Probabilistic Approach For Health Hazard Assessment of Trihalomethanes Through Successive Showering Events

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Research Article

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Abstract

Trihalomethanes (THMs) are common disinfection byproducts in chlorinated tap waters. They can cause various cancers and non-cancerous health hazards. Ingestion, dermal contact, and inhalation are the three exposure routes considered in the THM hazard/risk assessments. Among these, inhalation hazard is generally calculated by assuming the initial concentration as zero. This assumption fails to address the case of continuous showers that can happen in shared showering facilities such as student hostels or gymnasiums. In the present study, the leftover THM concentration from the previous bath was considered to assess the chronic daily intakes (CDI) and hazard index (HI) of the successive showers. For this, tap water of a university campus was analyzed to understand the extend of THMs at consumer points and the result obtained was used for the hazard assessment. Total THM concentration varied from 0.51 to 68.9 μg L^{-1}. To address the variability of the model input parameters, 50,000 iterations of Monte Carlo simulation were carried out. A maximum HI of 7.94E-02 ± 3.63E-02 and 6.69E-02 ± 3.08E-02 was observed for 1st shower for females and males. This value was found as exponentially increasing up to the 5th shower and thereafter the rate was decreasing. The methodology followed in the present study successfully determines the risk and hazard of THMs through successive showers.

Introduction

Drinking water is the main medium of trihalomethanes (THMs) introduction to humans. THMs are disinfection byproducts (DBPs), known to be probable/possible carcinogens, and to harm human reproductive systems (Cotruvo and Amato, 2019; Zeng et al., 2016). Cancer risk assessment of THMs follows the US environmental protection agency (USEPA) guidelines, first to predict the chronic daily intake (CDI) through various exposure routes, and then to determine the total risk (USEPA, 1980). Computational human exposure models for THM risk assessment which are generally practiced are modifications to the USEPA method based on the water as well as study population parameters. A deterministic approach to such models fails to address the variability in the parameters and hence a probabilistic method by considering the variabilities of input parameters is recommended (USEPA, 2019) and is lately being used in THM risk assessment (Chowdhury, 2013; Mosaferi et al., 2021).

The three exposure routes for THMs are ingestion (drinking water), dermal absorption, and inhalation. While the first route stays relatively unchanged over different populations, the other two that can happen while showering, washing, or cleaning with water are sensitive to the living situations and daily routines. For instance, dishwashing eliminates dermal absorption that can occur during the hand washing of utensils. A common assumption in the inhalation CDI assessment is that the shower room air is considered free of THMs before any showering events (initial THM concentration = 0) (Chowdhury, 2013; Kujlu et al., 2020). This assumption is correct only for the household shower rooms where members use separate bathrooms or there is enough time between successive showering events so that the THM concentration left by the previous user is subsided. However, this assumption fails in the case of shared showering facilities such as student hostels and dormitories, gymnasiums, swimming pools, backpackers' lodges, sports complexes, and small bed and breakfast establishments with common

bathrooms where multiple showering events can occur continuously and therefore from the second shower onwards the THMs in the shower air cannot be assumed to be zero. Often in these facilities, there is not much time between two successive shower events to diminish the THMs left by the previous user and hence this amount needs to be accounted for while calculating the inhalation CDI and subsequent risks.

In the present study, tap water samples were analyzed for the extent of THM concentration at consumer point and the impact of successive showering events on daily intake and non-cancerous health hazards of THMs were evaluated for a campus community. A probabilistic method to ascertain the variability and to reduce the uncertainty associated with the input parameters of the modified exposure models was adopted.

Methodology

Hazard quotient and hazard index

The two health hazard indices used in the present study are hazard quotient (HQ) and hazard index (HI). These two are typically used in the risk characterization of chemical substances to describe the non-cancerous health hazards and were first defined by the USEPA – National-scale Air Toxics Assessment (NATA) as HQ as "*the ratio of the potential exposure to a substance and the level at which no adverse effects are expected"* and HI as "*the sum of hazard quotients for toxics that affects the same target organ or organ system"* (USEPA, 2015). Thus, for a mixture of certain chemical compounds such as THMs, HI is the sum of HQs of individual THMs. An HQ or HI of 1 or lower indicates adverse non-cancerous health hazards are unlikely over a lifetime of exposure and can be considered to cause negligible hazards. As such, HQ or HI greater than 1 means an increased potential for adverse effects although the end effect will be dependent on several factors.

THM analysis and study population

Water samples for THM analysis were collected in triplicates from tap water 20 halls of residence of Indian Institute of Technology Kharagpur (IITKgp) in December 2019. For this, 100 mL brown glass vials with Teflon septa were prepared by acid washing followed by oven drying, and they were conditioned with ammonium thiosulfate to quench the residual chlorine present in samples. Collected samples were immediately transferred to the laboratory to keep at 4°C and were analyzed within 24 h. A gas chromatograph (GC) equipped with an electron capture detector (ECD) (Trace 1300, Thermo Fisher Scientific Ltd., Austria) was operated to analyze for THM concentration. For preconcentration of samples, a purge and trap (P&T) unit (Lumin, Teledyne Tekmar, USA) with nitrogen as purging gas was used. Standard preparation, quality check, sampling, and instrumental conditions were as per the USEPA method 501.1 (USEPA, 1979) with few modifications. The oven temperature program of GC and purging program of P&T are given in Table 1.

Table 1
Operation conditions of the gas chromatograph and preconcentration unit.

