP ingestion exposure outside the home varied considerably from residential exposures. The assumption of limited DBP variability within water systems may also not be applicable for systems reporting considerable intra-system differences in DBP concentrations (Rodriquez and Serodes, 2001; Sohn et al., 2001; Chen and Weisel, 1998). Previous research has shown that THM spatial variability can bias relative risk estimates reported in reproductive epidemiologic studies (Waller et al., 2001; Wright and Bateson, 2005), which could lead to additional misclassification in our ingestion exposure estimates.

We did not consider DBP inhalation or dermal absorption, so our analysis is most relevant for non-volatile DBPs that are impacted primarily by ingestion. The simulated data based on five possible water intake levels and a daily mean of 1.45 L/day was consistent with preliminary information from pregnant women enrolled in the Right from the Start study. Although our analyses assumed that water intake rates were not uniformly distributed across the 100 subjects, we did examine misclassification based on an assumption of equal weighting for the five possible consumption values (0.5, 1.0, 1.5, 2.0, 2.5 L/day). Compared to the non-uniform distribution analyses presented in this paper, average misclassification was 3% higher assuming a uniform consumption distribution (data not presented). The assumptions regarding DBP filtration removal effectiveness were based on existing literature. Approximately 90% of THMs are removed upon point-of-use filtration, while lower levels have been reported for non-volatile compounds such as the HAAs (Egorov et al., 2003; Eslinger and Weinberg, 2003; Kim, 1997). The 50% filtration removal assumption was used to estimate DBP removal over the life of a filter, since filter efficiency is dependent on proper filter maintenance and replacement. When data on all of the exposure modifying factors were considered together, the amount of misclassification was approximately 10% lower for the 50% DBP removal assumption compared to 90% removal efficiency.

Eslinger and Weinberg (2003) did not detect DBPs in four different brands of bottled water, so bottled water was assumed to not contain DBPs in our analysis. This assumption may not be applicable for bottled water drawn from disinfected municipal water that is not further treated. Our study also did not include information on boiling tap water prior to consumption or consider the impact of hot water-based beverage consumption. Heating water that contains residual chlorine has been shown to increase THM concentrations, while boiling water can greatly reduce THM concentrations (Weisel and Chen, 1994; Wu et al., 2001; Batterman et al., 2000). There is limited information on the impact of heating water on HAA levels, but some studies indicate that the concentrations of mono- and di-haloacetic acids can increase upon boiling (Kim, 1997; Weisel and Chen, 1994; Krasner and Wright, 2005). These data reinforce the need to consider thermal effects when estimating DBP exposures, especially since hot-water based beverages may account for a considerable percentage of total water intake in some populations (Kaur et al., 2004; Grosso et al., 2001).

The amount of misclassification that we observed for use of system average DBP surrogates is similar to Zender et al. (2001) who estimated 60% misclassification for three sources of variability: bottled and filtered water consumption, consumption outside the home, and relocation during pregnancy. Our findings are also consistent with Whitaker et al. (2003) who reported 43% misclassification for trichotomous chloroform exposures based on simulated water usage data that included information on swimming, bathing, and showering. King et al. (2004) found similar misclassification for household THM concentrations in relation to total THM exposures that included ingestion, showering and bathing activities. While the potential impact of exposure misclassification on previously reported epidemiologic findings are unknown, Reif et al. (2000) estimated that 20% non-differential misclassification of subjects with low to intermediate exposures into the high exposure groups could result in substantial attenuation of the observed effect estimates for the high exposure group. This may be of particular concern for smaller studies, since even minor exposure misclassification can result in substantial bias and reduced statistical power to detect subtle increases in health risk (Bachand and Reif, 2000).

We examined modifying factors that mainly reduced average DBP exposures, resulting in individuals with low exposures being misclassified into intermediate to very high exposure groups based solely on water system concentrations. Our findings further highlight the importance of collecting detailed individual-level information to improve exposure characterization and allow for examination of DBP exposure misclassification bias in epidemiologic studies. Quantifying and reducing uncertainty in risk estimates should help inform risk managers and aid the interpretation of epidemiologic findings for public health decision-making.

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