Journal of Water & Health

Journal of Water and Health Vol 21 No 5, 547 doi: 10.2166/wh.2023.222

Health risk assessment of trace elements in the Tonle Sap Great Lake and the Tonle Sap River in Cambodia during the rainy season

Kongkea Phan [a,b,*] and Kyoung-Woong Kim [c]

[a] Research and Development Unit, Cambodian Chemical Society, Street 598, Phnom Penh, Cambodia
[b] Faculty of Science and Technology, International University, Phnom Penh 120801, Cambodia
[c] School of Earth Sciences and Environmental Engineering, Gwangju Institute of Science and Technology, Gwangju 61005, Republic Of Korea
*Corresponding author. E-mail: phanklabs@gmail.com

KP, 0000-0003-2965-8415

ABSTRACT

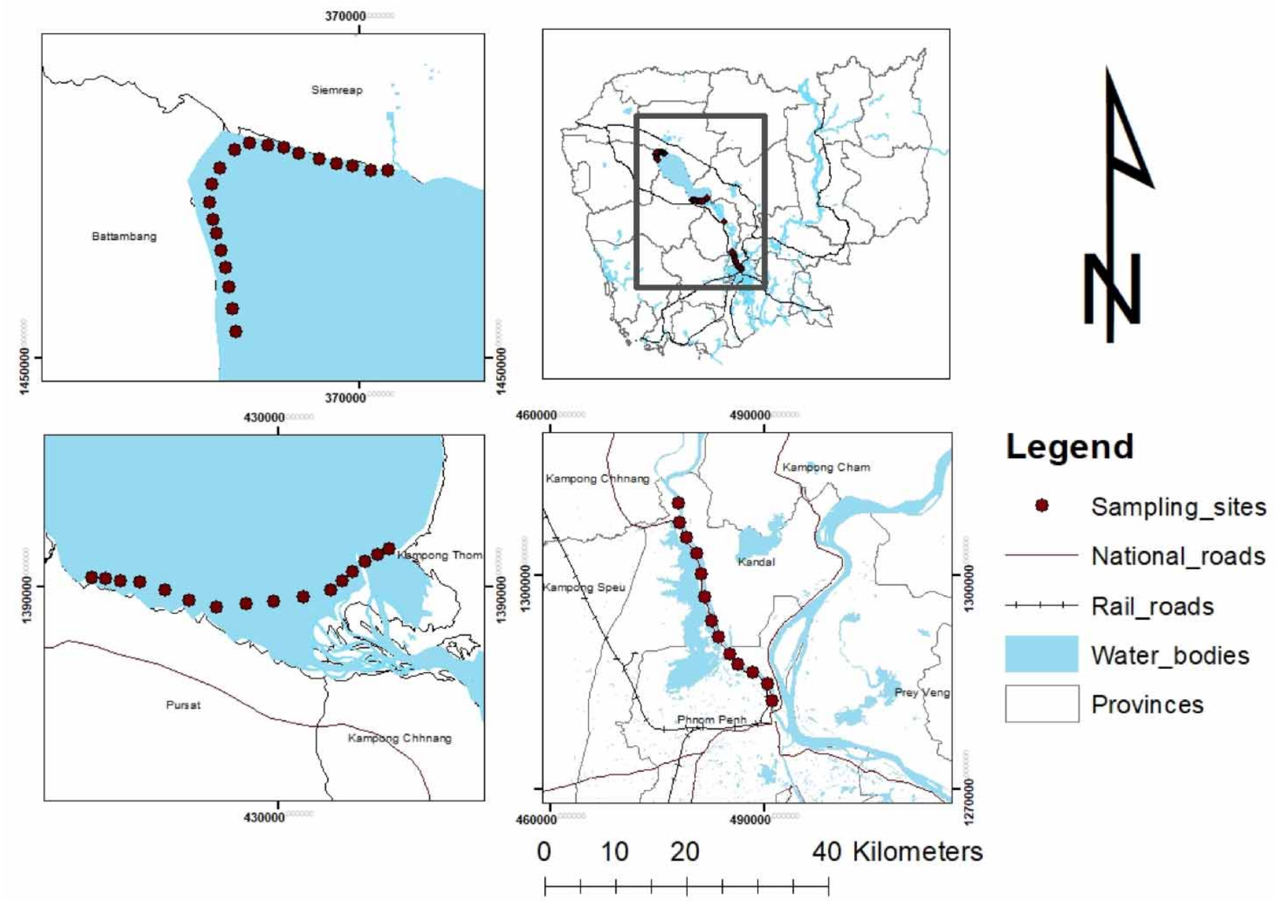
To investigate the potential health risk of trace elements in the Tonle Sap Great Lake system, lake ($n = 37$) and river ($n = 14$) water samples were collected and analyzed for 19 trace elements (Ag, Al, As, B, Ba, Cd, Co, Cr, Cu, Fe, Ga, Mn, Mo, Ni, Pb, Se, Tl, U and Zn) using inductively coupled plasma mass spectrometry. As a result, Cd was not detected in any river and lake water samples. Al, Fe and Mn in lake water exceeded the regulation limits of Cambodia, USEPA and WHO. Health risk assessment using the USEPA model indicated that male and female Cambodian residents are at minimal risk of non-carcinogenic effects from single and mixed trace elements through lake and river water consumption. Nevertheless, As, Tl, Co, Ba, Mn and Cr might pose high potential health risks to consumers which requires more attention. Therefore, regular monitoring and further studies are required to investigate the pollution trends and toxic behavior of these trace elements in the Tonle Sap Great Lake system.