Gas chromatograph	**Carrier gas: nitrogen at 1.2 mL/min, analytical column: TG5 MS – 30 m × 0.25 mm × 0.25 µm, injector: Split/splitless, 250˚C, detector: ECD, 300˚C.** **Oven program: 31˚C for 1 min, 31 to 40°C at 1˚C/min, 40°C to 200 at 80˚C/min, 200°C for 2 min.**
Purge and Trap unit	Purge gas: nitrogen at 10 mL/min, trap: VOCARB 3000, injection volume:5 mL Purging program: purge: 11 min, dry purge: 1 min, desorb: 2 min, bake: 2 min

The student community of the IITKgp were selected as the study population. The shower rooms in the halls of residence are shared by the inmates. Thus, in each shower room, successive showering events can happen, especially during the peak hours of mornings and evenings (before and after class hours). Therefore, this population was considered in the current study to apply the modified method to account for the incremental inhalation hazard due to successive showering events.

Modeling and simulation

Chronic daily intake (CDI) through inhalation of THMs in the shower room is predicted for the THM concentration in the shower air ($Cair_i$). The calculation of $Cair_i$ generally follows Little's theory which assesses $Cair_i$ for a given bathing duration as the average of initial (before the showering event, $C_{0.i}$) and final (at duration = t, $C_{t.i}$) concentration (Little, 1992).

$$Cair_i = \frac{C_{0,i}+C_{t,i}}{2} \quad \text{Eq. 1}$$

where, *i* represents individual THMs (*i* = 1 to 4 for TCM, BDCM, DBCM, and TBM). For the first shower, $C_{0.i}$ was taken as zero, and for the successive events, the $Cair_i$ of the previous bath was considered as the initial concentration. This was adopted by assuming that back-to-back showering events happen in the shower rooms, which is true in the case of student halls. Therefore, for the second bath of a given duration, $Cair_i$ will be equal to ¾ th of $C_{t.i}$. Hence, for n^{th} showering event,

$$Cair_i = \frac{2^n-1}{2^n} \times C_{t,i} \quad \text{Eq. 2}$$

The term $C_{t.i}$ represents the THM concentration (µg m^{-3}) in the air at a shower duration, which was determined using the following formula (Ahmed et al., 2019; Kujlu et al., 2020);

$$C_{t,i} = (1 - e^{-b\times t}) \times \frac{a}{b} \quad \text{Eq. 3}$$

where *t* is the showering duration (min),

$$b = \frac{1}{Vs} \times \{(\frac{Q_w}{H})(1 - e^{-N}) + Q_g\} \text{ , Eq. 4}$$

and

$$a = \frac{1}{Vs} \times \{(Q_w \times Cw_i \times (1 - e^{-N})\}$$, Eq. 5

where *Vs* is the volume of the bathroom (L), *Qw* is the water flow rate in the bathroom (L min^{-1}), *H* is unitless Henry's constant at 40°C for each THM, *Qg* is the airflow rate in the shower (L min^{-1}), Cw_i is the concentration of i^{th} THM in the shower water (µg L^{-1}), and *N* is the non-dimensional overall mass transfer coefficient. *N* can be calculated as;

$$N = \frac{KoLA}{Q_w}$$ Eq. 6

where *KoLA* is the overall mass coefficient of each THM (L min^{-1}) (Table 2).

The CDI of THMs by an individual through inhalation was determined using the US EPA guidelines of risk assessment, which is shown below (USEPA, 1980);

$$CDI_{inh,i} = \frac{Cair_i \times Er \times t \times R \times F \times EF \times ED \times CF}{BW \times AT}$$ Eq. 7

where, $CDI_{inh,i}$ is the inhalation chronic daily intake of i^{th} THM (mg kg^{-1} day^{-1}), *Er* is the absorption efficiency of THMs through the respiratory system, *R* is the breathing rate (m^3 min^{-1}), *F* is the showering frequency (events day^{-1}), *EF* is the exposure frequency (day $year^{-1}$), *ED* is the exposure duration (years), *CF* is the conversion from µg to mg (0.001), *BW* is the bodyweight of the individual (kg), and *AT* is the averaging time (days).

Similarly, the CDI through oral as well as dermal pathways were determined using the following equations (Chowdhury, 2013; Téllez Tovar and Rodríguez Susa, 2020);

$$CDI_{ing,i} = \frac{Cw_i \times IR \times EF \times ED \times CF}{BW \times AT}$$ Eq. 8

$$CDI_{der,i} = \frac{Cw_i \times SA \times Pd \times t \times F \times EF \times ED}{BW \times AT}$$ Eq. 9

where, $CDI_{ing,i}$ and $CDI_{der,i}$ are respectively the chronic daily intake of i^{th} THM through oral and dermal routes, *IR* is the drinking water ingestion rate (L day^{-1}), *SA* is the skin surface area (m^2), *Pd* is the permeability of THMs through human skin (m min^{-1}), *t* is showering duration (min $events^{-1}$), and *F* is showering frequency (events day^{-1}). The CDI was found by summing up respective individual CDIs, ie,.

$$TotalCDI = \sum_{i=1}^{4} \sum_{j=1}^{3} CDI_{i,j}$$ Eq. 10

Where *i* represents 4 THM species (TCM-TBM) and *j* represents 3 exposure routes (oral, dermal, and inhalation). Hazard quotient (HQ) and hazard index (HI) were assessed using the following equations (Mosaferi et al., 2021).

