

Reduction in health risk induced by semi-volatile organic compounds and metals in a drinking water treatment plant

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Abstract This study investigated health risk reduction in a drinking water treatment plant of Nanjing City (China) based on chemical detection of 22 semi-volatile organic compounds (SVOCs) and 24 metallic elements in source water and drinking water during 2009–2011. Chemical analysis showed that 15 SVOCs and 9 metals were present in the water. Health risk assessment revealed that hazard quotient of each pollutant and hazard index (HI) of all the detectable pollutants were below 1.00, indicating that the chemicals posed negligible non-carcinogenic risk to local residents. Benzo(a)pyrene may induce carcinogenic risk since its risk index via both oral and dermal exposure exceeded the safety level ($1.00E-6$), but other SVOCs induced no carcinogenic risk. Total HI of the SVOCs was $1.08E-3$ for the source water and $1.56E-3$ for the drinking water, suggesting that the used conventional treatment processes (coagulation/sedimentation, sand filtration and chlorine disinfection) cannot effectively reduce the non-carcinogenic risk. The source water had higher carcinogenic risk than the drinking water, but risk index of the drinking water still exceeded $1.00E-6$. This study might serve as a basis for health risk assessment of drinking water and also as a benchmark for the authorities to reduce health risk arising from trace-level hazardous pollutants.

Keywords Carcinogenic risk · Metallic elements · Non-carcinogenic risk · Semi-volatile organic compounds · Source and drinking water

Introduction

Recently, contamination of drinking water has received growing concern in developing countries along with economic development. In China, the Yangtze River provides the source of drinking water supplied for over 0.4 billion people living along the river. The Yangtze River basin generates 30–40 % of China's GDP, but annually over 30 billion tons industrial and domestic wastewater is discharged in the river; especially, at the middle and lower reaches, the river is suffering from enormous environmental deterioration due to rapid industrialization of this region. Previous studies have demonstrated that the Yangtze River has been contaminated by a variety of organic and inorganic pollutants, such as polycyclic aromatic hydrocarbons (PAHs) (Wu et al. 2011a, b; Xu et al. 2001), polychlorinated biphenyls (Sun et al. 2002), environmental endocrine disruptors (Wu et al. 2009a, b) and heavy metals (Muller et al. 2008; Wu et al. 2009a). Presence of the contaminants in the river water is possibly threatening the health of local residents.

Environmental health risk assessment models recommended by Environmental Protection Agency of the United Nations (USEPA) are generally accepted for health risk assessment and have been widely used to evaluate the potential health risk induced by the contaminants in the source water (Wu et al. 2009a) and drinking water (Wu et al. 2010). Our previous study has revealed that lab-scale biofilters are effective in pollutant removal and risk reduction in drinking water treatment, but non-carcinogenic and carcinogenic risk still cannot reached safety

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levels for finished water. It is known that the processes of coagulation/sedimentation, sand filtration and chlorine disinfection are usually used in drinking water treatment plants in China (Xie et al. 2010). However, few studies have been conducted to evaluate effects of the conventional treatment processes on the reduction in the induced health risk.

This study firstly determined the concentrations of 22 semi-volatile organic compounds (SVOCs) and 24 metallic elements in the source water and drinking water sampled from a tap water plant of Nanjing City located in the low reach of the Yangtze River during 2009–2011. Non-carcinogenic and carcinogenic health risk of each contaminant were further assessed to investigate the effect of the water treatment on health risk reduction.

Materials and methods

Sample collection

Water was sampled from the largest tap water plant (Beihou Tap Water Plant) in Nanjing City (located at 32.05°N and 118.72°E), which provides approximately 65,000 m³ drinking water per day for 50 % of the local residents in the city. Drinking water undergoes a series of treatment processes, including coagulation/sedimentation, sand filtration and chlorine disinfection before entering into pipeline distribution system. Source water was sampled from the influent of coagulation tank, and drinking water was sampled from effluent of disinfection tank.

To avoid seasonal bias, water samples were collected four times separately in March and June 2009, June 2010 and September 2011 to investigate the effect of the water treatment on health risk reduction. The information about baseline water quality of SW and DW has been described in previous studies (Chen et al. 2012; Shi et al. 2013). Water samples (10 L each) were collected in brown glass bottles, which were initially immersed in chromosulfuric acid for 24 h, then washed with deionized water eight times and finally rinsed with raw water three times. One or two drops of concentrated hydrochloric acid and 1 g ascorbic acid were added into each sample (10 L) to reach pH < 2.0 and inhibit biodegradation of the analytes. The samples were then transported to laboratory within 2 h before they went through 0.45- μ m micropore membrane filters. The filtered water samples were stored in three brown glass bottles (1 L each) at 4 °C until chemical analysis.