Key words: Cambodia, health risk assessment, Tonle Sap Great Lake, Tonle Sap River, trace element

HIGHLIGHTS

- We investigated the distribution of 19 trace elements in the Tonle Sap Great Lake system.
- As, B, Cu, Mo, Ni, Se and U in the Great Lake were higher than those in the river.
- Ag, As, B, Ba, Cu, Ga, Mn and Se were significantly different among the five provinces.
- Residents did not have the non-carcinogenic effect of trace elements through lake and river water consumption.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Contamination by trace elements has created substantial concern among environmental scientists. Although some trace elements are essential for the normal growth of humans and animals, high intake and low intake of essential trace elements can lead to toxicity and nutritional deficiency, respectively (Goldhaber 2003). For instance, trace elements in drinking water (Kavcar *et al.* 2009) and food grains grown in contaminated soils (Huang *et al.* 2008) can pose significant non-carcinogenic effects on their consumers. Ecological communities and living organisms in receiving water are also affected by the direct discharge of effluents from various industries into aquatic systems (Krishna *et al.* 2009). The Tonle Sap Great Lake is the largest freshwater lake in SE Asia, and hosts one of the most productive inland fisheries in the world, accounting for more than 75% of Cambodia's inland fish catch and 60% of the country's protein needs (Burnett *et al.* 2013). The temperature in Cambodia is likely to rise by between 0.13 and 0.36 °C per decade while rainfall patterns are not clear with some increase in average rainfall in hilly areas in the wet season and a decrease in the dry season (NCCC 2013). The rainfall distribution in Cambodia is strongly influenced by her topography and seasonal monsoons resulted in the highest rainfall (2,000–3,400 mm) occurring in the southwest in coastal areas followed by the northeast plateau area (1,800 to >2,200 mm) and the stretches from the northwest to the southeast which receives annual rainfall of <1,400 mm (Sok & Chuop 2017). Recently, many food industries and factories have been located on the bank of the Tonle Sap River. Industrialization and population growth along the river are believed to be major distributors of trace elements in the Tonle Sap River (Chanpiwat & Sthiannopkao 2014). In general, Cambodian residents living along the Tonle Sap River downstream of Phnom Penh rely on the river water, whereas those living around the Tonle Sap Great Lake rely on the lake water as a main source of their water supply. Although conventional water quality parameters had been continuously monitored (Irvine *et al.* 2011), a few assessments of trace element contaminations in the Tonle Sap River (Chanpiwat & Sthiannopkao 2014) and Tonle

Sap Great Lake (Ki *et al.* 2009) of Cambodia have been conducted to date. On the other hand, health risk assessment of trace elements of residents who drink the river and lake water has not yet been conducted. The overall objective of the present project was to investigate the distribution of trace elements in the Tonle Sap Great Lake and the Tonle Sap River in Cambodia and assess the health risks of residents who drink these waters. Specifically, it was to (1) determine the distribution of trace elements in the five surrounding provinces of the Tonle Sap Great Lake of Cambodia, (2) compare the concentration of trace elements among the five surrounding provinces, (3) compare the concentrations of trace elements in the Great Lake and its tributary and (4) assess the human health risk of trace elements through drinking water from the Tonle Sap River and the Tonle Sap Great Lake.

2. MATERIALS AND METHODS

2.1. Field work

The present project was designed as a cross-sectional study. Sampling was carried out in the middle of August 2013 around the Tonle Sap Great Lake (Figure 1). The water level of the lake varies from an average depth of less than 2 m during the dry season to a maximum depth of 8–10 m at the end of the rainy season (Masumoto *et al.* 2008). Water from the lake flows south every dry season (surface area of 2,200 km^2) through a tributary (Tonle Sap River) connecting the lake to the Mekong River near Phnom Penh (Burnett *et al.* 2013). When the wet monsoon rains begin around June, the flow of the Mekong River increases dramatically and water flows in the connecting tributary reverse, adding large volumes of water back into the lake, which results in an approximately six-fold increase in surface area (Burnett *et al.* 2013). Lake water was collected from the surrounding provinces, namely, Siem Reap ($n = 10$), Battambang ($n = 10$), Pursat ($n = 10$), Kampong Chhnang ($n = 4$), and Kampong Thom ($n = 3$). In addition, river water samples ($n = 14$) were also collected from the Tonle Sap

