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Joseph E. Goodwill
University of Rhode Island, goodwill@uri.edu

Mark W. Hagemann

Marc A. Edwards

David A. Reckhow

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Quantifying and contextualizing disinfection byproducts during the Flint Water Crisis: a case study, and framework for broader application

Quantifying and contextualizing disinfection byproducts during the Flint Water Crisis: A case study, and framework for broader application

Joseph E. Goodwill[1]*, Mark W. Hagemann[2], Marc A. Edwards[3], David A. Reckhow[2]

[1]Department of Civil and Environmental Engineering, University of Rhode Island, Kingston, RI, USA; [2]Department of Civil and Environmental Engineering, University of Massachusetts, Amherst, MA, USA; [3]Department of Civil and Environmental Engineering, Virginia Tech, Blacksburg, VA, USA. *Corresponding author Email: goodwill@uri.edu

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ABSTRACT

Total trihalomethanes (TTHMs) and other disinfection byproducts (DBPs) have been a concern in Flint, Michigan, in both delivered water and water from home water heaters. Historical TTHM data and DBP sampling results from Flint were combined with models for predicting hot water TTHMs to assess the probability of certain DBP concentrations. Results were compared with hot and cold water DBPs from a water system in Florida. Flint results were used to estimate cancer risk resulting from chronic exposure to hot water TTHMs, and compared to similar risk assessments in other water systems. Results indicate TTHM concentrations decreased in Flint following a return to water from the Detroit Water and Sewerage Department, and were very near the mean value for public drinking water systems in the United States. Measurement of other unregulated DBPs also indicated levels within the typical ranges. Monte Carlo simulations

coupled with modeling of hot water TTHMs indicated a low probability of TTHMs exceeding 80 µg/L in Flint in 2016. The estimated cancer risk from exposure to TTHMs in Flint is similar to other areas. The methods used in this work can apply broadly to other water systems to de-escalate perceptions of risk following a water crisis.

KEYWORDS | disinfection byproducts; water heaters; trihalomethanes; risk; modeling

INTRODUCTION

The City of Flint, Michigan (Flint) has experienced a well-documented water crisis (Schwake *et al*. 2016; Pieper *et al*. 2017). In April of 2014, Flint switched from using finished water from the Lake Huron Water Treatment Plant of the Detroit Water and Sewerage Department (DWSD) to water from the Flint River, treated in the City's Water Treatment Plant (Flint WTP). Differences in raw water chemistry and failure to add corrosion control chemicals caused extensive corrosion, and released lead (Pb) into consumers' water. The Flint water system also experienced elevated levels of total trihalomethanes (TTHMs), which exceeded United States Environmental Protection Agency (USEPA) regulations (State of Michigan Department of Environmental Quality 2014). Corrective action was recommended to address these water quality problems, although the response was delayed (Masten *et al*. 2017). On October 16, 2015, the Flint water system resumed using DWSD water in an effort to abate the public health crises. Public confidence in the water supply and government agencies was severely weakened.

Following the return to DWSD water, an advocacy group began measuring trihalomethanes (THMs) and other compounds in delivered and heated tap water in Flint homes, and publicly announced that "dangerous" levels of chloroform and other THMs were present

(Water Defense 2016). However, this group's sampling methods were unorthodox, and results were not peer reviewed. The accuracy and value of these results are indeterminable. Nevertheless, the findings were broadcasted by media outlets, with the implication that water in Flint was unsafe for bathing and other basic hygiene practices, and many consumers stopped bathing as a result. Simultaneously, outbreaks of preventable communicable disease such as Shigellosis appeared in Flint, which were possibly due to a decrease in hygiene behaviors arising out of the escalating fear (Hauser 2016; Roy 2017).

The results were difficult to assess for another reason: domestic hot water quality is not regulated, and data on DBP in heated water is scant. The possible risk from exposure to THMs in cold and especially hot water required further study. Published approaches exist for predicting hot water DBPs based on water quality parameters in the cold water (Chowdhury, Rodriguez, Sadiq, & Serodes 2011). Likewise, methods exist for estimating potential health risk posed by DBP concentrations (W. Wang, Ye, Yang, Li, & Wang 2007; Chowdhury, Rodriguez, & Sadiq 2011; Y. Wang, Small, & VanBriesen 2016). These modeling and risk approximation methods were combined to help provide an informed estimation of risk from hot water DBPs, despite limited data. Also, sampling results of cold and hot water DBPs from a surface water system in Florida were directly compared with Flint measurements to provide additional contextualization.

The overarching goal of this study was to enable more informed water usage decisions by providing defensible measurements and context to Flint DBP results. To that end, the specific objectives of this study were to: (1) measure THMs and other DBPs in Flint, allowing direct comparison with previously reported results; (2) compile, integrate, and review historical data for TTHMs and other DBPs from Flint, DWSD and prior national THM surveys; (3) use Monte Carlo simulations coupled with previously developed hot water TTHM predictive models to

develop probable hot and cold water TTHM ranges experienced by Flint water consumers from 2014–2016; and (4) contextualize probable hot-water THM risk levels against prior published cancer risk approximations in Flint following the return to DWSD. While applied to Flint here, the approach in this work may be useful as a framework for perceived risk management in other systems with limited DBP data and increasing customer concern.

MATERIALS AND METHODS

Sampling and measurement of cold and hot water disinfection byproducts

All DBP sampling and analysis for this study was executed using established methodology (Stevens & Symons 1976; Symons, Krasner, Simms, & Sclimenti 1993; APHA 2012). Both hot and cold water samples were collected from four sites selected based on previously known issues with elevated DBPs. Sampling was conducted on two dates in May 2016. Samples were collected from each site and analyzed for regulated and unregulated DBPs. Reporting focused on TTHMs and other volatiles since these were the constituents of interest in work by other groups. Compliance data show the City of Flint did not have a haloacetic acid (HAA) violation in 2014, 2015, or 2016 (City of Flint 2016), including during the peak of the water crisis. As such, they were not the focus of this study.

