Trihalomethanes in urban drinking water: measuring exposures and assessing carcinogenic risk

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Abstract

Trihalomethanes (THMs) have been proven to be potentially genotoxic and mutagenic for human. The aim of this study was to characterize the THMs spatiotemporal distribution and its carcinogenic risk potential in Ardabil water distribution system. Water samples were collected over consecutive months from twenty-six points in the city of Ardabil from April 2016 to March 2017. The potential carcinogenic risk assessment of THMs was evaluated quantitatively with uncertainty assessment based on Monte-Carlo simulation technique. The results showed that the mean concentrations of bromodichloromethane, Chloroform, dibromochloromethane and Bromoform in water consumed by residents were 101.97 ± 58.51 , 85.18 ± 47.79 , 51.67 ± 29.57 and 11.89 ± 6.64 $\mu\text{g/L}$, respectively, during the sampling period. According to the result of this study, the concentrations of THMs were higher in summer in comparison with other seasons. The mean values of lifetime cancer risks for residents through ingestion, inhalation and dermal contact are 2.85×10^{-4} , 6.46×10^{-7} , and 1.26×10^{-7} , respectively. The lifetime cancer risks for residents through ingestion was found to be 285 times more than the minimum or negligible level set by US.EPA (1.0×10^{-6}) and for dermal contact and inhalation lower than the minimum or negligible level set by US.EPA. The results of the present research may contribute to inform the decision makers of drinking water supply system about the role of water quality in the health of consumers.

Keywords Carcinogenic risk assessment · Trihalomethanes · Urban drinking water · Ardabil

Introduction

The access to safe drinking water is a human right; however, the process of conventional water disinfection poses one of the major concerns in developing countries [1–3]. Disinfection is applied as the last step in the water treatment processes to protect water safety from pathogenic microorganisms [4]. The residual concentration of chlorine prevents the

consequent pollutions after treated water enters the distribution system [5]. However, when chlorine reacts with natural organic matters (NOMs) existing in water as precursor, a numerous chlorinated disinfection by-products (DBPs) will be produced including trihalomethanes (THMs) such as Chloroform, dibromochloromethane (DBCM), bromodichloromethane (BDCM), and Bromoform as well as haloacetic acids (HAAs) [3, 4, 6–9]. The THMs have been proven to be potentially genotoxic and mutagenic for human and can cause bladder cancer, spontaneous abortions, colon-rectum and brain cancers in the case of long-term exposure [3, 5, 10, 11]. THM compounds have been classified in three classes by US environmental protection agency (EPA); class B1 (possible human carcinogenic with little human data), class B2 (probable human carcinogen with sufficient animal data), and class C (possible human carcinogen) [12–14]. A concentration of 80 $\mu\text{g/L}$ is proposed by US.EPA as the maximum level of four THM species in drinking water sources [15]. However, WHO has defined that total THM concentration must not exceed 100 $\mu\text{g/L}$ [8, 16]. Several parameters can

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influence THM formation in drinking water distribution system such as NOMs concentration, concentration of bromide ion (especially in groundwater resources), pH, temperature, seasonal variation and contact time of water in distribution system [17–19]. The levels of these variables differ seasonally and spatially, and thus drinking water consumers may receive various amounts of THMs. It is assumed that human exposure to DBPs and THMs in municipal drinking water can be occurred through ingestion (drinking), inhalation and dermal contact [20].

In recent years, more attention has been paid to measurement of toxic material concentrations and assessment the carcinogenic risk associated with exposure to THMs from public water supplies [21–25]. Several studies have been monitored the concentration of THMs in drinking water supply and reported different range of concentration such as 274–511 µg/l. Pardakhti et al. measured the trihalomethane from tap water in city of Tehran within 7 months and the average THMs concentration was between 0.81 to 9.0 µg/L [14]. Chowdhury et al. reported that inhalation and dermal contact contributed 25–60% of total exposure to THMs from municipal drinking water for individuals who live in Toronto [5].