$$HQ_i = \frac{CDI_i}{RfD}$$ Eq. 11

Where, *RfD* is the chronic reference dose of THMs (mg kg^{-1} day^{-1}), which were taken from USEPA IRIS and RAIS data directories (Table 2) (USEPA IRIS, 2021; USEPA RAIS, 2021). The inhalation reference dose of THMs is under study (USEPA, 2001) and is not yet updated in the IRIS database. When the RfD or cancer slope factors were not available for dermal or inhalation routes, the same for oral exposure was considered as many previous studies (Chowdhury et al., 2020). Total HI through any particular exposure route *j* was found by adding HQ of each THM through that route.

$$HI_j = \sum_{i=1}^{4} HQ_{i,j}$$ Eq. 12

similarly, the overall hazard index (HI_T) was calculated as follows:

$$HI_T = \sum_{i=1}^{4} \sum_{j=1}^{3} HQ_{i,j}$$ Eq. 13

In the case of successive showers, total CDI and HI were calculated for both females and males using the respective inhalation CDI and the final result was correlated against the health criterion as hazard index of unity.

Adjustment for water temperature

Generally, warm water of 35–45 °C is preferred for showers and baths, and for that cold (room temperature) and hot waters are mixed (Chowdhury et al., 2020). The term Cw_i in Equations 5, 8, and 9 is the THM concentration in cold tap water, which needs to be modified for inhalation and dermal HI to include the result of mixing with heated water. Ingestion HI can be left as it is since generally cold or room temperature water is preferred over hot water for consumption. This modification was admitted as the THMs formation continues in the tap water since water purification systems leave residual free chlorine in the supply water to protect the future contamination and natural organic matters are not completely removed by conventional treatment units. THM formation follows complex mechanisms, and it varies depending on water chemistry, residual chlorine, water temperature, and several other parameters (Padhi et al., 2019b). Therefore, it is difficult to incorporate all the reaction parameters, however, the effect of water temperature can be considered if the THM growth rates in both hot and cold water are determinable. To do that, the Cw_i in the current study was altered using a model suggested by Chowdhury et al (2020). Using the THM growth rate of hot water (k_h) and that of cold water (k_w), THMs in the mixed water can be predicted as;

$$Chw_i = Cw_i \times e^{(k_h - k_w)t}$$ Eq. 14

where Chw_i is the THM concentration in mixed water (μg L^{-1}), CW_i is the THM concentration in cold tap water, k_h and k_w (S^{-1}) were determined using the following equation.

$$k = 0.0011e^{0.0407T}$$ Eq. 15

where, T is the water temperature (℃), which was taken as 10 to 20℃ with a median of 15℃ for cold tap water since the sampling was carried out in the winter season. The parameters in all of the above equations, their values, and units are given in Table 2. Since these parameters are prone to uncertainty, triangular distribution was assumed for all of them, which is explained below.

Addressing the uncertainty and variability in the models used

Since exposure predictions that mathematical models stipulate are computational representations of complex real-life exposures, they involve many assumptions along with available data. Therefore, the accuracy and reliability of such models need to be assured. One way to do that is by addressing the variability associated with the inputs and parameters involved in the models. These parameters can be of time activity, gender, population, exposure-related, which can vary within and between individuals. Instead of a deterministic approach, the USEPA for human health exposure assessment guidelines (2019) recommends opting for probabilistic methods such as Monte Carlo simulation for model calculations. Accordingly, in the current study, the same was adapted with 50,000 iterations using Companion by MINITAB™ software. The overall variability in the model input parameters was incorporated through statistical distributions. The THM concentration data of the samples were analyzed with the distribution identification tool of MINITAB™ software to identify the statistical distributions. The distribution with the least Anderson-Darling (AD) value (with p-value > 0.05) and with the highest correlation coefficient was selected in the goodness of fit test. Besides that, a visual examination of the distribution ID plots was also done to finalize the most appropriate statistical distribution. For the other input parameters triangular distribution with the minimum, maximum, and mean as the most likely value was adopted. Triangular distribution was selected as it minimizes the biases associated with the possible outliers and incorporates the variability into the model (Table 2).

Table 2
Model input parameters and distribution. (Reference: (Census Commissioner of India, 2018; Chowdhury et al., 2020; Chowdhury, 2013; ICMR, 2021; Kujlu et al., 2020; Kumari and Gupta, 2018; Téllez Tovar and Rodríguez Susa, 2020))

Parameters	Distribution and values
Cwi,/ *Chw* – THM concentration (μg L^{-1}/ μg m^3)	Table 3
t – Showering duration (minutes)	T (5, 10, 15)
Vs – Shower stall volume (m^3)	T (2000, 3500, 5000)
H – Henry's constant	TCM: 0.25, BDCM: 0.124, DBCM: 0.0526, TBM: 0.0501.
Qw – Water flow (L min^{-1})	T (3, 4, 5)
Qg – Air flow / ventilation rate (L min^{-1})	T (40, 50, 60)
KoLA – Overall mass coefficient of each THM (L min^{-1})	TCM: 7.4, BDCM: 5.9, DBCM: 4.6, TBM: 3.7
Er – Absorption efficiency of THMs through the respiratory system (%)	T (0.7, 0.77, 0.84)
R – Breathing rate (m^3 min^{-1})	T (0.012, 0.014, 0.016)
F – Showering frequency (events day^{-1})	T (0.72, 0.74, 0.76)
EF – Exposure frequency (days $year^{-1}$)	T (300, 330, 365)
ED – Exposure duration (year)	Female: T (67, 72, 77) Male: T (65, 70, 75)
BW – Bodyweight (kg)	Female: T (50, 55, 60) Male: T (60, 65, 70)
AT – Averaging time (day)	Female: T (24455, 26280, 28105) Male: T (23725, 25550, 27375)
IR – Ingestion rate (L day^{-1})	T (1, 2, 3)
SA – Skin surface area (m^2)	$(4BW+7) / (BW+90)$
Pd – Permeability of THMs through skin (m min^{-1})	T (0.0000267, 0.00003, 0.000035)
T – water temperature (°C)	Cold: T (10, 15, 20) Hot: T (35, 40, 45)