Samples were collected from bathtub taps in three residential locations and from a sink in a separate commercial location. Samples were drawn in the middle of the day without prior consideration of water age. Water had previously been used at the sampling fixture in each location prior to the moment of sampling, and fixtures were not further flushed prior to drawing samples. Cold water samples were drawn first, directly from the respective water fixture with the hot water tap completely shut. Hot water samples were drawn immediately following cold water

by fully shutting the cold water valve and fully opening the hot water valve. Temperature was monitored until it reached a stable, maximum value (approximately 10–20 seconds) and then a hot sample was collected.

One sample for each family of DBPs (e.g., HAAs, THMs, etc.) was collected at each location in 3-litre acid-washed and chlorine demand free borosilicate glass bottles. Preservatives were added to each bottle prior to filling for the purpose of quenching residual chlorine and stabilizing the analytes. Sample bottles were filled completely without headspace, sealed securely, and kept cold (~4°C) and in the dark during transport. Hot water was sampled in variable-volume, headspace-free bottles developed specifically for the sampling of DBPs in hot water (Liu & Reckhow 2013). In short, these variable-volume bottles contain a piston that contracts as the water cools thereby stopping the development of negative pressure inside the bottle which would increase the likelihood of air intrusion and the loss of volatile analytes.

Analytes in this study included four chlorine- and bromine-containing THMs (e.g., summed to comprise TTHMs), three dihaloacetonitriles (DHANs; dichloro-, bromochloro-, and dibromoacetonitriles), two haloketones (HKs; dichloropropanone (DCP) and trichloropropanone (TCP)), and chloropicrin (CP). The four THMs comprising TTHMs are chloroform ($CHCl_3$), bromodichloromethane ($CHCl_2Br$), dibromochloromethane ($CHClBr_2$), and bromoform ($CHBr_3$). Arsenite was used as the quenching agent for all analytes. These compounds were measured by liquid/liquid extraction (LLE) with pentane followed by gas chromatography (GC) with electron capture detection (ECD). All analytical steps conformed to USEPA Method 551.1 (USEPA, 1995). DBP samples from the independent sampling event in Florida were treated in the same manner as the Flint DBP samples. Samples were analyzed in duplicate (e.g. two sub-samples from one bottle collected, as previously described) with two injections per sub-sample. Sampling

116 in Flint and Florida included a travel blank for each site, consisting of deionized (DI) water only.
117 The DI water was transferred on site to a DBP sampling bottle at the time other samples were
118 collected. TTHM concentrations in the travel blanks ranged from 1.0% to 1.4% of the TTHM
119 concentrations found in the domestic water samples. All other DBPs in the travel blanks were
120 below detection limits.
121 Chlorine was measured using an adapted DPD (N,N-diethyl-p-phenylenediamine
122 colorimetric method (APHA, 2012). Temperature and pH were measured using a calibrated field
123 pH meter and probe with automatic temperature correction.
124
125 **Modeling methods**
126 Published models for predicting hot water DBPs based on other water quality parameters were
127 adopted (Chowdhury et al. 2011b) including a main factors linear (MFL) model, and a log-linear
128 (LL) model. These two models were chosen based on previously assessed performance. The
129 MFL and LL models were found to have the best performance by Chowdhury et al. (2011b) in
130 terms of correlation coefficient, with respective values of 0.89 and 0.86. The inputs for the MFL
131 model were: free chlorine residual in distributed water (Cl_{2Free}); cold water THMs as measured in
132 the distribution system (THM_{WDS}); and cold water pH, shown in Equation (1). The LL model
133 also has inputs of Cl_{2Free} and TWH_{WDS}, shown in Equation (2). Model coefficients developed by
134 Chowdhury et al. (2011b) were utilized in this study without modification; however, they were
135 originally developed using water from multiple water sources with varying water quality (i.e.
136 raw water TOC ranged from 1.2 to 12.6 mg/L). Thus, the models are at least somewhat site
137 independent.
138

$$THM_{HWT} = \beta_0 + \beta_1 THM_{WDS} + \beta_2 Cl_{2Free} + \beta_3 pH \quad (1)$$

where THM_{HWT} = hot water tank THMs, β_0 = 307.1, β_1 = 1.073, β_2 = 48.91, β_3 = -40.4, Cl_{2Free} = distribution system free chlorine, THM_{WDS} = distribution system THMs.

$$THM_{HWT} = Exp(\beta_0 + \beta_1 Ln(Cl_{2Free}) + \beta_2 Ln(THM_{WDS}) \quad (2)$$

where β_0 = 2.367, β_1 = 0.431, and β_2 = 0.588.

Models were used to predict THM_{HWT} for each year from 2014 through mid-2016, a time period over which significant changes in water source, treatment operation and water quality occurred (Masten et al. 2017). Model inputs were generated from a distribution having the mean and variance equal to that of each year's measured data (see Supplementary Information, Table SI-1). For 2014 and 2015, data for THM_{WDS} were obtained from Flint's DBP monitoring program (City of Flint 2015), while pH and Cl_{2Free} values were taken from the Flint WTP Monthly Operation Reports (MORs) (City of Flint 2016). Model inputs for 2016 came from USEPA data produced by monthly sampling from January 2016 through June 2016 (24 sites, sampled monthly) (USEPA 2016a).

Monte Carlo sampling was used to assess the probability distribution of THM exposure from hot-water tanks. Similar approaches have been used successfully to inform DBP regulations (USEPA 1997) and to assess the effect of increasing bromide concentrations on THM risk (Wang et al. 2016). The sample mean and standard deviation for the data from each year were used to generate a random sample of size 10000 for pH, Cl_{2Free}, and THM_{WDS}. A log-normal

distribution was assumed for Cl_{2Free} and THM_{WDS}, and a normal distribution was used for pH. These samples were used to simulate a distribution of predicted THM_{HWT} via Equations (1) and (2). Model residual error was included in the MFL and LL predictions, based on the RMSE reported in Chowdhury et al. (2011b).