Human Risk assessment is usually estimated in terms of cancer and non-cancer risks to human health [26, 27]. Although ingestion has been thought to be the main pathway to which people are exposed, THMs are kind of volatile organic compounds and, therefore, the risk associated with THMs through dermal contact and inhalation cannot be ignored. During showering, the water is heated up and reaches temperature 35–45 °C, which make situations possible to increase THMs vaporizing into the shower air. Therefore, inhalation and dermal contact are believed the major exposure pathways to THMs during showering. To the best of authors' knowledge and literature review, no study has been conducted to monitor THMs in the drinking water supplies of Ardabil. Ardabil is one of the cities in northwest of Iran, which annually snow and rain precipitation provides of suitable water saving in this area. Therefore, it is necessary to conduct such relevant research in order to monitor the THMs concentration in water distribution system and to estimate the related risk assessment of THMs. This study was developed to investigate the seasonal and spatial variations of THMs concentration in tap waters passing through water distribution system in Ardabil. Additionally, the lifetime cancer risks from exposure to THMs through multiple ways including oral ingestion, dermal contact, and inhalation were estimated using a probabilistic approach.

Materials and methods

Sample collection

The drinking water supply in this area often comes from two basic water resources. Groundwater sources (wells) and the

Yamchi dam as shown in the Fig. 1. The wells are located in the east of the city and the dam in the southwest of Ardabil and provide 25% and 75% of the city drinking water, respectively. Water samples were collected from 26 points of Ardabil water distribution system and water resources (wells and dam) (Figs. 1 and 2). In this study the concentrations of THMs in drinking water distribution, wells and dam were measured. Sampling at the dam site was carried out from the dam water reservoir (from a depth of 2 m of dam surface and outlet point toward water treatment plant), also other sampling sites were near the dam before entering the raw water to the water treatment plant. The influent and effluent of water treatment plant were selected for sampling in this unit. 2 samples of well water were also provided and 20 samples were collected from water distribution system.

In this study, a standard questionnaire was used for gathering the required data from households. The questionnaire included several required parameters such as the amount of water consumption for drinking (water, tea, coffee and etc.) by members of each family, and frequent and duration of exposure with water in bath and other washing ways. The samples were selected from households in which water was used from distribution system. Random systematic sampling was used for electing the households. 1380 families were precipitated in this study to complete the questionnaire.

The treatment processes included coagulation, flocculation-sedimentation, sand filtration and chlorination in the water treatment plant of Ardabil. Seasonally samples (totally 104 samples) were taken from 26 different districts of Ardabil. Before sampling, 15 mg sodium thiosulfate was added to a clear 150-mL glass to quench any residual chlorine reaction. Water samples were directly collected from tap waters; at first water was discarded for several minutes ensuring that the water samples were collected from the main pipe. The samples were immediately transferred to laboratory and preserved at 4 °C for further analysis. Free chlorine residual; temperature and pH were measured at the sites concurrently with sample collection.

Analytical methods

THMs concentration measurement was performed based on the EPA Method 551.1 [28]. The concentration of individual THMs was measured by gas chromatography (Agilent) which was equipped with an electron capture detector and HP-5 capillary column (30 m × 0.32 mm × 0.25 µm). Oven temperature regime for gas chromatography was programmed for 280 °C with the rate of 8 °C / min [14]. With this method, the limit of detection (LOD) for different kinds of THMs (chloroform, BDCM, DBCM, and bromoform) was determined to be 0.02 µg/L. Total organic carbon (TOC) was also measured using a TOC analyzer (Shimadzu- TOC-VCSH model).

Fig. 1 Location of sampling sites

Statistical analysis

Statistical analyses were performed using SPSS (version 22). Kruskal–Wallis tests were used ($P < 0.05$) in order to evaluate the mean concentrations of THMs variations (depending upon seasons). Sensitivity and uncertainty analysis were performed using Oracle® Crystal Ball software.