Analytical methods for SVOCs

In this study, 5 mL of methanol was added into 1 L of each water sample before extraction using liquid–solid

extraction method (Zhang et al. 2011; Grimmer and Munch 2013). Firstly, water went through the C18 cartridges after they were cleaned with 5 mL ethyl acetate and 5 mL methylene chloride at a maximum flow rate of 10 mL/min. The cartridges concentrated with organic compounds were then connected with the drying tube and eluted with 5 mL ethyl acetate, followed by 5 mL methylene chloride and 3 mL mixture of ethyl acetate and methylene chloride (1:1 of v/v). The extracts were concentrated with nitrogen evaporation apparatus to reach 1 mL before analysis using a DSQ II Single Quadrupole GC/MS (ThermoQuest, San Jose, CA, USA) with selected ion monitoring (SIM) mode. Quantification of individual compounds was based on comparisons of peak areas with those of the standards.

The 22 SVOCs tested in this study included: 10 PAHs [acenaphthylene (ACE), anthracene (ANT), benzo(a)anthracene (BaA), benzo(a)pyrene (BaP), benzo(b)fluoranthene (BbF), benzo(k)fluoranthene (BkF), chrysene (CHR), fluorine (FLU), phenanthrene (PHE) and pyrene (PYR)], 6 phthalate ethers (PAEs) [bis-2-ethylhexyl adipate (DEHA), bis(2-ethylhexyl) phthalate (DEHP), di-*n*-butyl phthalate (DBP), diethyl phthalate (DEP), dimethyl phthalate (DMP) and benzyl butyl phthalate (BBP)], 3 organochlorine compounds (OCCs) [hexachlorocyclopentadiene (HCCP), hexachlorobenzene (HCB) and pentachlorophenol (PCP)] and other organic pollutants [isophorone (ISO), 2,4-dinitrotoluene (2,4-DNT) and 2,6-dinitrotoluene (2,6-DNT)].

Analytical methods for metallic elements

For metal analysis, water samples (10 mL each) were collected into a metal free polyethylene bottle and digested (pH < 2) with concentrated nitric acid before they were filtered through a cellulose acetate membrane filter (0.45- μ m pore size). Dissolved 24 metallic elements, including Al, B, Ba, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, Pb, Sb, Se, Si, Sn, Sr, Ti, V and Zn, were analyzed using inductively coupled plasma–atomic emission spectroscopy (ICP-AES; Jarrell-Ash 1100, USA). The sample pretreatment and instrumental analysis was conducted following the methods recommended by the Babu et al. (2007) and Liu et al. (2011, 2012). Significant difference for the concentrations of the detectable metals between source water and drinking water was analyzed by *t* test with heteroscedasticity assumptions of the two samples.

Analytical quality controls

All reagents used in this study were of chromatographic purity grade. Reagent blanks, standard reference materials and sample replicates were applied during the chemical analysis of the SVOCs and metallic elements to assess



Table 1 Concentrations of semi-volatile organic compounds (SVOCs) in the source water (SW) and drinking water (DW) (unit: ng L⁻¹)

SVOCs	Detection limits	Mar-09		Jun-09		Jun-10		Sep-11		Mean		Range	
		SW	DW	SW	DW	SW	DW	SW	DW	SW	DW	SW	DW
PAHs													
ACE	0.5	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	6.59	N.D.	1.65	N.D.	N.D.–6.59	N.D.
ANT	0.4	6.59	3.95	6.99	3.42	44.31	63.13	23.69	22.94	20.40	23.36	6.59–44.31	3.42–63.13
BaP	0.5	48.28	13.97	2.64	3.99	4.59	N.D.	N.D.	N.D.	13.88	4.49	N.D.–48.28	N.D.–13.97
BbF	0.5	41.10	19.87	1.62	2.12	5.72	N.D.	N.D.	N.D.	12.11	5.50	N.D.–41.10	N.D.–19.87
BkF	0.5	14.11	N.D.	1.39	2.04	3.55	N.D.	N.D.	N.D.	4.76	0.51	N.D.–14.11	N.D.–2.04
CHR	0.5	28.02	20.55	2.69	2.59	4.02	2.11	N.D.	N.D.	8.68	6.31	N.D.–28.02	N.D.–20.55
PAEs													
BBP	1.0	N.D.	N.D.	N.D.	N.D.	73.4	31.95	92.11	86.66	41.38	29.65	N.D.–92.11	N.D.–86.66
DEP	0.5	5.63	4.07	6.05	5.41	N.D.	N.D.	37.54	38.99	12.31	12.12	N.D.–37.54	N.D.–38.99
DMP	0.4	22.18	25.25	28.69	24.43	123.56	106.94	49.41	49.52	55.96	51.54	22.18–123.56	24.43–106.94
OCCs													
PCP	0.5	16.78	10.48	11.36	13.93	N.D.	N.D.	N.D.	N.D.	7.03	6.10	N.D.–16.78	N.D.–13.93
HCB	0.5	6.93	1.73	2.05	1.39	N.D.	N.D.	N.D.	53.74	2.25	14.22	N.D.–6.93	N.D.–53.74
HCCP	1.0	N.D.	N.D.	N.D.	20.23	N.D.	8.77	N.D.	N.D.	N.D.	7.25	N.D.	N.D.–20.23
Others													
2,4-DNT	1.0	5.63	4.07	6.05	5.41	60.3	36.37	N.D.	N.D.	17.99	11.46	N.D.–60.3	N.D.–36.37
2,6-DNT	0.5	N.D.	N.D.	0.38	N.D.	N.D.	N.D.	N.D.	N.D.	0.09	N.D.	N.D.–0.38	N.D.
ISO	1.0	N.D.	N.D.	N.D.	1.46	10.89	13.97	51.25	16.33	15.54	7.94	N.D.–51.25	N.D.–16.33