Risk assessment

Cancer risk from TTHMs was estimated using a published model that calculates a risk (lifetime cancer risk based on exposure) for each regulated THM species including $CHCl_3$, $CHCl_2Br$, $CHClBr_2$ and $CHBr_3$, and for each potential exposure pathway (oral, inhalation, and dermal), including cold water and heated water used for showering (Chowdhury, Rodriguez, & Sadiq 2011). This additive approach has also been used to assess the cancer risk associated with increasing bromine in drinking water sources (Wang et al. 2016). The specific cancer risks were based on the slope factors for each THM (mg kg^{-1} day^{-1}), which were taken from the Integrated Risk Information System (IRIS) (USEPA 2016b) and Risk Assessment Information System (RAIS) (US Department of Energy 2016). A slope factor for $CHCl_3$ is not available from IRIS as its classification is under reassessment, thus it has not been included in this calculation, an approach taken in similar risk assessments (Chowdhury 2016). Inhalation exposure slope factors for $CHCl_2Br$ and $CHClBr_2$ have not been determined and were taken to equal the oral exposure slope factors, an imperfect but necessary assumption. Many other assumptions went into the calculation of specific risk (e.g. body mass, bathroom ventilation) and these values may vary significantly across the Flint population. Values from these variables were taken from several sources (McKone 1987; United States Environmental Protection Agency 1998; Chowdhury & Champagne 2009). However, no model will be able to perfectly capture all of this variation, and

slope factors extrapolated from rodent studies of single contaminants carry additional limitations. For specific cancer risks, the three regulated THMs were multiplied by the hot water THMs measured in the May 2016 sampling event when calculating thermal exposure during showering, an inherently conservative approach compared with other studies attempting to calculate a blend of cold and hot water THMs. Cold water THMs measured in this study were assumed for the injection exposure pathway. The risk assessment did not consider haloacetic acids (HAAs) as there was no violation of HAA maximum contaminant levels at any point during the crisis. Also, HAAs are non-volatile and thus unlikely to pose significant risk through the inhalation pathway as opposed to TTHMs. The risk assessment did also not consider adjustment factors for potential early life exposure.

RESULTS AND DISCUSSION

Historical trihalomethanes

Results from THM sampling conducted by the City of Flint (May 2014 – October 2015) and the EPA (February 2016 – May 2016) are summarized in the Supplementary Information in Figure SI-1. TTHMs in the summer of 2014 were elevated. For August 2014, the lowest TTHM result in the system was above the locational running annual average (LRAA) regulatory limit of 80 μg/L. The maximum result approached 200 μg/L, and the median was 134 μg/L. This led to recommendations for corrective action including system flushing to reduce water age, and the cessation of filter prechlorination (Masten et al. 2017). Sampling in May and August of 2015 showed significant improvement, with median TTHMs of approximately 57 and 63 μg/L, respectively.

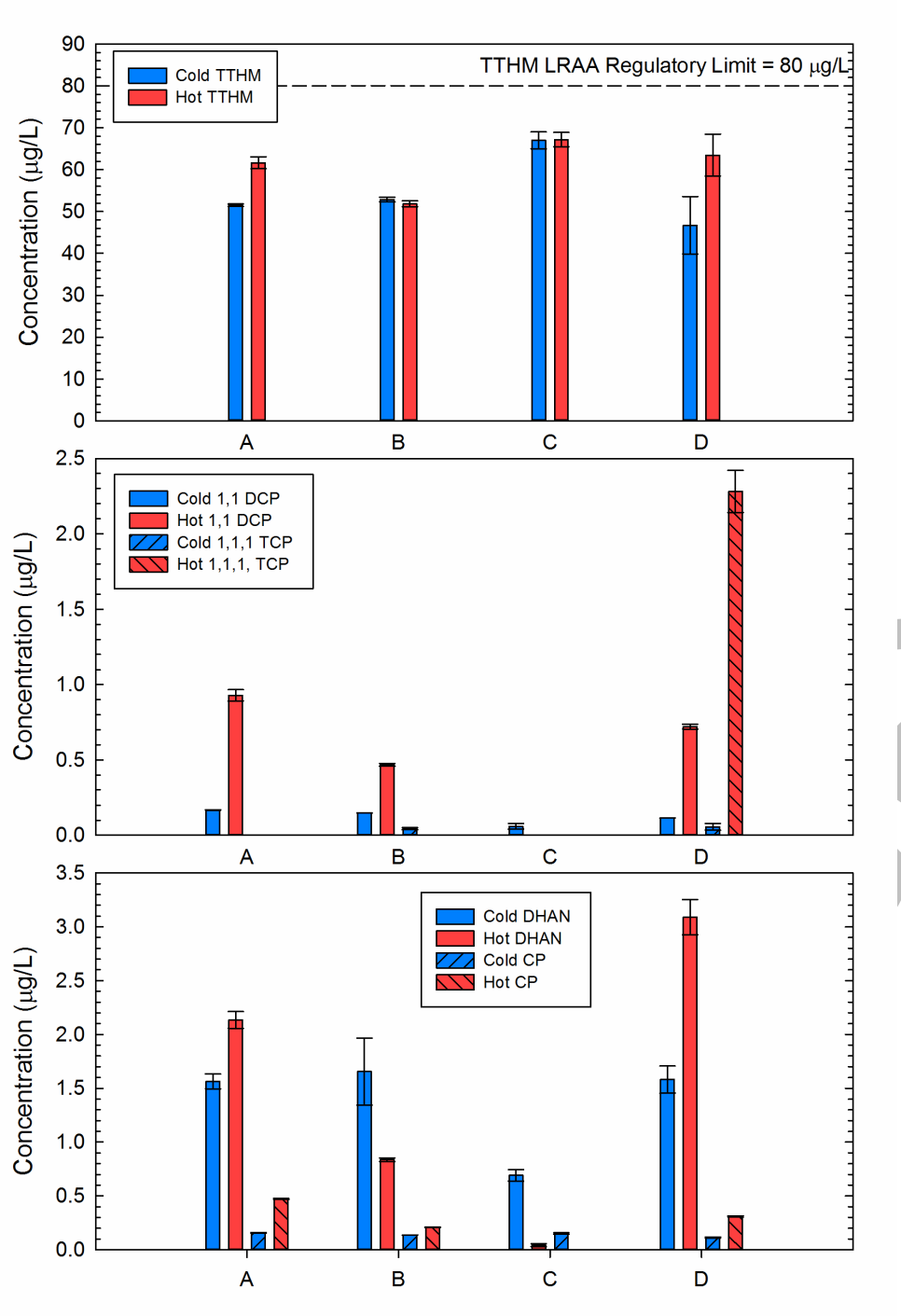
Figure SI-1 also includes the DWSD average highest LRAA, which was calculated from averaging the reporting highest LRAA from DWSD consumer confidence reports from 2006 through 2015 (City of Detriot 2016). Over the last 10 years, the highest LRAA of the DWSD system was approximately 35 μg/L, 55% less than the regulatory limit. The TTHM sampling results from 2016 again showed marked improvement over the results from 2015. The most recent data available for Flint shows a median TTHM concentration of 35 μg/L, 60% less than the median from May of 2014 (USEPA 2016a). A subsequent, independent study of one cold water site in Flint noted a TTHM concentration of 38.4 ±3.6 μg/L (Allen et al. 2017). A 2014 survey of TTHMs in 394 larger (> 100,000 customers) public water systems in the United States found upper and lower quartile limits of approximately 43 and 17 μg/L, respectively (Seidel, Samson, Bartrand, Ergul, & Summers 2017).