Exposure and risk assessment

Based on the THMs concentrations obtained from different areas of Ardabil water distribution system, human health risk assessment associated with THMs was estimated via different exposure routes (ingestion, inhalation and dermal). The lifetime cancer risk (LTCR) and the non-carcinogenic hazard of all four THMs through ingestion, dermal contact and inhalation pathways were calculated to estimate the human health impacts. The LTCR was calculated by multiplication of chronic daily intake (CDI) of trihalomethane by cancer slope factor (CSF) which is determined according to US EPA Integrated

Risk Information System (IRIS) [29]. The equation for LTCR is as follows:

$$\text{LTCR} = \text{CDI} \times \text{CSF} \quad (1)$$

According to the eq. 1, higher CSF (mg/kg/day) causes the higher values of LTCR and consequently higher mortality and morbidity resulting from exposure to THMs in life time. The CDI of THMs through different pathways can be estimated by the following equations:

$$\text{LADD}_{\text{ing}}(\text{mg/kg.day}) = (C_w \times \text{IR} \times \text{EF} \times \text{ED} \times \text{CF}) / (\text{BW} \times \text{AT}) \quad (2)$$

$$\begin{aligned} \text{LADD}_{\text{der}}(\text{mg/kg.day}) \\ = (C_w \times \text{As} \times \text{Pd} \times t \times F \times \text{EF} \times \text{ED} \times \text{CF}) / (\text{BW} \times \text{AT}) \end{aligned} \quad (3)$$

$$\begin{aligned} \text{LADD}_{\text{inh}}(\text{mg/kg.day}) \\ = (E_r \times C_a \times R \times t \times F \times \text{EF} \times \text{ED} \times \text{CF}) / (\text{BW} \times \text{AT}) \end{aligned} \quad (4)$$

Fig. 2 Annually average of THMs concentration distribution in the city of Ardabil

Where $LADD_{ing}$, $LADD_{inh}$, $LADD_{der}$ are intake values for ingestion, inhalation and dermal pathways (mg/kg/day), respectively. The description and the values of all corresponding parameters are listed in Table 1. C_a is the concentration of THMs in the air of shower and is calculated using the following equation:

$$C_a = Q_w \times P_v \times C_w \times (1 - e^{-K_a \times t}) / K_a \times V \quad (5)$$

The parameters of this equation are presented in Table 1.

In addition, the standard values for adults such as ingestion rate and exposure frequency were obtained through a questionnaire, in which voluntary people of the city participated (more than 1000 people).

A total lifetime cancer risk of different types of THMs through multi-pathway exposure was calculated with the following equations.

$$\begin{aligned} \text{Total Risk} = & (CDI_{Ingestion} \times CSF_{Oral}) \\ & + (CDI_{Inhalation} \times CSF_{inhalation}) \\ & + (CDI_{Dermal} \times CSF_{Oral}) \end{aligned} \quad (6)$$

An uncertainty analysis was performed to justify the impact of some variables on the uncertainty of calculated

carcinogenic and non-carcinogenic risk. In the present study, the Monte-Carlo simulation technique using Oracle® Crystal Ball software was applied for the uncertainty analysis [14]. The simulation for 1000 trials, were run to obtain a representative risk distribution.

Results and discussion

Concentration of THMs in water distribution system

Each samples station was indicated by S and numbered based on sampling station. The water supply of Ardabil city is feeding from different resources. According to Fig. 2 the drinking water in one of the city's areas (S3) is only provided from the wells, and the extra water returned to the big reservoir of the city. Another resource of drinking water is treated water of dam where it also transferred and saved in the big reservoirs of the city. According to the results the amount of THM, in the dam and before entering to the treatment plant was lower and acceptable (Table 2).

However, in the outlet of the water treatment plant, its concentration was increased considerably. This phenomenon has been predicted that at the end of the water treatment plant, by adding chlorine, natural organic