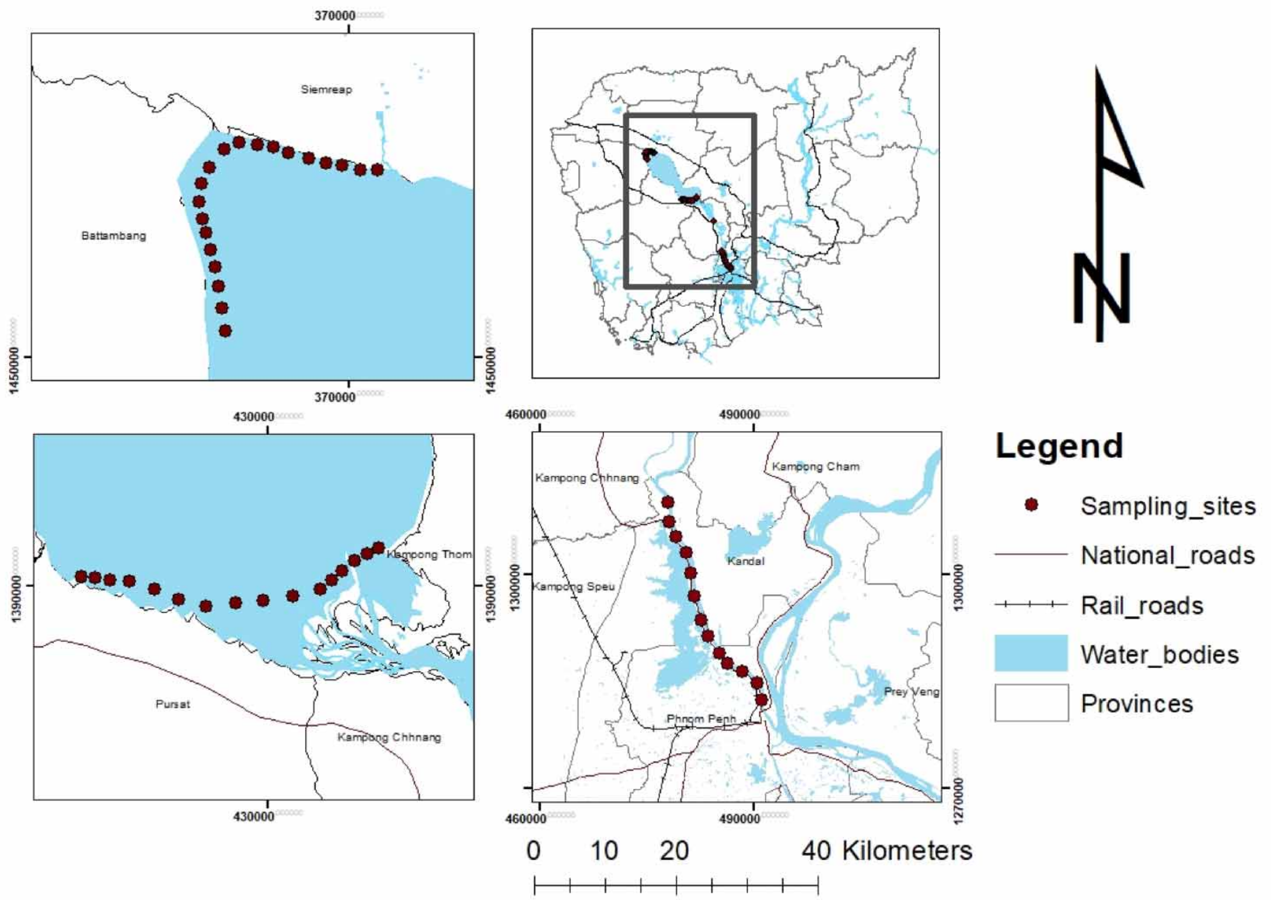


Figure 1 | Map of the sampling area.

River which connects the Mekong River to the Great Lake. Lake and river water samples were collected from each point of sampling at a depth of 30 cm below the water surface. At each sampling location, a composite sample was obtained from a grab sample of lake water. The water samples were then filled into an acid-cleaned polypropylene bottle. Immediately after collection, all samples were acidified with concentrated HNO_3 to pH < 2, kept in an ice-box, and transferred to a fridge where they were stored at 4 °C, and then delivered to the laboratory for chemical analyses.

2.2. Sample analyses

All chemical measurements were employed by inductively coupled plasma mass spectroscopy (ICP-MS, Agilent 7500 ce) using an external calibration method. Working standard solutions were prepared in a proper range of ICP-MS (0, 0.1, 1, 5, 10, 20, 50, 100 μg L^{-1}). For the solvent to use in solution preparation, and analytical procedures, 2% HNO_3 (percent by volume) was prepared from 18.2 MΩ cm^{-1} deionized water obtained from a Millipore Milli-Q water purification system. The possibility of trace metal contamination in the 2% HNO_3 was also checked and reported as an analytical blank. A standard reference material (Trace Element in Water, SRM 1643e) was analyzed to check the ICP-MS accuracy. If the recovery rate was out of the recommended range (90–110%), samples were reanalyzed with a new calibration curve.

2.3. Health risk assessment

Health risk assessment procedures from the USEPA (1989) were applied to calculate the non-carcinogenic effects of single and mixed trace elements. The average daily dose of a single element is calculated from the following equation.

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

where ADD is the average daily dose from ingestion (μg kg^{-1} d^{-1}); C_w is the trace element concentration in groundwater (μg L^{-1}); IR is the ingestion rate of groundwater (L d^{-1}); EF is the exposure frequency (d y^{-1}); ED is the exposure duration (y); BW is the body weight (kg) and AT is the averaging time (d). Non-carcinogenic effects of single elements, expressed as hazard quotient (HQ), are computed from Equation (2), whereas non-carcinogenic effects of mixed trace elements (hazard index) are calculated from Equation (3). C_w of the trace elements is measured in this study. Our field observation and communication with local people indicated that the residents in this study area use river and lake water the whole year around (365 d y^{-1}). The average body weight of Cambodian female adults (49 kg) and male adults (54 kg) and average age of Cambodian females (65 years) and males (59 years) are adapted from Phan *et al.* (2010, 2013):

$$HQ = \frac{ADD}{RfD} \tag{2}$$

HQ is a hazard quotient. Non-carcinogenic effects were considered if $HQ > 1$; RfD is a reference dose of a single element. The oral reference dose (μg kg^{-1} d^{-1}) of Ag (5), Al (1,000), As (0.3), B (200), Ba (200), Co (0.3), Cr (3), Cu (40), Fe (700), Mn (140), Mo (5), Ni (20), Se (5), Tl (0.01) U (3) and Zn (300) was obtained from a database of the Integrated Risk Information System (USEPA 2014a) and risk-based concentration tables (USEPA 2014b):

$$HI = \sum HQ = \frac{ADD_1}{RfD_1} + \frac{ADD_2}{RfD_2} + \ldots + \frac{ADD_i}{RfD_i} \tag{3}$$

HI is a hazard index which indicated the aggregate risk/risk of mixed trace elements. Non-carcinogenic effects of mixed trace elements are considered to occur in a circumstance where HI is greater than one.

2.4. Statistical data analyses

All statistical data analyses were performed by SPSS for Windows (Version 16.0). One-Way ANOVA tests and post hoc tests were conducted to certify the difference in trace element concentrations among the five surrounding provinces of the Tonle Sap Great Lake. An independent samples *t*-test was applied to access the difference in trace element concentrations in the Great Lake and its tributary.

Table 1 | Summary of trace elements (μg L^{-1}) in the Tonle Sap River, Tonle Sap Lake, and world natural river, and their regulation limit by the World Health Organization (WHO), US Environmental Protection Agency (USEPA), and Cambodia