Field measurements of disinfection byproducts and water-quality parameters

Figure SI-2 (Supplementary Information) includes results of pH, free chlorine residual, and temperature for the four sites sampled as part of this study in May 2016. For each sampling location, the cold water had higher concentrations of free chlorine than hot water. Sample location A had the largest decrease in Cl_2 residual between the hot and cold water, followed by location D. Location D was the only site with significant remaining Cl_2 residual in the hot water, suggesting relatively low water age in the water heater. Location D also had the lowest hot water temperature.

The hot and cold concentrations of multiple DBPs in each location is presented in Figure 1. Cold water TTHMs ranged from 50 to 63 μg/L with hot water TTHMs falling in the same range. All measured hot and cold water TTHMs were below the LRAA TTHM regulatory

limit. Two of the four sample sites, A and D, had significant differences between cold and hot water TTHM. For locations A and D, hot water TTHMs were 19.6% and 35.8% higher, respectively, than in cold water. An increase in hot water TTHMs has been noted previously, including up to 120% increase in TTHMs in a surface water-supplied drinking water system in Massachusetts (Liu & Reckhow 2015). Chloroform was also found to increase over 100% as a result of heating in bench-scale studies at pH 7, in waters with an age of less than 72 hours (Liu & Reckhow 2013). Other investigators comparing a single cold and hot water sample from the same tap in Flint from a similar time as this study reported a 105% increase in TTHMs (38.4 to 78.8 μg/L) (Allen et al. 2017). The exact mechanism resulting in TTHM increase is unclear, but it may be due to accelerated reactions between chlorine and precursors as well as accelerated hydrolysis of the immediate halogenated precursors (Liu & Reckhow 2013). The increase in TTHMs was also directly proportional to the magnitude of loss in residual chlorine due to heating, which was also noted in eleven additional study sites in Florida (see Figure 2).



244

245 Figure 1. Cold and hot water concentrations of total trihalomethanes (TTHM, top), 1,1-

246 dichloropropanone and 1,1,1-trichloropropanone (DCP, TCP, middle), and dihaloacetonitriles

247 and chloropicrin (DHAN, CP, bottom) at four sites sampled in May 2016 from the Flint

distribution system. Error bars represent two standard deviations. (LRAA = location running annual average)

The presence of halopropanones (i.e., DCP and TCP) in hot water was noted in a previous study of DBPs in home heating systems (Liu & Reckhow 2015). 1,1-DCP was found to increase in Locations A, D and, to a lesser extent, B in the hot water samples. Following heating, 1,1-DCP increased between 300% and 700%. The increase in 1,1-DCP was also noted in a bench-scale study where heating increased DBPs of up to 500% at neutral or slightly acidic pH, regardless of water age (Liu & Reckhow 2013). Location D had a significant increase in TCP between the hot and cold sample, increasing from 0.1 to 2.3 μg/L. This increase was unexpected, as heating to 55°C has been previously shown to degrade TCP to non-detectable levels after 3 hours (Liu & Reckhow, 2013), ultimately undergoing hydrolysis reactions and forming chloroform (Reckhow & Singer 1985). However, location D was found to have both the lowest hot water temperature (41°C) and the highest hot water chlorine residual, suggesting a short residence time in the hot water tank. Therefore, increased TCP could be explained by active formation at elevated temperature, with hydrolysis rates below those observed at 55°C. A prior DBP survey reported median quarterly values of 0.6 to 2.8 μg/L for TCP in chlorinated, surface water systems (McGuire, McLain, & Obolensky 2002). All cold and hot water samples from this study fall within this range.

Chloropicrin concentrations followed a similar pattern to DCP, but cold-water concentrations were all less, ranging from 0.16 to 0.11 μg/L, leading to larger percent increase for locations A and D. Liu and Reckhow (2013) also noted a similar change in CP concentration with heating for waters with ages less than 48 hours. Krasner et al. (1989) reported a first quarter

(e.g., spring) median chloropicrin concentration of 0.16 μg/L in their survey of DBPs in US drinking water.