Parameters	Distribution and values
RfD – Reference dose (mg kg^{-1} day^{-1})	
Trichloromethane	Oral – 0.01, Dermal – 0.002
Bromodichloromethane	0.02
Dibromochloromethane	0.02
Tribromomethane	0.02

Results And Discussion

THM concentration at consumer points

The water distribution network of the study area was served mainly by a conventional water treatment plant (WTP) which is situated within few kilometers of sampling locations. The WTP was being fed by a river and few deep wells, and the treated water was stored in various overhead tanks before distribution to most of the sampling locations. Few deep wells within the university campus were either feeding those overhead tanks with chlorination as the only treatment process -bypassing the WTP- or were used entirely for a hall of residence after passing through an in-house treatment unit of pressure filtration followed by chlorination.

THMs were observed at 18 out of 20 sampling stations at concentrations less than the maximum contamination levels (MCL = 80 µg L^{-1}) recommended by the USEPA (Table 3) for drinking water. As shown in Table 3, the statistical distribution of each THM was identified by considering each one of the triplicate samples to meet the criteria for the number of samples needed for distribution identification. The two sampling locations which were devoid of any THMs were found to have zero free and total residual chlorine, indicating that these two halls were served by in-house deep wells and were not disinfected before supply. Total THM (TTHM) at all locations varied between 0.51 µg L^{-1} to 68.91 µg L^{-1} with a mean of 17.65 ± 11.43 µg L^{-1}. This amount is comparatively less than what has been observed in other parts of India, including in the same state where the current study was carried out where TTHMs at a WTP were found as high as 594 µg L^{-1} (Mishra et al., 2014). It needs to be noted that, the previous studies from India either considered THM formation potential after laboratory chlorination as TTHM concentration or the samples for analysis were collected from the WTPs (Basu et al., 2011; Padhi et al., 2019a; Tak and Kumar, 2017). Formation potential represents the maximum THMs that can be formed by a water sample in a laboratory and in real-life, they might not be occurring at the same magnitude at the consumer points. THMs tend to degrade or transform to other classes of DBPs over time or they even get formed when they are in the distribution line or in the storage tank (Yu et al., 2019).

To understand the actual case of THMs at consumer points, samples from taps of households need to be collected and analyzed as in the case of the present study. Although such studies are available from

different parts of the world (Cotruvo and Amato, 2019; Wang et al., 2019), India lacks information about THM concentration at consumer points. A close comparison to the present study is a DBP survey from Rajasthan by Furst et al (Furst et al., 2018) in which they analyzed distribution system samples from storage tank taps for 24 DBP classes. A TTHM concentration in the range of 35–99 μg L^{-1} was observed in their study, which is larger than what was observed in the present study.

Table 3
THM concentrations and their distribution in tap water and heated shower water.

THM compound	Average concentration (μg L^{-1}) and distribution	
	Normal tap water	After mixing with heated water
Trichloromethane	3 – Parameter Weibull, Shape: 1.438, scale: 5.595, threshold: 0.3189	3 – Parameter Weibull, Shape: 1.440, scale: 5.832, threshold: 0.3318
Bromodichloromethane	Normal, Mean: 8.415, SD: 5.332	Normal, Mean: 8.710, SD: 5.527
Dibromochloromethane	Normal, Mean: 10.76, SD: 6.106	Normal, Mean: 11.20, SD: 6.308
Tribromomethane	Normal, Mean: 3.243, SD: 1.662	Normal, Mean: 3.365, SD: 1.725

THM production in heated water

The THM growth rate(*k*) determined using Eq. 15 was found to exponentially increasing with increasing temperature (Fig. 1). There was a slight increase in the THM formation in the mixed water for all 4 compounds. 50,000 random realizations were generated for the THM concentration in the heated water (*Chw*) (Table 3) using the statistical parameters of THM concentration in the normal tap water (*Cw*) in Eqs. 14 and 15, and the result was used in the CDI and HI assessments. The distribution identification test of *Chw* data showed the best-fit statistical distributions of each THMs. The AD values for each of the best-fit distributions were 0.329 ($p > 0.5$), 0.324 ($p = 0.525$), 0.729 ($p = 0.057$), and 0.558 ($p = 0.149$) respectively for TCM, BDCM, DBCM, and TBM.

CDI and HQs through ingestion and dermal routes

The Monte Carlo simulation for CDI assessment resulted in 50,000 realizations of the daily intakes of THMs for females and males. The minimum-maximum range of CDI for ingestion of females was 1.85E-06–3.36E-03 mg kg^{-1} day^{-1} with a median of 9.51E-04 mg kg^{-1} day^{-1} and that of males was 2.16E-06–2.71E-03 mg kg^{-1} day^{-1} with a median value of 7.69E-04 mg kg^{-1} day^{-1}. In the case of dermal

absorption females had a CDI of 2.05E-07–5.63E-04 mg kg^{-1} day^{-1} with a median of 1.58E-04 mg kg^{-1} day^{-1} and males had a CDI of 5.06E-07–5.03E-04 mg kg^{-1} day^{-1} with a median of 1.48E-04 mg kg^{-1} day^{-1}. For both exposure routes, DBCM had the highest contribution to CDI as it had the highest concentration among all four THMs. The results of HQ assessment for individual THMs through each of the exposure routes are summarised in Table 4. As shown in the table, females had a higher hazard rate than males through all routes. This can be attributed to the lower body weight (*BW*) and higher exposure duration (*ED*) (life expectancy) compared to that of males.