		Tonle Sap River ($n = 14$)					Tonle Sap Lake ($n = 37$)					World natural river[a]		Regulation limit		
Elements	**LOD**	**Mean**	**Median**	**SD**	**Min**	**Max**	**Mean**	**Median**	**SD**	**Min**	**Max**	**Average**	**SD**	**WHO[b]**	**USEPA[c]**	**Cambodia[d]**
Ag	0.001	0.81	0.87	0.29	0.41	1.21	0.79	0.22	1.39	0.002	5.48	–	–	–	100	–
Al	0.261	11.26	5.92	13.07	3.59	45.55	86.23	16.59	400.23	3.91	2,453.00	32.00	179.00	200	200	200
As	0.005	0.69	0.64	0.18	0.59	1.31	1.16	1.17	0.27	0.70	1.78	0.60	0.60	10	10	50
B	0.101	5.50	5.37	0.49	5.19	7.15	10.11	12.52	3.51	5.70	14.48	–	–	500	–	–
Ba	0.008	19.47	19.21	1.18	18.27	22.89	20.38	18.74	5.33	14.14	37.22	23.00	13.50	700	200	700
Cd	0.011	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.10	0.10	3	5	3
Co	0.001	0.06	0.06	0.01	0.05	0.09	0.11	0.05	0.24	0.03	1.30	0.20	0.10	40	–	–
Cr	0.013	0.08	0.05	0.08	0.01	0.27	0.19	0.11	0.42	0.01	2.32	0.90	2.80	50	100	50
Cu	0.010	0.81	0.76	0.17	0.61	1.20	1.29	1.39	0.63	0.26	3.14	1.50	0.70	2,000	1,300	1,000
Fe	0.292	21.30	5.24	45.02	2.37	169.80	111.37	30.82	331.29	11.40	2,041.00	66.00	185.90	300	300	300
Ga	0.003	4.02	3.91	0.28	3.83	4.80	3.97	3.84	0.99	2.76	7.13	–	–	–	–	–
Mn	0.001	9.21	8.11	3.50	5.43	17.11	13.49	2.07	37.01	0.27	220.10	34.00	12.50	–	50	100
Mo	0.010	0.14	0.13	0.04	0.10	0.26	0.21	0.21	0.04	0.12	0.33	0.40	0.50	70	–	–
Ni	0.021	0.19	0.15	0.07	0.13	0.36	0.38	0.33	0.30	0.14	2.02	0.80	2.20	70	–	20
Pb	0.004	0.10	0.07	0.09	0.01	0.30	0.13	0.08	0.21	0.02	1.28	0.10	0.90	10	15	10
Se	0.017	0.06	0.06	0.01	0.04	0.08	0.08	0.08	0.03	0.03	0.14	–	–	10	50	10
Tl	0.004	0.008	0.008	0.001	0.006	0.011	0.008	0.008	0.004	0.004	0.029	–	–	–	2	–
U	0.001	0.02	0.02	0.01	0.02	0.04	0.03	0.03	0.01	0.01	0.09	–	–	15	30	–
Zn	0.052	3.87	1.50	6.94	0.49	26.67	1.98	1.62	1.27	0.45	5.08	0.60	4.60	3,000	5,000	3,000

LOD, limit of detection; N/A, not applicable because it is below LOD; SD, standard deviation; Min, minimum; Max, maximum.
[a]Adapted from Chanpiwat & Sthiannopkao 2014.
[b]WHO 2011.
[c]USEPA 2014c.
[d]MIME 2004.

Table 2 | Comparison of trace elements in the Tonle Sap Great lake and Tonle Sap River

Variable	Mean	SD	*t*	*df*	*p*
Ag[a]			0.055	31.214	0.956
River	0.806	0.290			
Great lake	0.790	1.392			
Al			−0.696	49	0.489
River	11.26	13.07			
Great lake	86.23	400.23			
As[a]			−7.084	35.265	<0.01
River	0.686	0.182			
Great lake	1.155	0.273			
B[a]			−7.793	39.507	<0.01
River	5.499	0.489			
Great lake	10.107	3.508			
Ba[a]			−0.983	43.896	0.331
River	19.469	1.181			
Great lake	20.384	5.331			
Co			−0.759	49	0.451
River	0.060	0.013			
Great lake	0.109	0.243			
Cr			−0.941	41	0.352
River	0.085	0.078			
Great lake	0.191	0.416			
Cu[a]			−4.222	46.39	<0.01
River	0.811	0.169			
Great lake	1.286	0.627			
Fe			−1.008	49	0.319
River	21.30	45.02			
Great lake	111.37	331.29			
Ga[a]			0.318	46.93	0.752
River	4.025	0.279			
Great lake	3.968	0.995			
Mn			−0.429	49	0.67
River	9.21	3.50			
Great lake	13.49	37.01			
Mo			−5.333	49	<0.01
River	0.142	0.037			
Great lake	0.205	0.038			
Ni			−2.416	49	0.019
River	0.185	0.070			
Great lake	0.384	0.303			
Pb			−0.446	49	0.657
River	0.105	0.094			
Great lake	0.131	0.207			

(*Continued*.)

Table 2 | Continued

Variable	Mean	SD	*t*	*df*	*p*
Se[a]			−4.003	48.864	<0.01
River	0.056	0.011			
Great lake	0.079	0.029			
Tl			−0.564	49	0.575
River	0.008	0.001			
Great lake	0.008	0.004			
U			−2.159	49	0.036
River	0.022	0.006			
Great lake	0.029	0.012			
Zn[a]			1.013	13.331	0.329
River	3.867	6.939			
Great lake	1.978	1.271			

SD, standard deviation.
[a]The *t* and *df* were adjusted because variances were not equal.

3. RESULTS AND DISCUSSION

3.1. Distribution of trace elements in the Great Lake and its tributary

All chemical measurements of trace elements in the Tonle Sap River and the Tonle Sap Great Lake are presented in Table 1. Cadmium was not detected in any lake ($n = 37$) and river ($n = 14$) water samples. Trace elements in the Tonle Sap River ranged from 0.006 μg L^{-1} (Tl) to 169.80 μg L^{-1} (Fe), whereas trace elements in the Tonle Sap Great Lake ranged from 0.002 μg L^{-1} (Ag) to 2,453.00 μg L^{-1} (Al). As and Zn concentrations in the Tonle Sap River were up to 2.2 and 6.45 times, respectively, higher than the average levels in the world natural rivers. The present findings were consistent with the previous ones reported by Chanpiwat & Sthiannopkao (2014). Likewise, As and Pb concentrations in the Tonle Sap Great Lake were up to 3 and 12.8 times, respectively, greater than the average levels in the world natural rivers. The mean concentrations of other trace elements in both Tonle Sap River and Great Lake were below the average levels of world natural rivers. Another comparison indicated that none of the trace elements in river water exceeded the regulation limits of Cambodia, WHO and USEPA. Likewise, most of the trace elements in lake water were lower than the regulation limits, except Al, Fe and Mn. The concentrations of Al, Fe and Mn in the Tonle Sap Great Lake in the present study were comparable to those reported by Ki *et al.* (2009). The sources of trace elements in the Tonle Sap River were more likely from the discharge of municipal sewage wastewater into the river (Chanpiwat & Sthiannopkao 2014). Since water flows from the connecting tributary to the Great Lake during the wet monsoon season, trace elements in the Tonle Sap River water can be transported and deposited in the Great Lake. Further investigations on temporal and spatial variations of trace elements in the Great Lake and its tributaries are required to better understand their pollution trends and toxic behaviors which may impact the ecological system of the Tonle Sap Great Lake.