DHANs increased between the cold water and the hot water in locations A and D. In location A, DHAN increased from 1.5 to 2.1 μg/L, or 36.5%. At location D, DHAN increased from 1.5 to 3.1, or 95.4%. While this increase is significant, the DHAN levels in the hot water samples were still within the range typically encountered in public drinking water distribution systems in the United States. A 2002 survey noted a mean DHANs values of 2.21 μg/L for surface water-sourced distribution systems (Chiu 2004). Krasner et al. (1989) reported quarterly median DHAN values ranging from 2.5 to 4.0 μg/L. DHANs decreased in locations B and C, which may be attributed to the presumed older water age in those locations. DCAN levels have been noted to drop with increasing time in hot water tanks with temperature above 35°C in a residential system (Lui & Reckhow, 2015).

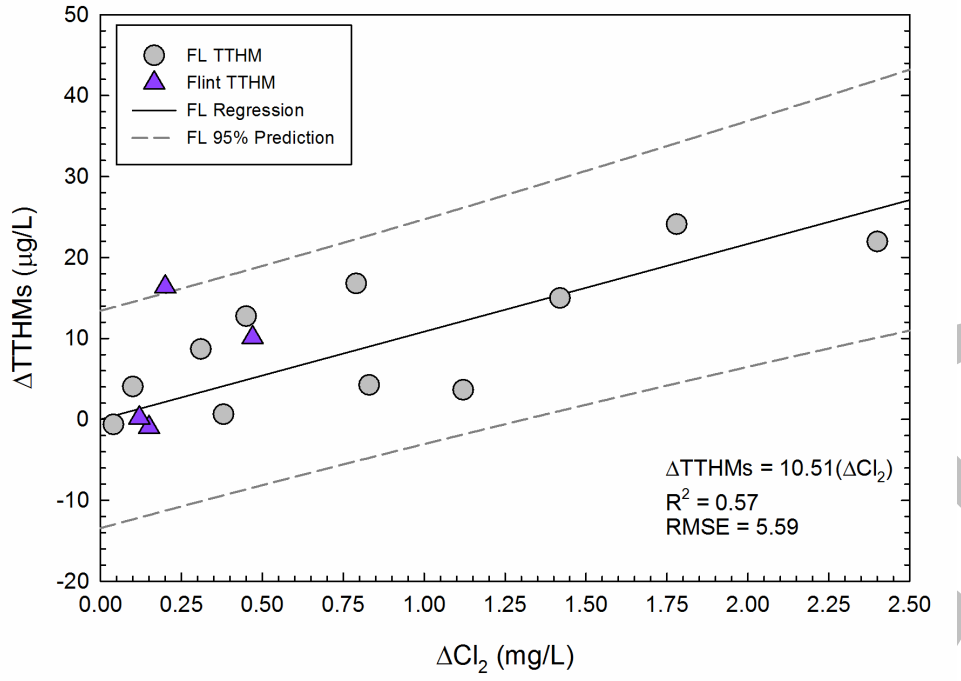
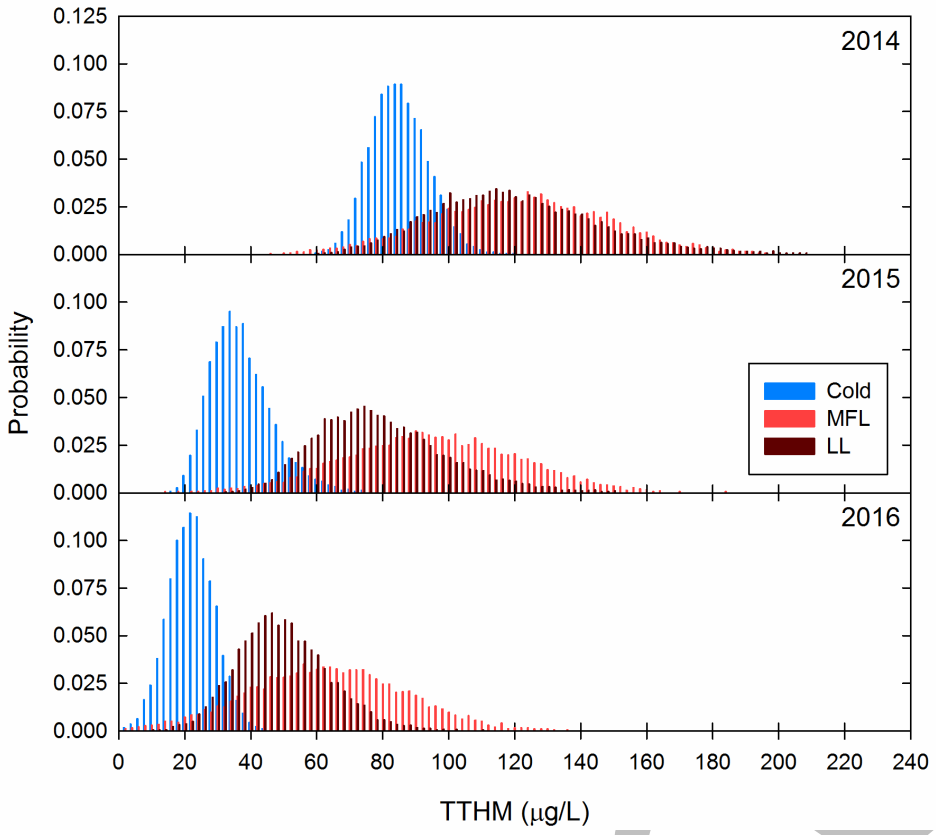


Figure 2. Change (Δ) in total trihalomethanes (TTHMs) as a function of free chlorine (Cl_2) residual loss across hot water heaters in both Flint, Michigan, and eleven sites in Florida (FL).

Figure 2 includes data from two sources: one from Flint and one from a surface-sourced chlorinated public drinking-water system in Florida. A positive correlation between the two parameters for both water systems is shown. This indicates that water heaters tend to drive reactions between free chlorine and DPB precursors to completion, which has also been noted in bench-scale simulations (Liu & Reckhow 2013).