N.D. not detectable, PAHs polycyclic aromatic hydrocarbons, PAEs phthalate ethers, OCCs organ chlorine compounds, Others other organic pollutants

contamination and precision. For recovery studies of the SVOCs and metallic elements, a series of standard solutions were made up from a stock solution and the recovery rates were above 82.8 % for the SVOCs and above 90.5 % for the trace elements, suggesting the efficiency of the used methods. The detection limits of contaminants were determined with a signal-to-noise ratio (S/N) of 3 (Tables 1 and 2). Chemical analysis of the SVOCs (Zhang et al. 2011; Chen et al. 2012; Grimmitt and Munch 2013) and metallic elements (Babu et al. 2007; Wu et al. 2009a) was conducted in triplicate for each sample, and the average concentration of each chemical in the different samples collected during 2009–2011 was used for health risk assessment.

Health risk assessment

The induced health risk was assessed for the detectable SVOCs and metallic elements in the source water and finished water. Health risk assessment was carried out on a basis of reliable exposure pathways of contaminants (USEPA (US Environmental Protection Agency) 2012a, c). Exposure to the chemicals was considered mainly via the

following pathways: direct ingestion of water consumption and dermal absorption of contaminants in water adhered to exposed skin. Carcinogenic and non-carcinogenic risks were assessed based on the two exposure pathways in this study. The assessment included exposure dose determination (ingestion and dermal absorption pathway), hazard quotient calculation, non-carcinogenic hazard index (HI) and carcinogenic risk index (RI) calculation, and uncertainty analysis.

The ingestion and dermal exposure doses were calculated by Eqs. 1 and 2, respectively, which were adapted from USEPA (US Environmental Protection Agency) (2012c):

$$D_i = \frac{C_w \times IR \times EF \times ED}{BW \times AT} \tag{1}$$

$$D_d = \frac{C_w \times SA \times K_p \times ET \times EF \times ED \times CF}{BW \times AT} \tag{2}$$

where D_i ($\mu\text{g kg}^{-1} \text{day}^{-1}$), exposure dose through ingestion of water; D_d ($\mu\text{g kg}^{-1} \text{day}^{-1}$), exposure dose through dermal absorption; C_w ($\mu\text{g L}^{-1}$), average concentration of organic pollutant and metallic element in water samples collected during 2009–2011; K_p (cm h^{-1}),

Table 2 Concentrations of metallic elements in the source water (SW) and drinking water (DW) (unit: $\mu\text{g L}^{-1}$)

Elements	Detection limits	Mar-09		Jun-09		Jun-10		Sep-11		Mean		Range	
		SW	DW	SW	DW	SW	DW	SW	DW	SW	DW	SW	DW
Al	9	918	850	23	863	619	35	11	36	393	446	11–918	35–863
Ba	4	46	50	43	52	45	50	38	59	43	53	38–46	50–59
Ca ($\times 10^3$)	5	29.44	28.41	30.83	31.44	32.16	32.29	44.27	39.63	34.17	32.94	29.44–44.27	28.41–39.63
Fe	2	462	424	14	417	257	12	N.D.	N.D.	183	213	N.D.–462	N.D.–424
K ($\times 10^3$)	21	2.46	2.60	2.27	2.59	2.79	2.63	7.54	2.54	3.77	2.59	2.27–7.54	2.54–2.63
Mg ($\times 10^3$)	12	6.95	6.96	7.15	6.93	6.43	6.15	19.13	8.72	9.92	7.19	6.43–19.13	6.15–8.72
Na ($\times 10^3$)	5	8.53	9.19	8.67	8.82	8.77	8.17	77.37	16.00	25.83	10.55	8.53–77.37	8.17–16.00
Si ($\times 10^3$)	10	4.75	4.51	3.28	4.75	3.62	2.87	5.48	3.95	4.28	4.02	3.28–5.48	2.87–4.75
Sr	6	186	201	200	207	180	180	237	240	201	207	180–237	180–240