3.2. Comparisons of trace elements in the Great Lake and its tributary

The *t*-tests revealed that there were no significant differences in Ag, Al, Ba, Co, Cr, Fe, Ga, Mn, Pb, Tl and Zn in the Tonle Sap Great Lake and its tributary river ($p > 0.05$; Table 2). However, As, B, Cu, Mo, Ni, Se and U concentrations in the Great Lake were significantly higher than those in the river (t-test, $p < 0.05$; Table 2). Ki *et al.* (2009) revealed that concentrations of trace elements in the Tonle Sap Great Lake were generally higher than those in other water systems because it is the final depository. There were also significant differences in Ag, As, B, Ba, Cu, Ga, Mn and Se among the five surrounding provinces of the Great Lake (one-way ANOVA, $p < 0.05$; Table 3). Nevertheless, Al, Co, Cr, Fe, Mo, Ni, Pb, Tl, U and Zn were not significantly different among the five provinces (one-way ANOVA, $p > 0.05$; Table 3). Games–Howell post hoc test indicated there were no significant differences in Ag among Siem Reap, Battambang, Pursat, Kampong Chhnang and Kampong Thom ($p > 0.05$). There were significant differences in B, Cu and Se between Siem Reap and Pursat, Kampong Chhnang and Kampong Thom, between Battambang and Pursat, and between Kampong Chhnang and Kampong Thom ($p < 0.05$). Likewise, there

Table 3 | One-way analysis of variance comparing regional groups on trace elements in the Tonle Sap Great Lake

Source		*df*	SS	MS	*F*	*p*
Ag	Between groups	4	18.19	4.55	3.11	0.036
	Within groups	22	32.20	1.46		
	Total	26	50.39			
Al	Between groups	4	420,148.80	105,037.20	0.63	0.646
	Within groups	32	5,346,395.66	167,074.86		
	Total	36	5,766,544.46			
As	Between groups	4	0.85	0.21	3.73	0.013
	Within groups	32	1.83	0.06		
	Total	36	2.68			
B	Between groups	4	432.41	108.10	325.66	<0.01
	Within groups	32	10.62	0.33		
	Total	36	443.03			
Ba	Between groups	4	630.15	157.54	12.83	<0.01
	Within groups	32	392.85	12.28		
	Total	36	1,023.00			
Co	Between groups	4	0.52	0.13	2.59	0.055
	Within groups	32	1.60	0.05		
	Total	36	2.12			
Cr	Between groups	4	0.59	0.15	0.83	0.517
	Within groups	24	4.25	0.18		
	Total	28	4.84			
Cu	Between groups	4	11.44	2.86	33.80	<0.01
	Within groups	32	2.71	0.08		
	Total	36	14.14			
Fe	Between groups	4	222,215.21	55,553.80	0.48	0.752
	Within groups	32	3,728,824.68	116,525.77		
	Total	36	3,951,039.89			
Ga	Between groups	4	17.56	4.39	7.78	<0.01
	Within groups	32	18.06	0.56		
	Total	36	35.62			
Mn	Between groups	4	25,364.03	6,341.01	8.47	<0.01
	Within groups	32	23,950.16	748.44		
	Total	36	49,314.20			
Mo	Between groups	4	0.01	0.00	1.20	0.329
	Within groups	32	0.05	0.00		
	Total	36	0.05			
Ni	Between groups	4	0.62	0.16	1.84	0.145
	Within groups	32	2.70	0.08		
	Total	36	3.32			
Pb	Between groups	4	0.11	0.03	0.64	0.638
	Within groups	32	1.43	0.04		
	Total	36	1.54			
Se	Between groups	4	0.02	0.01	20.73	<0.01
	Within groups	32	0.01	0.00		
	Total	36	0.03			
Tl	Between groups	4	0.00	0.00	0.49	0.744
	Within groups	32	0.00	0.00		
	Total	36	0.00			
U	Between groups	4	0.00	0.00	0.86	0.496
	Within groups	32	0.00	0.00		
	Total	36	0.01			

(*Continued.*)

Table 3 | Continued

Source		*df*	*SS*	*MS*	*F*	*p*
Zn	Between groups	4	8.61	2.15	1.39	0.259
	Within groups	32	49.52	1.55		
	Total	36	58.13			

df, degree of freedom; *SS*, sum of squares; *MS*, mean square.

were significant differences in Ga among Siem Reap and Pursat and Kampong Chhnang and between Pursat and Kampong Chhnang ($p < 0.05$). There was a significant difference in Mn between Siem Reap and Pursat ($p < 0.05$). The Tukey HSD (honestly significant difference) test indicated that As was significantly different among Kampong Chhnang and Battambang and Kampong Thom ($p < 0.05$). There were significant differences in Ba between Siem Reap and Pursat, Kampong Chhnang and Kampong Thom and between Battambang and Pursat, Kampong Chhnang and Kampong Thom as well as between Pursat and Kampong Thom ($p < 0.05$). The differences in metal concentrations between sampling locations of the same lake have been found in the literature. For instance, Oyoo-Okoth *et al.* (2013) reported that the mean concentrations of Cd, Co, Cr, Cu, Ti and Zn in lake water were significantly different in locations of Lake Victoria, Kenya. Concurrently, the mean concentrations of Cu, Zn, Cd, Pb, Co, and Fe in lake water were found significantly different between locations of Lake Titicaca, South America (Monroy *et al.* 2014). When compared to lakes in other countries (Table 4), it indicated

Table 4 | Comparisons of trace elements (μg L^{-1}) in the Tonle Sap Great Lake and lakes in other countries