Figure 2 contains a linear regression of the Florida data. The linear model shows a potential stoichiometry of 10.5 µg/L TTHM produced per 1 mg/L of Cl_2 lost during heating. All Flint data fall within or nearly within the 95% prediction interval of the linear regression which

298 indicate that there is no strong evidence that Flint hot water TTHMs have a different relationship
299 with changes in free chlorine as a result of water heating than those in the Florida water system.
300 In other words, measured hot water TTHMs from Flint would have been predicted based on the
301 Florida results. In this way, there was nothing exceptional about the changes in DBPs due to
302 water heating in Flint in the context of the Florida results. Other factors may affect changes in
303 TTHMs as a result of heating that are not captured in the linear regression model ($R^2 = 0.57$).
304 Examples could include heating time, heating temperature, and the nature of natural organic
305 material (NOM). It was not possible to quantify the nature of the Flint water NOM within the
306 scope of field sampling. This intersystem linear regression model comparison technique may
307 assist other investigators exploring the exceptionality of changes to DBPs as a result of heating.
308
309 **Modeling of probable trihalomethane concentrations**
310 Figure 3 shows a drastic decrease in simulated cold and hot water TTHMs from May 2014 to
311 May of 2016. For 2014, both models suggested a high probability ($p > 0.9$) of hot water TTHMs
312 being above 80 µg/L. The MFL results for 2016 suggested a probability of 0.77 for hot water
313 TTHMs falling below 80 µg/L, with the LL producing a corresponding probability of 0.97.
314 Independent of sampling of Flint hot water DBPs at two locations in July 2016 noted hot water
315 TTHMs of 78.8 ±3.6 and 69.5 ±1.4 µg/L (Allen *et al*. 2017). Hot water TTHMs for all model
316 years were directly proportional to cold water TTHMs, as shown in Equations (1) and (2).



317

318 Figure 3. Results of Monte Carlo simulation (ten thousand iterations) of probable cold and hot
319 water total trihalomethanes concentrations in delivered Flint water in 2014, 2015 and January–
320 May 2016. (MFL = hot water TTHMs from main factors linear model; LL = hot water TTHMs
321 from log-linear model). 80 µg/L is the current USEPA TTHM LRAA regulatory limit for
322 delivered water.

323

324 While this study generated samples of Cl_{2Free}, pH and THM_{WDS} independently of one another
325 when conducting the Monte Carlo simulation, a more accurate account of THM_{HWT} distribution
326 would have considered the covariance structure between these quantities. Unfortunately,
327 available data did not allow covariance to be quantified as, with very few exceptions, the
328 measurements of different water quality parameters were not concurrent, and instead came from

329 different water samples at different times and/or locations. Therefore, the assumption that all
330 model input variables are independent was necessary. If the predictor variables were positively
331 correlated then the true variance could have been larger, resulting in a higher probability of
332 THM_{HWT} exceeding 80 μg/L.
333
334 **Risk comparison**
335 While TTHMs are regulated in aggregate, there are individual health considerations for each
336 compound. Results from DBP field sampling form the USEPA and this study for each regulated
337 THM are shown in Figure SI-3 (Supplementary Information). The average bromide
338 incorporation factor (BIF) (Obolensky & Singer 2005) for all USEPA cold water results was
339 0.175. Siedel et al. (2017) reported an annual median BIF of THMs from 121 large drinking
340 water systems in the United States ranging from of 0.13 to 0.21. In this study, the BIF was 0.131
341 and 0.120 for cold and hot water samples, respectively, indicating bromide incorporation less
342 than many large drinking water systems in the US.
343 The median estimated cancer risk for the Flint system was estimated at 3.1×10^{-5}, or 3.1
344 per 100,000 (Chowdhury 2016). Based on the limitations of the estimation methods
345 (extrapolation from rodent exposure studies, lack of slope factors for all pathways, etc.), it is
346 anticipated that this result is more valuable when compared with the results of prior, similar risk
347 assessments of other potable water systems, and not as a quantification of specific risk in Flint.
348 Other investigators have reported similar risks from TTHMs, including a median average risk for
349 the Providence of Ontario of 1.9 per 100,000 and a 90^{th} percentile risk of 5.5 per 100,000
350 (Chowdhury, Rodriguez, & Sadiq 2011). A study of THMs in Taiwanese cities reported median
351 and 90^{th} percentile cancer risk for the city of Kaohsiung of 6.4 and 19.3 per 100,000, respectively

(Wang, Ye et al. 2007). The estimated cancer risk in Flint falls between the median and 90th percentile risk assessed for Ontario, and less than the median risk for Kaohsiung. Cancer risk assessment from DBPs, both in cold and hot water, remains challenging; however, these assessments and comparison may prove helpful to water utilities when concerns over "dangerous" levels of DBPs emerge following a crisis.

Broader hot water DBP concerns

Concerns regarding hot water DBPs extend beyond Flint. These concerns persist partly because regulations do not cover heated water DBPs in premise plumbing. Yet, heated water represents a significant contribution to the overall exposure to THMs. Federal regulatory jurisdiction limits what can be done to protect the public from drinking water contaminants. Thus, there is an inherent, persistent gap between risk and regulatory protection. In this gap, perceived risk can expand leaving some to propose that a problematic level of unreasonable fear is becoming common among water consumers (Mercer 2017). While actual risk may not be possible to quantify exactly, the perception of risk from treated water can be de-escalated using the approaches described here. In this way, the response to hot water TTHMs in Flint can be seen as a broader framework for the contextualization and de-escalation of perceived risk following a water crisis, as shown in Figure 4.