N.D. not detectable

dermal permeability coefficient; IR (1.43 L day^{-1}), ingestion rate; ET (20 min day^{-1}), exposure time (USEPA (US Environmental Protection Agency) 2012d); EF ($365 \text{ days year}^{-1}$), exposure frequency; ED (year), exposure duration (73.91 years), in this study, equal to the life expectancy at Jiangsu Province, China (MHPRC (Ministry of Health of the People's Republic of China) 2012); CF, unit conversion factor; BW (57.38 kg), average body weight, in this study, equal to the average weight of urban males and females in the 18–80 age group (MHPRC (Ministry of Health of the People's Republic of China) 2012); AT (day), averaging time, for non-carcinogens and carcinogens; SA (cm^2), exposed skin area calculated by Eq. 3 (Zhang et al. 2011):

$$SA = 0.007182 \times H^{0.7252} \times BW^{0.425} \times 10^4 \quad (3)$$

where H (152.09 cm^2), average body weight of urban males and females in the 18–80 age group according to MHPRC (Ministry of Health of the People's Republic of China) (2012); 10^4 , area unit conversion factor.

Non-carcinogenic risk is expressed in terms of a hazard quotient (HQ) for a single substance, or HI for multiple substances and/or exposure pathways. HQ was calculated by Eq. 4 to estimate non-carcinogenic risk of each contaminant:

$$HQ = D/\text{RfD} \quad (4)$$

where D ($\mu\text{g kg}^{-1} \text{ day}^{-1}$), the exposure dose obtained from the Eqs. 1 and 2; RfD ($\mu\text{g kg}^{-1} \text{ day}^{-1}$), the reference dose of the contaminant. The ingestion reference dose (RfD_i) values were obtained from the USEPA (US Environmental Protection Agency) (2012b). The RfD_i was multiplied by a gastrointestinal absorption factor (ABS_g) to yield the corresponding dermal absorption reference dose (RfD_d).

Hazard index (HI), the total HQ for multiple substances, was summed by Eq. 5 to assess the overall non-carcinogenic risk posed by all chemicals:

$$HI = HQ_1 + HQ_2 + \dots + HQ_n \quad (5)$$

Lifetime carcinogenic risk (LCR) is defined as the incremental probability that an individual will develop cancer during one's lifetime due to chemical exposure under specific scenarios (Chen and Liao 2006). LCR induced by ingestion and dermal exposure was calculated using Eq. 6:

$$LCR = D \times \text{SF} \quad (6)$$

where LCR, the probability of developing cancer over a lifetime as a result of exposure to a contaminant; D ($\mu\text{g kg}^{-1} \text{ day}^{-1}$), the exposure dose obtained from the Eqs. 1 and 2; SF ($\mu\text{g kg}^{-1} \text{ day}^{-1}$)⁻¹, the carcinogenic slope factor of the contaminant.

The ingestion slope factor (SF_i) values were obtained from the USEPA (US Environmental Protection Agency) (2012b). The SF_i was divided by a gastrointestinal absorption factor (ABS_g) to yield the corresponding dermal absorption slope factor (SF_d). RI of all chemicals was calculated by summing the LCR of individual chemical using Eq. 7 to assess the overall potential for carcinogenic risk effects:

$$RI = \text{LCR}_1 + \text{LCR}_2 + \dots + \text{LCR}_n \quad (7)$$

To avoid the uncertainty in the estimation of exposure risk, the toxicity values (RfD, Kp and SF) of each contaminant recommended by USEPA (US Environmental Protection Agency) (2012b) were directly applied, and the variables of Cw, IR, ED, SA, BW and ET were evaluated based on the local statistical data and USEPA reference data. Table 3 lists the values of Kp, RfD_i, SF_i and ABS_g used for health risk assessment.