Table 4
Average hazard quotients of individual THMs through various exposure routes.

	Compound	Ingestion	Dermal	Inhalation 1	Inhalation 5	Inhalation 10
Female	TCM	1.74E-02	1.45E-02	3.03E-06	5.88E-06	6.06E-06
	BDCM	1.52E-02	2.55E-03	2.39E-06	4.63E-06	4.78E-06
	DBCM	1.96E-02	3.26E-03	2.61E-06	5.06E-06	5.22E-06
	TBM	5.88E-03	9.86E-04	7.01E-07	1.36E-06	1.40E-06
Male	TCM	1.40E-02	1.36E-02	2.58E-06	4.99E-06	5.15E-06
	BDCM	1.24E-02	2.38E-03	2.05E-06	3.96E-06	4.09E-06
	DBCM	1.58E-02	3.05E-03	2.21E-06	4.28E-06	4.41E-06
	TBM	4.79E-03	9.19E-04	5.93E-07	1.15E-06	1.18E-06

CDI and HI through inhalation during successive showers

The CDI and the HI for 10 successive showering events for both females and males are displayed in Fig. 2 and Fig. 3, respectively. In the case of females, the CDIs of TCM, BDCM, DBCM, and TBM for the first shower were 3.03E-08 ± 2.83E-08, 4.78E-08 ± 3.90E-08, 5.23E-08 ± 3.90E-08, and 1.40E-08 ± 9.85E-09 which all increased 1.94 times to 5th and 2 times to 10th showers (Fig. 2a). The same increase rate was observed for the CDIs of males which were 2.58E-08 ± 2.40E-08 for TCM, 4.09E-08 ± 3.33E-08 for BDCM, 4.41E-08 ± 3.30E-08 for DBCM, and 1.19E-08 ± 8.31E-09 for TBM for the first showers (Fig. 3a). For all showering events, the CDIs were in the order of DBCM > BDCM > TCM > TBM for both genders. Interestingly, the DBCM - CDIs of 5th and 10th showers were 7.2 and 7.4 times higher than the TBM-CDI, 3.3 and 3.4 times higher than the TCM-CDI, and 2.0 and 2.1 times higher than the BDCM-CDI of the first shower. This tendency was observed for both genders. Overall, there was a significant increase in CDI up to the 5th showering event (Fig. 2a and 3a), thereafter the rate of increase was slow.

In the case of HI, the same trend CDI followed was observed as the rate of increase was exponential till the 5th shower and it slowed down consequently. The HQs of individual THMs for 1st, 5th, and 10th showers are listed in Table 4. For the first shower, the mean TCM-HI was 3.03E-06 ± 2.83E-06 and 2.58E-06 ± 2.40E-06, BDCM-HI was 2.39E-06 ± 1.95E-06 and 2.05E-06 ± 1.67E-06, DBCM-HI was 2.61E-06 ±

1.95E-06 and 2.21E-06 ± 1.65E-06, and TBM-HI was 7.01E-07 ± 4.92E-07 and 5.93E-07 ± 4.16E-07, for females (Fig. 2b) and males (Fig. 3b), respectively. The rate of increase in HI was also similar to that of CDI, i.e., the 5th and 10th showers had respectively 1.94- and 2-times higher HI than that of the first shower for all THMs. However, the order of HIs for all showering events was TCM > DBCM > BDCM > TBM for both genders. This change from DBCM as the highest CDI to TCM as the highest HI is because of the high RfD of TCM compared to DBCM. The TCM-HI of the 10th shower was 8.6 times higher than the TBM-HI of the 1st shower and 4.3 times than the 10th shower. Similarly, the TCM-HI of the 10th shower was at least 1.2 times than the BDCM-HI and at least 1.1 times than the DBCM-HI of any showering event.

Total hazard index through successive showers

The total HI was calculated for both genders by summing the HIs of each exposure routes (Fig. 4). For both genders, the order of significance of exposure route HIs to total HI was ingestion > dermal > inhalation. The inhalation HI was significantly less than that of both ingestion and dermal HIs. The HI through ingestion route for females (5.80E-02 ± 2.39E-02) and that of males (4.70E-02 ± 1.92E-02) were respectively 6642 and 6334 times higher than the inhalation-HI of the first shower, which decreased to 3324 and 3170 times by the time of the 10th shower. Similarly, the HI through the dermal route was 2.7 and 2.3 times less than the ingestion-HI for females and males, respectively.

As shown in Fig. 4, total HI was less than unity and hence the water supply under study was unlikely to cause any non-cancerous health hazard to the study population. It needs to be noted that, the main health concern regarding THMs is that they are carcinogens to humans. Thus, a cancer risk assessment study using the same CDIs calculated in the present study and cancer slope factors of each THM can reveal the cancer risk for the same water. The findings of the present study were in accordance with the observations of Chowdhury et. al (Chowdhury et al., 2020). This is the only study that had the same approach for successive showering incidences, but with a different model. They observed similar patterns in the incremental increases of CDIs as well as HIs and cancer risk for up to 9 showering events, exponential increase in the beginning, and slower rate towards the 9th event. Generally, in the studies, the HI of inhalation is left unattended either because the inhalation-CDI is less than ingestion and dermal CDIs or because of the lack of RfD values for inhalation risk (Kujlu et al., 2020; Kumari and Gupta, 2018; Mosaferi et al., 2021). However, assessing the inhalation-HI along with the other two gives a clear idea about how much it differs from them and can be used in future studies for inclusion in the database.