Figure 4. Framework for de-escalation of perceived risk following water crisis event

Figure 4 contains all of the approaches contained in this study including a historical comparison (Figure SI-1), a geographical comparison (Figure 2, and literature references), defensible

375 measurements (Figure 1), hot water THM modeling and Monte Carlo Sampling (Figure 3), and
376 risk comparison. Each step in this framework may serve to decrease a water quality knowledge
377 gap, enabling more informed perceptions of risk and choices regarding personal water use.
378 Communication with the public is an important part of shifting perception (Fischhoff
379 1995; Johnson 2003). Results in this study were disseminated to the public through several
380 pathways including traditional media press conferences and social media. While examining
381 specific communication techniques is not in the scope of this work, communication with water
382 customers is an active field of applied research within the water industry (K. Smith 2016).
383 Recently, former technical leadership at Water Defense retracted prior statements regarding
384 dangerous disinfection byproducts in Flint citing several components of this study and
385 framework (S. Smith 2018).
386
387 **CONCLUSIONS**
388 Results show TTHMs and other unregulated DBPs in Flint water were likely near median values
389 for delivered drinking water from surface water treatment plants across the United States,
390 following a return to DSDW. There were very few noteworthy or exceptional characteristics
391 about the Flint DBP profile found in this study, or by the sampling of the USEPA and other
392 investigators. The changes in Flint TTHM concentrations and speciation as a result of water
393 heaters is also similar to those noted in a Florida surface water system. The approximated cancer
394 risks from DBPs in Flint based on results in this study are similar to or less than those in other
395 developed regions of North America and Asia.
396 Additionally, models and field measurements suggest it is unlikely that hot water TTHMs
397 and some unregulated DBPs were elevated in the first half of 2016. These results are important,

as there has been persistent heightened consumer concern over TTHMs in Flint. This concern increased due to several factors, including credence given to DBP sampling by third parties using unproven methodology. This concern caused changes in hygiene practices requiring water such as handwashing, and a subsequent increase in Shigellosis cases in Flint. Results in this study suggest these changes in handwashing may not be supported by the estimated cancer risk posed by TTHM concentrations in Flint, especially the low risk contributed by the dermal exposure pathway.

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SUPPORTING INFORMATION

for

Quantifying and contextualizing disinfection byproducts during the Flint Water Crisis: A case study, and framework for broader application

(JWSRTAQUA-D-18-00075)

Joseph E. Goodwill[1], Mark W. Hagemann[2], Marc A. Edwards[3], David A. Reckhow[2]

[1]Department of Civil and Environmental Engineering, University of Rhode Island, Kingston, RI, USA; [2]Department of Civil and Environmental Engineering, University of Massachusetts, Amherst, MA, USA; [3]Department of Civil and Environmental Engineering, Virginia Tech, Blacksburg, VA, USA.

This file (5 pages) includes:

1 table and 3 figures addressing additional experimental data that are available for further information.

Table SI-1. Sources and basic statistical information for model inputs

Model Year	Model Variable	Source*	Mean	Units	SD	N
2014	THM_{WDS}	A	93.1	µg/L	45.1	27
2014	Cl_{2Free}	B	0.75	mg/L	0.54	938
2014	pH	B	7.6	na	0.30	363
2015	THM_{WDS}	A	45.3	µg/L	22.3	27
2015	Cl_{2Free}	B	0.87	mg/L	0.56	1000
2015	pH	B	7.57	na	0.27	365
2016	THM_{WDS}	C	21.1	µg/L	7.0	96
2016	Cl_{2Free}	C	0.59	mg/L	0.34	822
2016	pH	C	7.23	na	0.02	626

*(A) City of Flint disinfection byproduct monitoring program

(B) City of Flint drinking water treatment plant monthly operating reports

(C) US Environmental Protection Agency Flint water quality monitoring

Notes: THM_{WDS} = cold water trihalomethanes in distributed water (µg/L); Cl_{2Free} = free chlorine residual in distributed water (mg/L); SD = standard deviation.

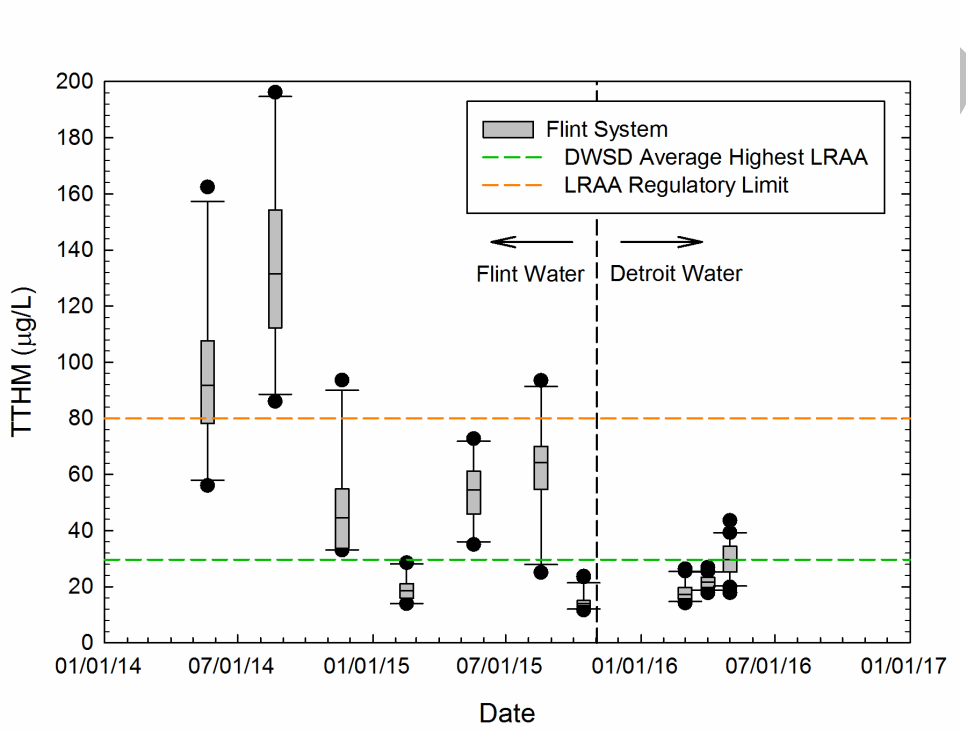


Figure SI-1. Total trihalomethanes results from May 2014 through May 2016 for the Flint drinking water system. Publicly available data provided by City of Flint, and United States Environmental Protection Agency. (DWSD = Detroit Water and Sewerage District; LRAA = locational running annual average)