Table 3 Values of parameters in calculation models used for health risk assessment

Types	Pollutants	K_p (cm h^{-1})	RfD_i ($\mu\text{g kg}^{-1} \text{day}^{-1}$)	SF_i ($\mu\text{g kg}^{-1} \text{day}^{-1}$)	ABS_g
PAHs	Acenaphthylene	1.41E-01	1.50E+04	N.D.	6.00E-01
	Anthracene	2.25E-01	3.00E+02	N.D.	7.60E-01
	Benzo(a)pyrene	1.20E+00	N.D.	7.30E-03	7.00E-01
	Benzo(b)fluoranthene	N.D.	N.D.	7.30E-04	7.00E-01
	Benzo(k)fluoranthene	N.D.	N.D.	7.30E-05	7.00E-01
	Chrysene-d12	8.10E-01	N.D.	7.30E-06	8.00E-01
PAEs	Benzyl butyl phthalate	N.D.	2.00E+02	1.90E-06	5.00E-01
	Diethyl phthalate	2.80E-05	8.00E+02	N.D.	5.00E-01
	Dimethyl phthalate	1.60E-03	8.00E+02	N.D.	5.00E-01
OCCs	Hexachlorobenzene	2.10E-01	8.00E-01	1.30E-04	5.00E-01
	Hexachlorocyclopentadiene	1.56E-01	6.00E+00	N.D.	5.00E-01
	Pentachlorophenol	6.50E-01	5.00E+00	4.00E-04	5.00E-01
Others	2,4-dinitrotoluene	3.76E-03	2.00E+00	3.10E-04	8.50E-01
	2,6-dinitrotoluene	4.57E-03	1.00E+00	1.05E-03	8.50E-01
	Isophorone	4.40E-03	2.00E+02	9.50E-07	5.00E-01
Metals	Al	2.14E-03	1.00E+03	N.D.	1.00E-01
	Ba	4.03E-04	2.00E+02	N.D.	7.00E-02
	Fe	N.D.	7.00E+02	N.D.	2.00E-01
	Sr	N.D.	6.00E+02	N.D.	2.00E-01

N.D. not detectable, PAHs polycyclic aromatic hydrocarbons, PAEs phthalate ethers, OCCs organ chlorine compounds, Others other organic pollutants, K_p dermal permeability coefficient, RfD_i ingestion reference dose, SF_i ingestion slope factor, ABS_g gastrointestinal absorption factor

Results and discussion

Concentration of SVOCs and metallic elements

Table 1 shows the concentration of the individual SVOCs present in the source water and drinking water. Among the 22 SVOCs tested in this study, 15 chemicals were detectable, including 6 PAHs (ACE, ANT, BaP, BbF, BkF and CHR), 3 PAEs (DEP, DMP and BBP), 3 OCCs (HCB, HCCP and PCP) and other organic pollutants (2, 4-DNT, 2, 6-DNT and ISO). The total concentration of SVOCs was 214.01 ng L^{-1} in the source water and 180.40 ng L^{-1} in the drinking water. Concentrations of most SVOCs showed evident variation at different sampling time points. The average concentration of PAHs, PAEs, OCCs and others was 60.47, 109.64, 9.28 and 33.62 ng L^{-1} in the source water and 40.17, 93.31, 27.52 and 19.40 ng L^{-1} in the drinking water, respectively. The total concentration of the detectable SVOCs (especially for PAEs) in source water was lower than the results of Wu et al. (2009a) who quantified the organic contaminants in the Yangtze River in 2007. The Yangtze River source water had the lower level of PAHs than the Nantong reach of the Yangtze River (Han et al. 2013), the Minjiang River ($72.4 \mu\text{g L}^{-1}$) (Zhang et al. 2004), the Qiantang River (288.2 ng L^{-1}) (Zhu et al. 2008)

and the Yellow River (453.9 ng L^{-1}) (Li et al. 2006). However, the concentrations of PAEs in the drinking water were comparable to those of other regions in Jiangsu Province (China) (Li et al. 2012). The high level of PAEs may result from the wide use of plastics in these areas and high aqueous solubility of PAEs (Li et al. 2006). Comparatively, the source water had higher concentration of the SVOCs than the drinking water. In this drinking water treatment plant, more than 15.70 % of the detectable chemicals were removed, which is similar to the removal efficiency of the plants in the cities of Pexian, Dafen, Wojin and Binhu (China) applying the same treatment processes (Li et al. 2012). However, the concentration of OCCs in the source water was lower than in the drinking water. HCB had higher concentration in the drinking water than in the source water, which is close to concentration of HCB in drinking water of Canada (Oliver and Nicol 1982). HCCP was not detectable in the source water, but occurred in the drinking water. This may result from the chlorination effects in disinfection process that produces free and combined chlorine species, particularly HClO and $\text{NH}_2\text{Cl}/\text{NHCl}_2$, since previous studies have indicated that various chlorides tend to have higher levels in drinking water after chlorine disinfection (Qin et al. 2010; Florentina et al. 2011; Zhao et al. 2012). Recently, growing concerns focus



upon the removal of SVOCs in drinking water. Activated carbons (Dąbrowski et al. 2005) and porous polymeric resin (Król et al. 2011) are considered reliable methods for absorption of the organic compounds, while the operational cost is too high for large-scale application of the processes in drinking water plants. Chen et al. (2012) showed that biofilters combined backwashing with air and water at an appropriate intensity are effective on removal of the pollutants.