[a] Of 1st shower

[b] Of 5th shower

[c] Of 10th shower

Conclusion

The computational human exposure model developed in this study can be used to evaluate the effect of successive shower events for daily intakes and risk assessment. This method is useful for the case of shared shower stalls where successive events of showering can take place. The THM analysis carried out at the consumer points gave a better idea about the true exposure concentrations than the formation potential approach and the present study is the first one to address it from India. The inhalation CDI and HI of THMs was found to increase exponentially up to the 5th showering event and thereafter at a slower rate for both females and males. Out of all four THMs, DBCM contributed the highest to CDI and TCM to the total HI for both genders. The total HI was found to be less than 1, indicating the water is unlikely to have adverse non-cancerous health hazards. Even though, a cancer risk assessment using the same methodology needs to be carried out to examine the cancer risk potential of the water as THMs are proven as probable/possible carcinogens.

Declarations

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

NP: conceptualisation, design of study, THM analysis, modelling, Monte Carlo simulation, and writing – original draft; SG: design of study, supervising, and writing – review, editing, and correspondence; SC: supervising and writing – review and editing. All authors read and approved the final manuscript.

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Figures

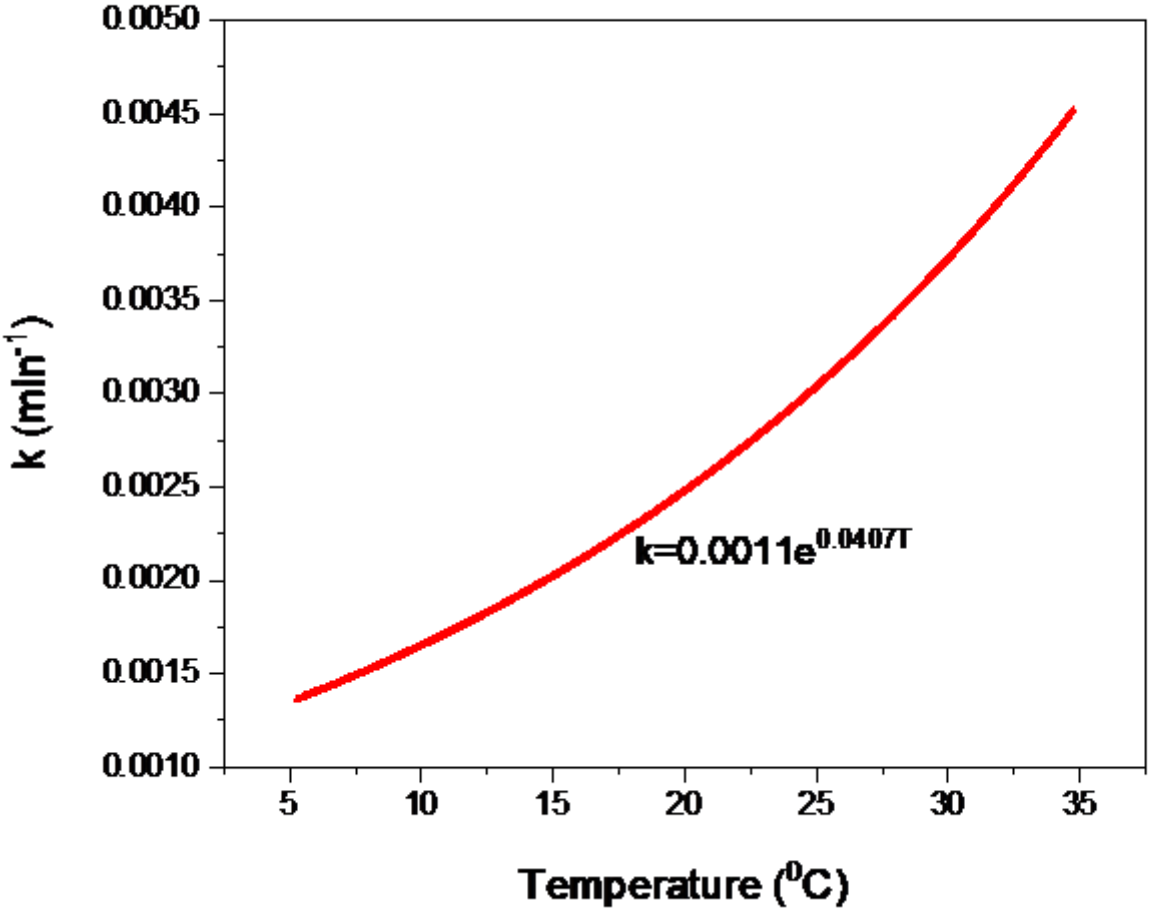

Figure 1

Effect of water temperature on THM formation in mixed shower water

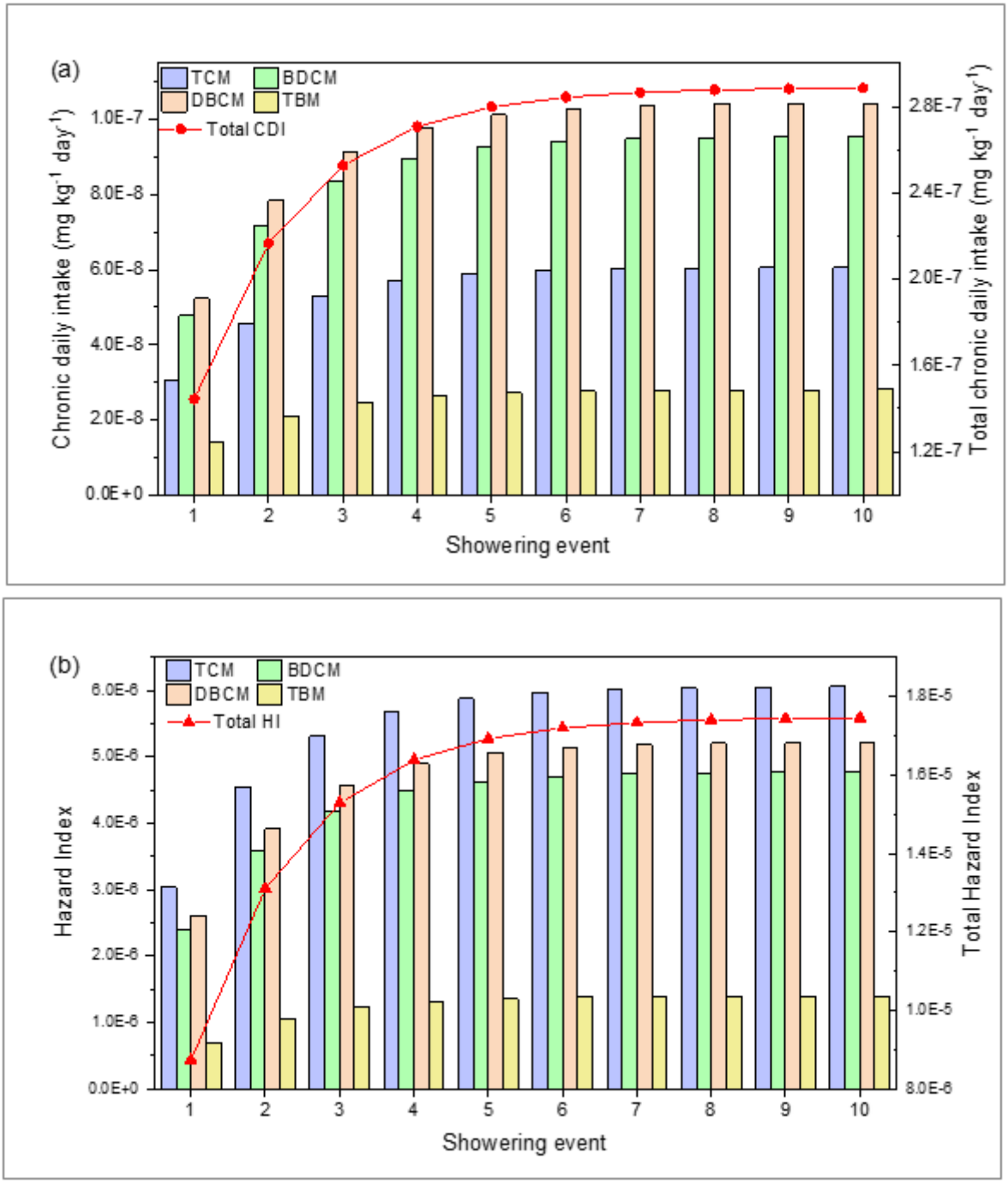

Figure 2

Incremental increase in inhalation (a) chronic daily intake and (b) hazard index for females through successive showers