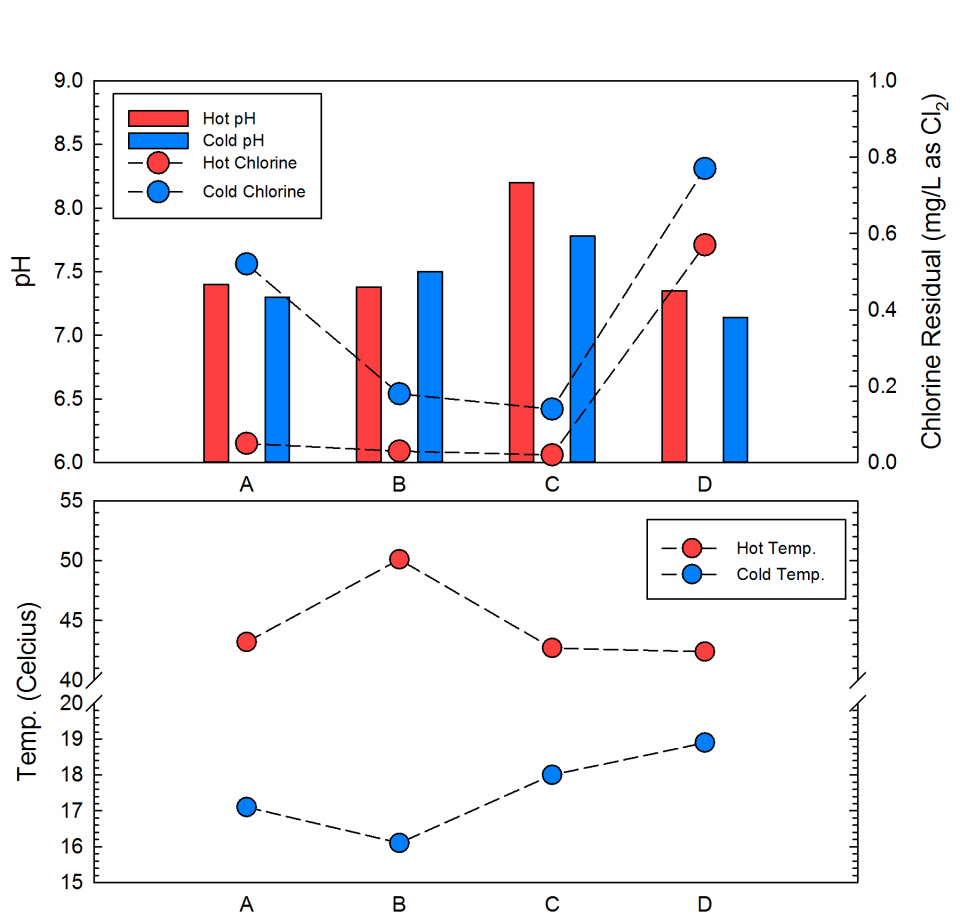
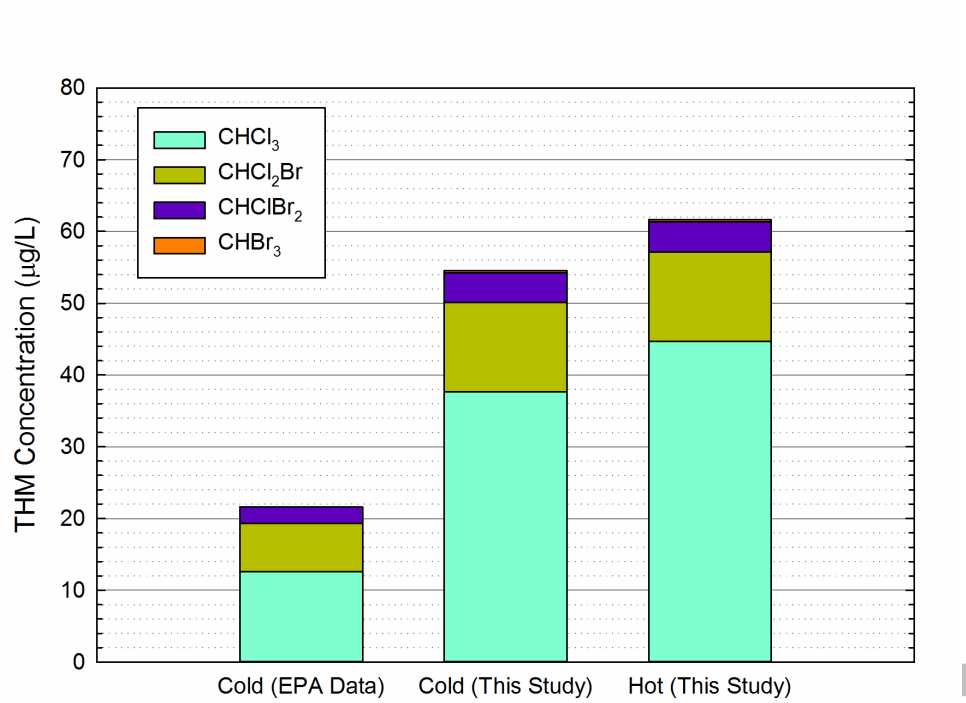


Figure SI-2. Differences in temperature, pH and chlorine residual at four studied sample locations from the May 2016 sampling in Flint distribution system.



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554 Figure SI-3. Speciation of trihalomethanes in Flint water in May 2016 from USEPA (N = 34)

555 collected data and this study (N = 4).

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