Table 1 Input parameters for exposure assessment

Input parameters	Unit	Statistical distribution	Values	Reference
THMs in tap water (C_w)	$\mu\text{g/L}$	Lognormal	See Table 4	This study
Ingestion rate (IR)	L/day	Lognormal	1.52	This study
Exposure frequency (EF)	day/year	–	365	This study
Exposure duration (ED)	year	–	70	(4)
Body weight (BW)	kg	–	71	(5)
Averaging time (AT)	day	–	25,550	(4)
Conversion factor (CF)	$\mu\text{g/mg}$	–	0.001	(5)
Area of skin surface (A_s)	m^2	–	1.82	(5)
Permeability coefficient through dermal (P_d)	m/min	–	3.06×10^{-5}	(5)
Absorption efficiency in alveoli (E_r)	percent	–	8.76	(5)
Inhalation rate (R)	m^3/min	–	0.014	(5)
Water flow rate (Q_w)	L/min	–	5	(4)
Shower frequency (F)	shower/day	Triangular	Min:0.2 Likeliest: 1.0 Max: 3	This study
Shower duration (t)	min/shower	Triangular	Min:1.0 Likeliest: 3.0 Max: 8.0	This study
Shower stall volume (V)	m^3	Triangular	Min:1.67 Likeliest: 2 Max: 2.25	(5)
Air change(K_a)	(ACM)	Triangular	Min:0.018 Likeliest: 0.021 Max: 0.023	(5)
THMs transformation rate from water to air phase (P_v)	(%)	Triangular	Min:7.66 Likeliest: 8.76 Max: 9.86	(5)
Dimensionless Henry's law constants (H) at 40 °C	(CHCl ₃) (CHCl ₂ Br) (CHClBr ₂) (CHBr ₃) (CHCl ₃) (CHCl ₂ Br) (CHClBr ₂) (CHBr ₃) (CHCl ₃) (CHCl ₂ Br) (CHClBr ₂) (CHBr ₃) (CHCl ₃) (CHCl ₂ Br) (CHClBr ₂) (CHBr ₃) (CHCl ₃) (CHCl ₂ Br) (CHClBr ₂) (CHBr ₃)	–	0.25 0.124 0.0526 0.0501 7.4 5.9 4.6 3.7 0.031 0.062 0.084 0.0079 8.05×10^{-5} 0.13 0.095 0.00385	(4)
Overall mass transfer coefficient (KOLA)	(L/min)	–		(4)
Cancer risk factor for ingestion and dermal exposure	mg/ kg. day	–		(4)
Cancer risk factor for inhalation exposure	mg/ kg. day	–		(4)

matter may react with chlorine and increase the amount of THM in the water. In this study statistical analyzes that provided in Table 3 showed the significant relation between Cl and THMs forming. This is clear that a component of chlorine and natural organic matter in the water solution react together and make THMs formation; in the absence of any of these, THMs formation is not possible without of these precursors. Chlorine plays main roll in forming of the THM that in end of water treatment is added to water to protection of water safety from microorganisms. The amount of THM was low in both before and after chlorination in samples of wells. The reason of low concentration of THM in wells water sources was due to low concentration of NOM in underground water.

Figure 3 illustrates trend of THM concentration in different seasons in which summer concentration of THM was maximum compared to other seasons. The trend of TOC concentration was also similar to the measured THMs concentration. TOC is an index that indicates the amount of NOMs in water or wastewater media. The relation of NOMs and chlorine is clear as precursors of THM forming.

As shown in Fig. 2, the THMs concentration at the beginning of the water distribution path (S2 and S4) is low. However, with increasing distance from the center of the starting point of water distribution, the amount of THMs increased. This can be due to the creation of a sufficient time for chlorine to react with the natural organic matter on this long path, and therefore, the amount of THM in the pipes increases with the increase of pipe length. In fact, with increasing distance from center to city's margin, THM becomes even more. As seen in Fig. 2 the concentration of THM in S3 is lower compared to the other areas, because the source of drinking water of this area is provided individually from wells, with low concentrations of THMs.

Table 3 shows the effects of basic variables (temperature, pH, and Cl) in THMs concentration. According to multivariate linear regression results, there was a statistically significant relation between temperature, pH, Cl and THM forming ($p < 0.05$). The increasing in temperature, pH and Cl contents resulted in increasing the THM concentration. According to Table 3 the maximum B standardized coefficients were allocated to the temperature. Temperature has important role in THM formation. The summer season has high temperature and in this season growth of algae is higher than other seasons in dam reservoirs. Algae growing depends on sun light and temperature. Algae produce NOMs as one of the precursors of THM formation in aqueous solution [30]. Several studies have shown similar results according to the relation of these parameters and THMs. Liang et al. reported in their study that increasing pH, makes an increase in THMs formation [30]. The results of this study showed also the positive association between THM and pH with B standardized coefficients of 0.17.