Among the 24 metallic elements tested, 9 metals were found to be present in the source water or drinking water (Table 2). Ca, Na, Mg, Si and K contributed 99 % of the total amount of the detectable metals in the source water and drinking water. Although Ca and Na had evidently higher levels than other metals in the water samples, the concentrations of the two metals did not exceed the prescribed levels of WHO (World Health Organization) (2012). The concentrations of the metals in the Yangtze River source water were lower than or close to previous studies (Zhang 1995; Muller et al. 2008). However, levels of Al determined in this study were approximately ten times higher than those in the River Thames (Neal et al. 2006a, b). The drinking water treatment processes seemed not effective in removing most of the metals, since the levels of the metals showed no significant difference between the source water and drinking water ($p > 0.05$). This is supported by previous studies indicating that the conventional processes of coagulation and sand filtration cannot effectively remove the soluble metals in drinking water (Dubey et al. 2009; Noubactep 2010).

Non-carcinogenic risk of SVOCs and metallic elements

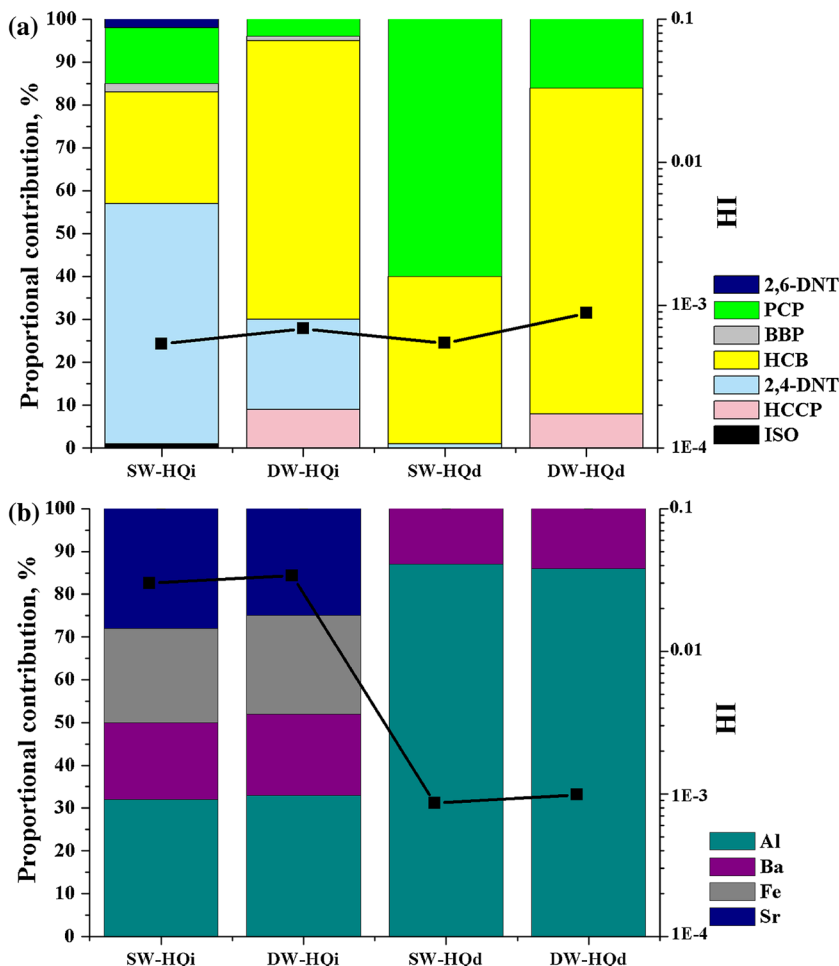
To further assess the health risk induced by the SVOCs and metals in the source water and drinking water, non-carcinogenic risk was assessed using the methods recommended by USEPA. For most chemicals, the potential for non-carcinogenic effects is evaluated by calculating HQ (USEPA (US Environmental Protection Agency) 2012c). If the HQ exceeds 1.00, there is some possibility that non-carcinogenic effects may occur. Otherwise, it is believed that there is no appreciable risk that non-carcinogenic health effects will occur.