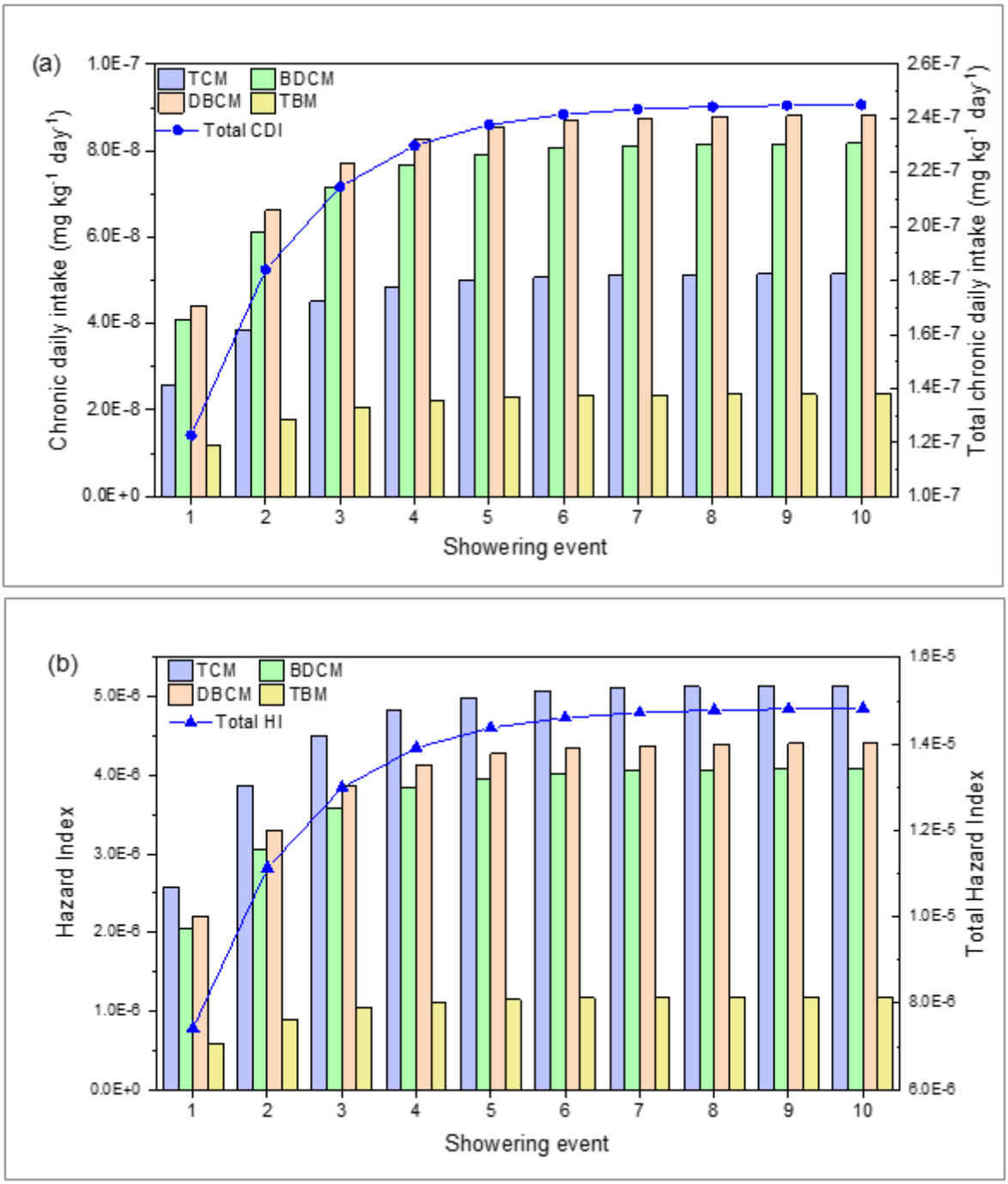

Figure 3

Incremental increase in inhalation (a) chronic daily intake and (b) hazard index for males through successive showers

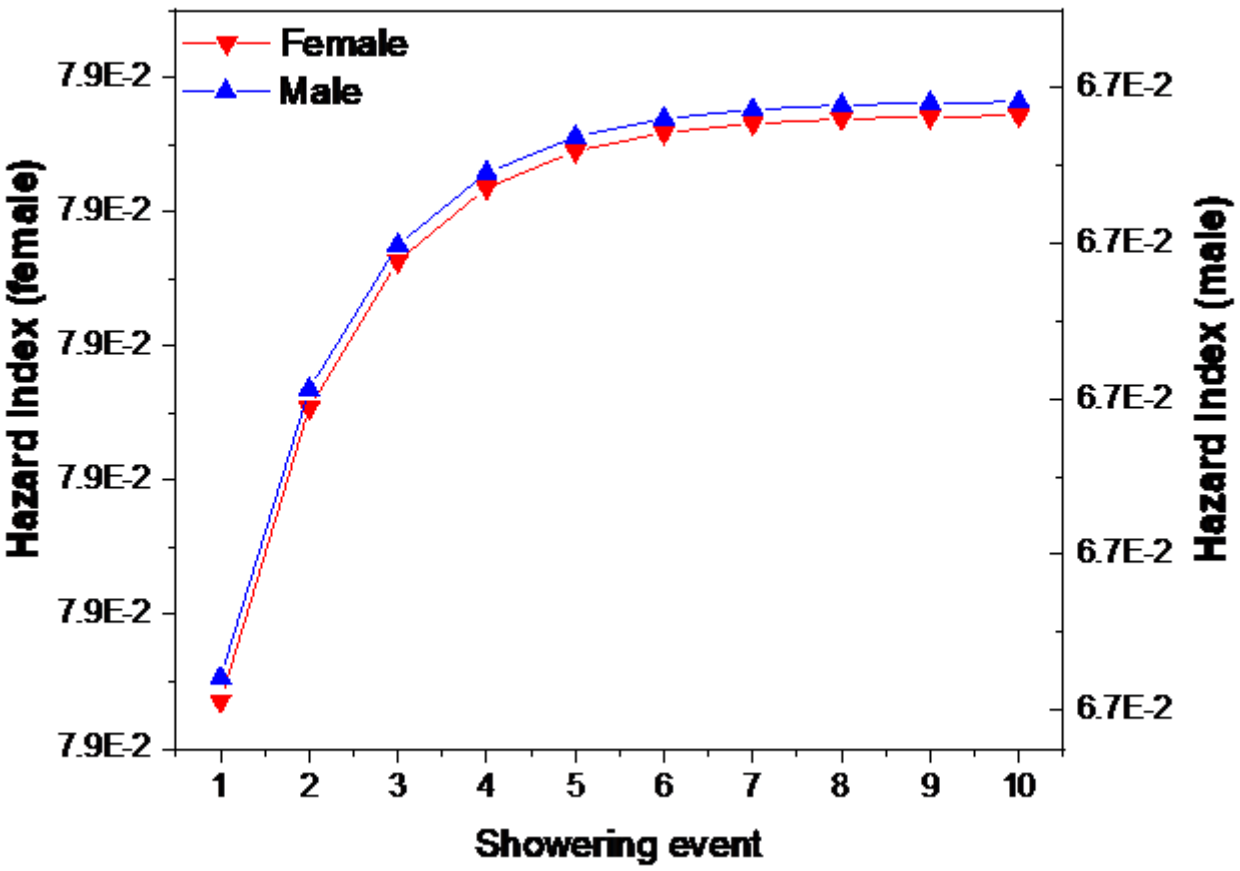

Figure 4

Total hazard index for females and males through successive showers