	Cambodia Tonle Sap Great Lake (present study)					China[a]	Kenya[b]	Pakistan[c]	New Zealand[d]	South America[e]	USA[f]
Elements	**TSB**	**TSS**	**TSP**	**TSC**	**TST**	**Taihu Lake**	**Victoria**	**Rawal Lake**	**Lake Hauroko**	**Titicaca**	**Hough Park Lake**
Ag	0.21	1.95	0.23	0.15	0.30	–	–	–	–	–	–
Al	27.72	261.16	19.90	12.04	18.16	–	–	–	–	–	436.00
As	1.14	1.28	1.15	0.77	1.33	1.86	–	–	–	–	–
B	13.32	13.18	6.18	6.33	7.31	–	–	–	–	–	–
Ba	16.44	17.53	22.58	24.82	29.80	–	–	–	–	–	43.00
Cd	N/A	N/A	N/A	N/A	N/A	0.06	0.12	6.00	0.0013	0.06	–
Co	0.048	0.143	0.050	0.045	0.483	–	0.05	11.00	0.005	0.25	–
Cr	0.109	0.383	0.032	0.130	0.057	0.99	0.13	9.00	–	–	1.00
Cu	1.57	1.98	0.76	0.80	0.45	5.81	2.20	10.00	0.235	2.45	–
Fe	39.00	224.51	87.42	28.73	165.50	–	–	93.00	0.005	111.6	298.00
Ga	3.26	3.57	4.28	4.78	5.53	–	–	–	–	–	–
Mn	0.71	4.92	10.12	9.85	100.72	–	–	4.00	0.080	–	93.00
Mo	0.210	0.210	0.206	0.212	0.160	–	–	–	–	–	–
Ni	0.33	0.57	0.33	0.16	0.46	5.34	–	–	0.106	–	1.00
Pb	0.109	0.220	0.095	0.075	0.095	2.74	–	162.00	0.002	3.07	0.40
Se	0.100	0.101	0.059	0.046	0.043	–	–	–	–	–	–
Tl	0.008	0.009	0.009	0.007	0.006	–	–	–	–	–	–
U	0.033	0.027	0.029	0.033	0.019	–	–	–	–	–	–
Zn	1.26	2.46	2.12	1.83	2.48	15.86	8.3	14.00	0.054	23.67	3.00

TSB, Tonle Sap Battambang; TST, Tonle Sap Siem Reap; TSP, Tonle Sap Pursat; TSC, Tonle Sap Kampong Chhnang; TST, Tonle Sap Kampong Thom.
[a]Jiang *et al.* (2012).
[b]Oyoo-Okoth *et al.* (2013).
[c]Iqbal *et al.* (2013).
[d]Sander *et al.* (2013).
[e]Monroy *et al.* (2014).
[f]Ikem & Adisa (2011).

that the mean concentrations of Co, Cr, Cu, Pb and Zn in water of the Tonle Sap Great Lake were lower than those in the Rawal Lake, Pakistan in summer, reported by Iqbal *et al.* (2013). It was also apparent that mean concentrations of Cu, Pb and Zn in water of the Tonle Sap Great Lake were much lower than those in the Lake Dalinouer, China (Hou *et al.* 2013) and mean concentrations of As, Cr, Cu, Ni, Pb and Zn were lower than those in the Taihu Lake, China (Jiang *et al.* 2012). Although Fe and Co concentrations in lake water were similar between the Tonle Sap Great Lake and the Lake Titicaca (Monroy *et al.* 2014), the concentrations of Cu, Pb and Zn in water of the Tonle Sap Great Lake were relatively lower. The mean concentrations of Pb, Cr and Cu in water of the Tonle Sap Great Lake were much lower than those in Lake Victoria, Kenya, reported by Oyoo-Okoth *et al.* (2010).

3.3. Assessment of health risks from drinking lake and river water

The average daily doses (ADDs) of single trace elements are provided in Table 5. The *HQ* of a single trace element and the hazard index (*HI*) of multiple trace elements are presented in Table 6. In total, 16 trace elements were included in the health risk assessment. Cadmium was excluded because it was not detected in any river and lake water samples. Gallium and lead were excluded because their oral reference doses (RfDs) were not available at the USEPA. Calculations indicated that male and female Cambodian residents ingested less amount of trace elements in water from the Tonle Sap River and the Tonle Sap Great Lake than those in Pakistan (Iqbal *et al.* 2013) and China (Wu *et al.* 2009; Li & Zhang 2010). Moreover, risk calculation indicated that all *HQ*s of each single trace element and the *HI* of the multiple trace elements were less than one, indicating male and female Cambodian residents were at minimal risk of single and multiple trace elements through consumption of the Tonle Sap Great Lake and River water. Health risk assessment of trace metals in freshwater Rawal Lake, Pakistan revealed that Co and Pb were the major pollutants during summer and Cd, Co, Cr and Pb were the major pollutants during winter, which could pose adverse health effects to the local consumers through the water drinking pathway (Iqbal *et al.* 2013). Recently, a health risk assessment of trace elements in the upper Han River, China indicated that As, Pb, Sb, Se and V were the largest contributor to chronic risk in the dry season while As, Co, Pb, Sb and V in the rainy season (Li & Zhang 2010). Concurrently, a health risk assessment of trace metal in surface water from the Yangtze River in Nanjing section, China suggested trace

Table 5 | Summary of average daily intake ($\times 10^{-2}$ μg kg^{-1} d^{-1}) of trace elements of Cambodian residents through drinking water from the Tonle Sap River and the Tonle Sap Great Lake