The concentrations of THMs in Ardabil water distribution system during the sampling period are summarized in Table 4. The concentration of bromodichloromethane was the highest among the four kinds of THMs with concentration of $101.97 \pm 76.08 \mu\text{g/L}$, followed by chloroform, dibromochloromethane, and bromoform with concentrations of $85.18.97 \pm 66.65 \mu\text{g/L}$, $51.67 \pm 37.91 \mu\text{g/L}$, and $11.88 \pm 8.29 \mu\text{g/L}$, respectively during the sampling period. All THMs, were detected lower than (LOD = $0.02 \mu\text{g/L}$) in some samples, except chloroform. As shown in Table 4, the total THMs concentration in Ardabil water distribution system ranges from $1.41 \mu\text{g/L}$ to $574.21 \mu\text{g/L}$, so that it is much higher than concentration recommended by WHO ($100 \mu\text{g/L}$) [16] and US.EPA ($80 \mu\text{g/L}$) for drinking water in some cases [15].

The concentrations of total THMs in water distribution system of Ardabil are much higher compared to

Table 2 Concentration of THMs based on seasons and sampling points

	wells		Dam		Water treatment plant		Water supply system
	Before chlorination	After chlorination	Dam	Dam effluent	Water treatment influent	Water treatment effluent	
Spring	2.78	2.86	3.76	4.29	4.52	265.19	396.43
summer	3.38	3.14	4.59	4.81	4.76	319.51	443.14
autumn	3.26	3.67	4.46	4.12	3.87	234.07	328.05
winter	1.87	2.35	2.59	1.41	1.93	63.49	88.45
Annual average	2.82	3.01	3.85	3.66	3.77	220.57	314.02

Table 3 Association between THM and temperature, pH, and Cl using multivariate linear regression

univariate					Multivariate			
Variable	B	B Standardized Coefficients	<i>P</i> value	R Square	B	B Standardized Coefficients	<i>P</i> value	R Square
Temperature	21.658	0.821	<0.0001	0.674	18.02	0.683	<0.0001	0.766
pH	940.136	0.534	<0.0001	0.285	300.333	0.170	<0.0001	
Cl ⁻	750.33	0.589	<0.0001	0.347	247.057	0.194	0.017	

other locations in Iran. Pardakhti et al. measured the THMs in water drinking of Tehran, the capital of Iran, and found that the highest concentration of THMs was 19.5 µg/L [14]. They reported that Chloroform had the highest concentration among the kinds of THM, followed by BDCM, DBCM, and bromoform. According to Wang's study [31] brominated-THM species were detected in most of the samples in Taipei indicated that the THMs in water increase with the raising concentrations of the organic matter. The main supply source of Ardabil drinking water is from the dam that stores the upstream river water. Algae in this dam are one of the sources of natural organic matter presenting in water. Several studies were conducted for monitoring of THMs concentration in different water sources. In a study by Kumari et al. THMs concentration was found to be varied in the range of 274–511 µg/l. Chloroform was the most dominant THMs followed by bromodichloromethane, and dibromochloromethane [29]. Other study showed that the most dominant THM compounds are chloroform, bromodichloromethane, and dibromochloromethane in Istanbul tap water [25]. Results of Hassanis' study showed that the four components of the THMS observed in total samples and chloroform was the major component in the water sample, but CHCl₃ and

TTHM concentrations did not exceed the maximum permissible value of 100 µg/L for TTHM of the USEPA standard [32].