In this study, the HQ value of each detectable pollutant in the source water and drinking water was <1.00 (Fig. 1), indicating that each contaminant individually posed no potential non-carcinogenic risk to local residents via ingestion and dermal exposure. In terms of the integrated health risk, the HI values of the SVOCs in both the source water and drinking water were <1.00 via ingestion or dermal exposure (Fig. 1a). It should be noted that OCCs contributed most to the total non-carcinogenic risk in the

source water and drinking water. In the case of ingestion exposure, OCCs accounted for 39.14 % of HI in source water and 77.85 % of HI in drinking water; especially, the contribution proportion of OCCs was approximately 99 % when dermal exposure to the source water or drinking water. Among various OCCs, HCB and PCP contributed most to the total non-carcinogenic risk of the drinking water, although the concentrations of the two chemicals were lower than most of the other organic compounds. As a typical carcinogen, HCB can cause systemic impairment (thyroid, liver, bone and skin), as well as damages to the kidneys, blood cells, and the immune, endocrine, developmental and nervous systems (Reed et al. 2007). In vitro and in vivo evidences have revealed that PCP can induce reproductive (Orton et al. 2009), immune (Corsini et al. 2008) and nervous (McLean et al. 2009) toxicities.

Among the 9 detectable metals in the water samples, 4 metals were selected for the HQ calculation (Fig. 1b) since the RfD values are available for those metals (USEPA (US Environmental Protection Agency) 2012b). Similar to the SVOCs, the metals induced no potential non-carcinogenic risk since both the HQ of each individual metal and the HI of all the metals were <1.00 . This result is confirmed by previous studies demonstrating that metals in the Yangtze River source water pose negligible hazards to public health of local residents (Wu et al. 2010; Liu et al. 2011). It has also been indicated that metals in source water of Huaihe River (China) pose little threat to human health (Liu et al. 2012), but HQ (via ingestion) levels of metals in source water of the Khanpur Lake (Pakistan) are higher than 1.00 (Iqbal et al. 2012). This study showed that ingestion exposure led to higher non-carcinogenic risk than dermal contact, which is similar to the study from Iqbal et al. (2012). In the source water, the HI values of the metals via ingestion and dermal exposure were $3.00E-2$ and $8.59E-4$, respectively. For the drinking water, the HI values were $3.46E-2$ (ingestion) and $1.86E-3$ (dermal). Among the metals, Al contributed most to the total non-carcinogenic risk via ingestion, followed by Sr, Fe and Ba, although concentrations of these elements were lower than most of the other elements. It is well known that Al, Ba, Fe and Sr in drinking water can cause metabolic/gastrointestinal disorders and cytotoxic and neurotoxic effects (WHO (World Health Organization) 2012). Interestingly, in the case of dermal exposure, Al contributed more than 80 % to the total HI of the metals in both the source water and drinking water (Fig. 1b). This may result from the easy adsorption of the metallic element on skin to facilitate its absorption into human bodies (USEPA (US Environmental Protection Agency) 2012b, d). However, Liu et al. (2011) has indicated that Pb contributes most to HI of the metals in source water of Jiangsu Province (China), followed by Cd and Cr.

Fig. 1 Total non-carcinogenic hazard index (HI) of the detectable semi-volatile organic compounds (SVOCs) (a) and trace elements (b) in source water (SW) and drinking water (DW) (in *black blot and line*), and the contribution proportion of each detectable pollutant via ingestion (HQi) and dermal (HQd) exposure (in *color rectangle*). *BBP* benzyl butyl phthalate, *HCCP* hexachlorocyclopentadiene, *HCB* hexachlorobenzene, *PCP* pentachlorophenol, *ISO* isophorone, *2,4-DNT* 2,4-dinitrotoluene, *2,6-DNT* 2,6-dinitrotoluene



Carcinogenic risk of SVOCs and metallic elements

Under most regulatory programs, LCR value over $1.00E-6$ indicates potential carcinogenic risk (De Miguel et al. 2007). In this study, the metals in the source water and drinking water showed no carcinogenic risk (data not shown). Figure 2 shows the LCRs of the individual SVOCs and the integrated RIs of all the chemicals. Except for BaP, ingestion and dermal exposure to each SVOC in the source water and drinking water might induce no carcinogenic risk since the LCRs were $<1.00E-6$. Similarly, Li et al. (2012) have also indicated that OCCs, PAHs and PAEs in drinking water of several cities in Jiangsu Province pose no or little carcinogenic risk. However, our results showed that RI values of both the source water and drinking water exceeded $1.00E-6$ in the case of oral or dermal exposure, suggesting the joint carcinogenic risk induced by the various pollutants in the water.

Among the SVOCs in the source water, BaP seemed to have carcinogenic risk since the LCR value was $3.37E-6$ via ingestion exposure and $2.06E-5$ via dermal exposure, both higher than the safety level. For BaP in the drinking water, LCR via dermal exposure was 5.0×10^{-6} , but was $<8.17E-7$ via ingestion exposure. However, Shi et al.