	Tonle Sap River						Tonle Sap Great Lake					
	Female			Male			Female			Male		
Elements	Mean	Median	SD	Mean	Median	SD	Mean	Median	SD	Mean	Median	SD
Ag	1.29	1.39	0.46	1.52	1.64	0.55	1.26	0.36	2.23	1.49	0.42	2.62
Al	18.03	9.48	20.93	21.20	11.15	24.62	138.08	26.56	640.87	162.39	31.24	753.72
As	1.10	1.02	0.29	1.29	1.20	0.34	1.85	1.88	0.44	2.18	2.21	0.51
B	8.80	8.60	0.78	10.35	10.11	0.92	16.18	20.05	5.62	19.03	23.58	6.61
Ba	31.17	30.76	1.89	36.66	36.18	2.22	32.64	30.01	8.54	38.39	35.29	10.04
Co	0.10	0.09	0.02	0.11	0.10	0.02	0.18	0.08	0.39	0.21	0.09	0.46
Cr	0.14	0.09	0.12	0.16	0.10	0.15	0.31	0.18	0.67	0.36	0.21	0.78
Cu	1.30	1.22	0.27	1.53	1.44	0.32	2.06	2.23	1.00	2.42	2.62	1.18
Fe	34.11	8.39	72.09	40.11	9.87	84.79	178.33	49.35	530.48	209.74	58.04	623.89
Mn	14.76	12.99	5.61	17.35	15.27	6.60	21.60	3.31	59.26	25.40	3.90	69.70
Mo	0.23	0.21	0.06	0.27	0.25	0.07	0.33	0.33	0.06	0.39	0.39	0.07
Ni	0.30	0.25	0.11	0.35	0.29	0.13	0.62	0.53	0.49	0.72	0.62	0.57
Se	0.09	0.09	0.02	0.11	0.11	0.02	0.13	0.12	0.05	0.15	0.15	0.05
Tl	0.01	0.01	0.00	0.01	0.01	0.00	0.01	0.01	0.01	0.02	0.01	0.01
U	0.03	0.03	0.01	0.04	0.04	0.01	0.05	0.05	0.02	0.05	0.06	0.02
Zn	6.19	2.41	11.11	7.28	2.83	13.07	3.17	2.59	2.03	3.72	3.05	2.39

SD, standard deviation.

Table 6 | Summary of RfD ($\mu g\ kg^{-1}\ d^{-1}$) and non-carcinogenic risks of single (HQ $\times 10^{-2}$) and mixed (HI $\times 10^{-2}$) elements of Cambodian residents through drinking water from the Tonle Sap River and the Tonle Sap Great Lake

		Tonle Sap River						Tonle Sap Great Lake					
		Female			Male			Female			Male		
Elements	RfD	Mean	Median	SD	Mean	Median	SD	Mean	Median	SD	Mean	Median	SD
Ag	5	0.26	0.28	0.09	0.30	0.33	0.11	0.25	0.07	0.45	0.30	0.08	0.52
Al	1000	0.02	0.01	0.02	0.02	0.01	0.02	0.14	0.03	0.64	0.16	0.03	0.75
As	0.3	3.66	3.40	0.97	4.31	4.00	1.14	6.17	6.25	1.46	7.25	7.35	1.71
B	200	0.04	0.04	0.00	0.05	0.05	0.00	0.08	0.10	0.03	0.10	0.12	0.03
Ba	200	0.16	0.15	0.01	0.18	0.18	0.01	0.16	0.15	0.04	0.19	0.18	0.05
Co	0.3	0.32	0.30	0.07	0.38	0.35	0.08	0.58	0.27	1.29	0.69	0.31	1.52
Cr	3	0.05	0.03	0.04	0.05	0.03	0.05	0.10	0.06	0.22	0.12	0.07	0.26
Cu	40	0.03	0.03	0.01	0.04	0.04	0.01	0.05	0.06	0.03	0.06	0.07	0.03
Fe	700	0.05	0.01	0.10	0.06	0.01	0.12	0.25	0.07	0.76	0.30	0.08	0.89
Mn	140	0.11	0.09	0.04	0.12	0.11	0.05	0.15	0.02	0.42	0.18	0.03	0.50
Mo	5	0.05	0.04	0.01	0.05	0.05	0.01	0.07	0.07	0.01	0.08	0.08	0.01
Ni	20	0.01	0.01	0.01	0.02	0.01	0.01	0.03	0.03	0.02	0.04	0.03	0.03
Se	5	0.02	0.02	0.00	0.02	0.02	0.00	0.03	0.02	0.01	0.03	0.03	0.01
Tl	0.01	1.23	1.22	0.19	1.45	1.43	0.22	1.32	1.22	0.60	1.56	1.43	0.70
U	3	0.01	0.01	0.00	0.01	0.01	0.00	0.02	0.02	0.01	0.02	0.02	0.01
Zn	300	0.02	0.01	0.04	0.02	0.01	0.04	0.01	0.01	0.01	0.01	0.01	0.01
HI		6.03	5.65	1.61	7.09	6.65	1.89	9.42	8.44	5.99	11.08	9.92	7.05

RfD, Reference Dose; SD, standard deviation

metals could pose a minimal hazard to local residents (Wu *et al.* 2009). It is apparent that the Tonle Sap River and the Tonle Sap Great Lake water were substantially safe in trace elements and could be used as drinking water sources, considering the treatments of microbial contaminants and organic pollutants as well as emerging environmental pharmaceuticals. However, Cambodian local residents were at relatively high potential health risks of As, Tl, Ba, Co, Mn and Cr when compared to other trace elements (Table 6). The management and control of the contamination sources should be taken into account. In fact, if industrial and municipal sewages are well managed and controlled prior to discharges to the Tonle Sap River, it might reduce the potential health risks to the consumers who rely on the Tonle Sap Great Lake resources such as water and fishery products. It might also reduce the ecological risks to the aquatic plants and animals in the Great Lake system. Nevertheless, we have not investigated seasonal changes which are believed to influence the concentrations of these trace elements and the water quality of the Great Lake and its tributary due to budget and time constraints. These limitations allowed us to assess the health risks of consumers only in the rainy season (May to November). However, the authors feel that it is substantially informative because a few people would consume lake and river water in the dry season (December to April) due to a long-distance carrier. Our previous study showed that groundwater in the Mekong River basin is the main source of drinking although many people live alongside surface water (Phan *et al.* 2010). Many people switched from the consumption of surface water to groundwater owing to their concerns about microbial contaminations (Phan *et al.* 2010). Of course, surface water is consumed during the raising stage of the Mekong River water which results in an overflow and flooding.