The distribution of different kinds of THMs in 26 samples measured during the sampling period and different seasons are presented in Table 4. The values of THMs were found to be maximum in summer (353.96 µg/L), however there was a decreasing trend for THMs values in the seasons of spring, autumn and winter (315.85, 262.10 and 70.87 µg/L), respectively. It is important to note that the THMs concentration in spring, summer and autumn were higher than the concentration recommended by US.EPA (80 µg/L) while

Fig. 3 Trend of mean TOC and THMs concentration during the sampling**Table 4** Concentrations of THMs in Ardabil water distribution system

Season	THMs	Unit	Mean	Standard deviation	Range
Spring	Chloroform	µg/L	107.60	60.90	2.53–164.14
	BDCM	µg/L	129.31	74.77	0.11–209.38
	DBCM	µg/L	63.93	37.76	0.02–99.30
	Bromoform	µg/L	15.04	8.51	0.05–23.17
	Total	µg/L	315.85	180.68	2.78–487.58
Summer	Chloroform	µg/L	128.30	72.72	2.75–212.25
	BDCM	µg/L	140.55	80.60	0.02–228.87
	DBCM	µg/L	69.52	39.55	0.02–99.30
	Bromoform	µg/L	15.61	8.79	0.02–24.01
	Total	µg/L	353.96	201.33	3.14–574.21
Autumn	Chloroform	µg/L	85.22	47.55	2.96–135.96
	BDCM	µg/L	107.42	61.68	0.03–170.06
	DBCM	µg/L	57.15	32.94	0.02–99.30
	Bromoform	µg/L	12.30	6.86	0.04–21.15
	Total	µg/L	262.10	148.78	3.26–414.79
Winter	Chloroform	µg/L	19.59	10.53	1.13–31.80
	BDCM	µg/L	30.59	17.50	0.02–46.87
	DBCM	µg/L	16.09	9.33	0.02–99.30
	Bromoform	µg/L	4.60	2.57	0.04–7.94
	Total	µg/L	70.87	39.33	1.41–106.76

this value dropped to lower than 80 µg/L in winter. The highest concentration of THMs occurred in spring followed by summer and this phenomenon might be attributed to high temperature within these two first seasons of a year. Other reason can be explained by turn over phenomena in dam that causes thermal stratification in dam mixing materials in bottom with water in the upper level of the dam. These materials may contain organic gradients and after passing through the water treatment processes react with chlorine in higher concentration. Spring, summer and autumn are the seasons that turn over phenomena is more likely to be happened. According to statistical analysis illustrated in Table 4, there was a significant difference between THMs concentrations within four seasons (P value<0.05).

Carcinogenic risk assessment

In this study, the lifetime cancer risk exposure to THMs in water distribution system and consumed by residents in Ardabil was estimated based on the US.EPA guidelines for carcinogenic risk assessment [26]. The distribution of lifetime cancer risks of THMs within Ardabil water distribution system by consuming and exposure to water through multi-ways: ingestion, dermal contact and inhalation were simulated and are summarized in Table 5.

Inhalation pathway

As shown in Table 5, the mean value of lifetime cancer risks of THMs for residents through inhalation is 6.46×10^{-7} , which is lower than the minimum or negligible level set by US.EPA (1.0×10^{-6}) [26]. The LTCR calculated in the present research for inhalation of THMs is lower than findings resulted in different areas such as Seoul, Korea (7.35×10^{-5}) [6] and Islamabad, Pakistan (1.24×10^{-4}) [1]. In the Pardakhti et al. study, the lifetime cancer risk assessment for total THMs showed that inhalation was the most important route of entry followed by ingestion and dermal exposure for the city of Tehran [14]. The percentage of LTCR for each type of THM compounds are summarized in Table 5. Inhalation allocation was 72.8%, 26.9%, 0.25% and 0.04%, for BDCM, DBCM, Chloroform, and Bromoform, respectively. Figure 4 shows the distribution of the total cancer incidence through inhalation exposure to different kinds of THMs compounds. In the WHO guideline for drinking water, acceptable lifetime cancer incidence rate is 10^{-6} .

Skin pathway

As provided in Table 5, the mean value of lifetime cancer risks for residents through dermal contact is 1.26×10^{-7} , which is lower than the minimum or negligible level set by USEPA (1.0×10^{-6}) [26]. The LTCR calculated in this study for dermal contact seems to be higher than the results from studies in other areas of Iran [14]. The LTCR calculated for dermal contact was different in Seoul, Korea (3.63×10^{-6}) [6], Tehran (1.19×10^{-7}) [14] and Islamabad, Pakistan (2.0×10^{-4}) [22]. The result of present study showed that The LTCR calculated for dermal contact was higher than Tehran (1.19×10^{-7}) (15). As summarized in Table 5, dermal contact allocation was 48.2%, 32.1%, 19% and 0.7%, for BDCM, DBCM, Chloroform, and Bromoform, respectively. Figure 5 shows the distribution of total cancer incidence through dermal contact for in four THMs compounds.