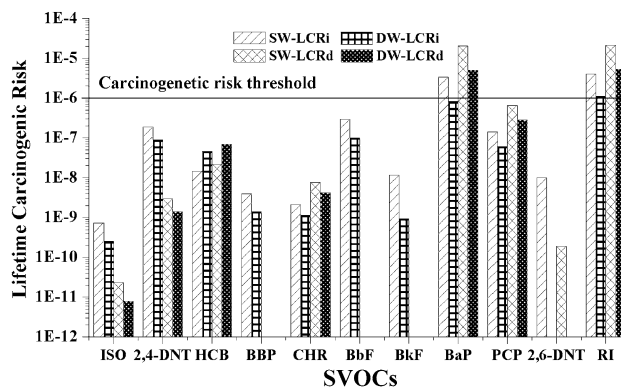


Fig. 2 Carcinogenic risk (RI) of the detectable semi-volatile organic compounds (SVOCs) in source water (SW) and drinking water (DW) via ingestion (LCRi) and dermal (LCRd) exposure. *2,4-DNT* 2,4-dinitrotoluene, *2,6-DNT* 2,6-dinitrotoluene, *BaP* benzo(a)pyrene, *BbF* benzo(b)fluoranthene, *BkF* benzo(k)fluoranthene, *CHR* chrysene, *BBP* benzyl butyl phthalate, *HCB* hexachlorobenzene, *ISO* isophorone, *PCP* pentachlorophenol

(2011) revealed that dibenz[a,h]anthracene among the PAHs detected in Huaihe River contributed most to carcinogenic risk. It has been indicated that chronic exposure to BaP in drinking water can result in skin, lung, bladder,

liver and stomach cancers in animals (Armstrong et al. 2004; Bosetti et al. 2005; Shimada and Fujii-Kuriyama 2004). Epidemiological studies have also confirmed that occupational exposure to BaP may increase the risk of skin, lung, bladder and gastrointestinal carcinogenesis in humans (Boffetta et al. 1997; Kogevinas et al. 2003), demonstrating that BaP in the drinking water of Yangtze River might pose potential carcinogenic health risk to the local consumers.

Effects of water treatment processes on reduction in health risk

The conventional drinking water treatment processes of coagulation/sedimentation, sand filtration and chlorine disinfection were found not effective in reducing potential non-carcinogenic health risk induced by SVOCs. The drinking water had higher non-carcinogenic risk than the source water, since total HI of the SVOCs via ingestion and dermal exposure was $1.08E-3$ for the source water and $1.56E-3$ for the drinking water (Fig. 1a). This might result from the increased level of OCCs in the drinking after chlorine disinfection (Table 1). This study indicated that the potential non-carcinogenic health risk induced by SVOCs in the drinking water was below safety level, but the increase in the concentrations of OCCs and other disinfection by-products induced by chlorination should receive more concern.

Overall, results showed that metallic elements caused higher non-carcinogenic risk than SVOCs, but the treatment processes were not effective in removal of the metals and reduction in the induced non-carcinogenic risk (Fig. 1b). Frequent use of polyaluminum flocculant in treatment processes might result in the high level of Al in the finished water (Dubey et al. 2009), so the non-carcinogenic risk induced by Al was high in drinking water, partially contributing the failure of the non-carcinogenic risk reduction.

The potential carcinogenic health risk of SVOCs in the source water was higher than the drinking water (Fig. 2), but the carcinogenic risk of drinking water still deserves great concern since its RI was higher than $1.00E-6$ (Fig. 2). Advanced processes have to be developed and applied in water treatment plants to ensure drinking water safety. So far, few studies have been conducted to investigate the health risk reduction in drinking water treatment plants. Our previous studies have shown that biofilters can effectively remove the SVOCs in drinking water, but the health risk induced by some PAEs and PAHs in the finished water cannot reach safety levels (Zhang et al. 2009, 2012).

Conclusion

This study assessed the carcinogenic and non-carcinogenic risks based on chemical detection of 22 SVOCs and 24

metallic elements in source water and drinking water at a full-scale water treatment plant of China. Various PAHs, OCCs, DNTs and metals are present in the water. Both the SVOCs and metals pose negligible non-carcinogenic risk, but the local consumers might suffer carcinogenic risk due to BaP exposure. The conventional water treatment processes have no obvious effects on the reduction in the induced carcinogenic and non-carcinogenic risks, and carcinogenic risk of the finished water should receive more concern. This study is expected to provide some useful baseline information for health risk assessment of drinking water. Advanced drinking water treatment processes should be developed and used to reduce public health risk in a more efficient manner.

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