Ingestion pathway

Table 5 provides the mean value of lifetime cancer risks for residents through ingestion that is 2.85×10^{-4} , and is 285 times higher than the minimum or negligible level set by USEPA (1.0×10^{-6}). The LTCR calculated in the present research for ingestion is much higher than findings comparison with other area of world such as Seoul, Korea (7.23×10^{-6}) [6] and Islamabad, Pakistan (5.76×10^{-4}) [22] and Tehran (1.90×10^{-7}) [14], however it was lower than Islamabad, Pakistan (5.76×10^{-4}) (22). As summarized in Table 5, the percentage of LTCR each THMs compound through ingestion was 47.6%, 32.2%, 19.5%, and 0.7% for BDCM, DBCM, Chloroform, and Bromoform, respectively. Figure 6 shows the distribution of total cancer incidence through ingestion exposure to the four THMs compounds.

Total carcinogenic risk assessment

The mean values of lifetime cancer risks for residents through ingestion, dermal contact and inhalation are 11.05×10^{-2} , 3.05×10^{-7} , and 5.46×10^{-4} , respectively. The lifetime cancer risks for residents through ingestion was found to be 285 times more than the minimum or negligible level set by US.EPA (1.0×10^{-6}) and for dermal contact and inhalation lower than the minimum or negligible level set by US.EPA. As shown in Table 5, the percentage contribution of ingestion, inhalation and dermal contact to total cancer risks were 99.73%, 0.23%, and 0.05%, respectively. The results indicated that the major source of risk was ingestion way followed by inhalation and dermal contact. The dominance of ingestion for cancer risk occurrence are consistence with other studies [5] and is in disagreement with the study conducted in Tehran [14] that considered inhalation with highest contribution for cancer risk arising from THMs. The results of the risk cancer percentage

Table 5 Lifetime cancer risk of TTHMs through multi-routes in water distribution system

THMs species	Exposure route														
	Ingestion			Dermal contact			Inhalation								
	Mean	SD	10th	50th	90th	Mean	SD	10th	50th	90th	Mean	SD	10th	50th	90th
Chloroform	5.55E-05	6.53E-05	7.12E-06	5.14E-05	1.36E-04	2.37E-8	4.32E-8	1.44E-9	1.19E-8	6.75E-8	2.42E-10	2.88E-10	5.76E-11	2.04E-10	5.94E-10
BDCM	1.35E-04	1.50E-04	2.12E-05	1.26E-04	3.23E-04	6.02E-8	1.01E-7	4.84E-9	3.06E-8	1.67E-7	4.74E-7	5.06E-7	1.30E-7	4.00E-7	1.09E-6
DBCM	9.14E-5	9.86E-5	1.73E-5	8.39E-5	2.14E-4	4.01E-8	6.51E-8	3.55E-9	2.09E-8	1.08E-7	1.75E-7	1.83E-7	4.99E-8	1.47E-7	4.08E-7
Bromoform	1.98E-06	2.01E-06	4.17E-07	1.85E-06	4.51E-06	8.59E-10	1.45E-9	8.28E-11	4.36E-10	2.33E-9	1.62E-9	1.65E-9	4.68E-10	1.35E-9	3.74E-9
THMs	2.85E-4	2.30E-4	9.97E-5	2.63E-4	5.80E-4	1.26E-7	1.08E-7	4.33E-8	1.10E-7	2.68E-7	6.46E-7	5.83E-7	2.14E-7	5.37E-7	1.40E-6

for each four THMs were Chloroform (12.3%), BDCM (54.2%), DBCM (28.9%), and Bromoform (4.5%). In this study, BDCM had a significant relation with total risk, which is similar to the other studies [6, 33]. In addition, as shown in Table 5, the highest risk cancer through ingestion, dermal contact and inhalation were attributed to BDCM, DBCM, Chloroform, and Bromoform, respectively, in Ardabil. These results indicate that there is a remarkable risk from THMs exposure in tap water for residents who frequently ingest the water from distribution system.

Sensitivity analysis

Sensitivity analysis was performed to investigate how variability of the outputs can be apportioned quantitatively to different sources of variability in the inputs. The results for risk assessment through inhalation show that the important parameter that affected the variable in model predictions, was the concentration of THMs and frequency of exposure with correlation coefficient ranging 0.60–0.69 and 0.19–0.25 for different kinds of THMs, respectively. These results highlight the importance of concentration of THMs in inhalation and showering media. The higher concentration of THMs, increases likely THMs risk assessment as shown in Fig. 7. Other studies may report different results. According to Kumari's study, the sensitivity analysis of THMs showed that chloroform was the major factor followed by body weight and exposure duration impacting cancer risk [29].

Figure 8 shows the sensitivity analysis for the variables influencing the uncertainty of the risk through skin pathway. As shown in this figure, the correlation coefficients for time of exposure to THMs and concentration of THMs were found to be in the range of 0.42–0.53 and 0.37–0.50 for different kinds of THMs, respectively. It seems logical that increasing the number of exposures will increase the risk of cancer. Concentration of THMs will also increase the risk of cancer risk.

Ingestion route is another way of exposure to THMs. Figure 9 shows the correlation coefficient for different parameters that influence risk assessment. According to Fig. 9, correlation coefficients of concentration of THMs and ingestion rate were in range of 0.57–0.64 and 0.36–0.43, respectively, for ingestion exposure. The concentration of THMs in water has dominant effect for this kind of exposure that increases cancer risk. According to Fig. 9, correlation coefficient of ingestion rate and concentration of THMs were in range of 0.75–0.78 and 0.57–0.61, respectively, for ingestion exposure. The amount of water consuming by individual per day has dominant effect for this kind of exposure that increases cancer risk.

Fig. 4 Probabilistic carcinogenic risk assessment of THMs through drinking water: inhalation pathway

Fig. 5 Probabilistic carcinogenic risk assessment of THMs through drinking water: skin pathway

Fig. 6 Probabilistic carcinogenic risk assessment of THMs through drinking water: ingestion pathway

Fig. 7 Sensitivity analysis of input variables contribution to the uncertainty of obtained risk through inhalation pathway

Fig. 8 Sensitivity analysis of input variables contribution to uncertainty of obtained risk through skin pathway

Fig. 9 Sensitivity analysis of input variables contribution to the uncertainty of obtained risk through ingestion pathway

Conclusion

In this study, we analyzed spatiotemporal distributions of THMs and estimated the corresponding carcinogenic risk assessment based on the method recommended for exposure to THMs through multiple-ways: ingestion, inhalation and dermal contact. High concentrations of THMs were found in drinking water which exceeded the permissible US.EPA standards of 80 µg/L for total THMs. The concentration of BDCM was the highest amongst the four different THMs with concentration of 101.97 ± 58.51 µg/L. Also, the concentrations of chloroform, DBCM, and bromoform were 85.18 ± 47.79 , 51.67 ± 29.57 , and 11.89 ± 6.64 µg/L, respectively, during the sampling period. The concentration of BDCM was higher in summer than other seasons. The seasonal changes of DBCM, chloroform and bromoform were similar.

The results showed that the maximum LTCR values for the ingestion belonged to BDCM, followed by DBCM, Chloroform and Bromoform which all values, and all were higher than the values recommended by US.EPA (1.0×10^{-6}). The risk assessment of THMs in this study showed that the most important way of exposure was ingestion. Among all factors influencing LTCR, the concentration of THMs had the highest importance for exposure. The risk assessment of THMs in this study showed that the most important way was from ingestion, followed by inhalation. Among all factors influencing LTCR, the time of exposure to THMs had the highest importance. The results of this study are applicable for understanding and controlling human health cancer risks from exposure to THMs in drinking water.

Because of the high concentration of THM in drinking water, it is recommended to use disinfection methods other than chlorination, such as ozonation. Also, to reduce the concentration of THM, the use of a granular activated carbon (GAC) column after chlorination is recommended.

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