4. CONCLUSIONS

The total number of 19 trace elements (Ag, Al, As, B, Ba, Cd, Co, Cr, Cu, Fe, Ga, Mn, Mo, Ni, Pb, Se, Tl, U and Zn) in the Tonle Sap Great Lake and its tributary were determined. Cadmium was not detected in any river and lake waters. Comparisons did not show significant differences in Ag, Al, Ba, Co, Cr, Fe, Ga, Mn, Pb, Tl and Zn concentrations in the Great Lake and its tributary. However, As, B, Cu, Mo, Ni, Se and U concentrations in the Great Lake were significantly higher than those in the river. Concurrently, there were significant differences in Ag, As, B, Ba, Cu, Ga, Mn and Se among the five surrounding provinces of the Great Lake. Nevertheless, Al, Co, Cr, Fe, Mo, Ni, Pb, Tl, U and Zn were not significantly different among the five provinces. Although a number of river and lake water samples had certain trace elements greater than the average levels in the world natural rivers, only Al, Fe and Mn in lake water exceeded the regulation limits. When compared to lakes in other countries, the Tonle Sap Great Lake was less polluted than the others. Moreover, health risk assessment indicated that male and female Cambodian residents are at minimal risk of non-carcinogenic effects of single and mixed trace elements through lake and river water consumption. However, more attention should be paid to As, Tl, Co, Ba, Mn and Cr because they might pose high potential health risks to local residents. Therefore, regular monitoring and further investigations of temporal and spatial distribution are warranted to advance understanding of the pollution trends and toxic behavior of these trace elements in the Tonle Sap Great Lake system.

ACKNOWLEDGEMENTS

The authors would like to thank Mr Sundeth Say and Mr Rithy Aem for their invaluable field assistance.

FUNDING

This work was supported by GIST Research Institute (GRI) grant funded by the Gwangju Institute of Science and Technology (GIST) in 2023.

CONSENT TO PUBLISH

All authors read and approved the content of the final manuscript.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Burnett, W. C., Peterson, R. N., Chanyotha, S., Wattayakorn, G. & Ryan, B. 2013 Using high-resolution in situ radon measurements to determine groundwater discharge at a remote location: Tonle Sap Lake, Cambodia. *J Radioanal Nucl Chem* **296**, 97–103.

Chanpiwat, P. & Sthiannopkao, S. 2014 Status of metal levels and their potential sources of contamination in Southeast Asian rivers. *Environ Sci Pollut Res Int* **21**, 220–233.

Goldhaber, S. B. 2003 Trace element risk assessment: Essentiality vs. toxicity. *Regul Toxicol Pharmacol* **38**, 232–242.

Hou, D., He, J., Lu, C., Ren, L., Fan, Q., Wang, J. & Xie, Z. 2013 Distribution characteristics and potential ecological risk assessment of heavy metals (Cu, Pb, Zn, Cd) in water and sediments from Lake Dalinouer, China. *Ecotoxicol Environ Saf* **93**, 135–144.

Huang, M. L., Zhou, S. L., Sun, B. & Zhao, Q. G. 2008 Heavy metals in wheat grain: Assessment of potential health risk for inhabitants in Kunshan, China. *Sci Total Environ* **405**, 54–61.

Ikem, A. & Adisa, S. 2011 Runoff effect on eutrophic lake water quality and heavy metal distribution in recent littoral sediment. *Chemosphere* **82**, 259–267.

Iqbal, J., Tirmizi, S. A. & Shah, M. H. 2013 Statistical apportionment and risk assessment of selected metals in sediments from Rawal Lake (Pakistan). *Environ Monit Assess* **185**, 729–743.

Irvine, K. N., Richey, J. E., Holtgrieve, G. W., Sarkkula, J. & Sampson, M. 2011 Spatial and temporal variability of turbidity, dissolved oxygen, conductivity, temperature, and fluorescence in the lower Mekong River–Tonle Sap system identified using continuous monitoring. *Intl. J. River Basin Management* **9**, 151–168.

Jiang, X., Wang, W., Wang, S., Zhang, B. & Hu, J. 2012 Initial identification of heavy metals contamination in Taihu Lake, a eutrophic lake in China. *J Environ Sci (China)* **24**, 1539–1548.

Kavcar, P., Sofuoglu, A. & Sofuoglu, S. C. 2009 A health risk assessment for exposure to trace metals via drinking water ingestion pathway. *International Journal of Hygiene and Environmental Health* **212**, 216–227.

Ki, S. J., Kang, J. H., Lee, Y. G., Lee, Y. S., Sthiannopkao, S. & Kim, J. H. 2009 Statistical assessment for spatio-temporal water quality in Angkor, Cambodia. *Water Sci Technol* **59**, 2167–2178.

Krishna, A. K., Satyanarayanan, M. & Govil, P. K. 2009 Assessment of heavy metal pollution in water using multivariate statistical techniques in an industrial area: A case study from Patancheru, Medak District, Andhra Pradesh, India. *J Hazard Mater* **167**, 366–373.

Li, S. & Zhang, Q. 2010 Risk assessment and seasonal variations of dissolved trace elements and heavy metals in the Upper Han River, China. *J Hazard Mater* **181**, 1051–1058.

Masumoto, T., Hai, P. T. & Shimizu, K. 2008 Impact of paddy irrigation levels on floods and water use in the Mekong River basin. *Hydrol Process* **22**, 1321–1328.

MIME 2004 *Drinking Water Quality Standards*. Ministry of Industry Mines and Energy (MIME), Phnom Penh, Cambodia.

Monroy, M., Maceda-Veiga, A. & de Sostoa, A. 2014 Metal concentration in water, sediment and four fish species from Lake Titicaca reveals a large-scale environmental concern. *Sci Total Environ* **487**, 233–244.

NCCC 2013 *Cambodian Climate Change Strategic Plan 2014-2023*. National Climate Change Committee, Royal Government of Cambodia, Phnom Penh, Cambodia.

Oyoo-Okoth, E., Admiraal, W., Osano, O., Ngure, V., Kraak, M. H. & Omutange, E. S. 2010 Monitoring exposure to heavy metals among children in Lake Victoria, Kenya: environmental and fish matrix. *Ecotoxicol Environ Saf* **73**, 1797–1803.

Oyoo-Okoth, E., Admiraal, W., Osano, O., Manguya-Lusega, D., Ngure, V., Kraak, M. H., Chepkirui-Boit, V. & Makwali, J. 2013 Contribution of soil, water and food consumption to metal Exposure of children from geological enriched environments in the coastal zone of Lake Victoria, Kenya. *Int J Hyg Environ Health* **216**, 8–16.

Phan, K., Sthiannopkao, S., Kim, K. W., Wong, M. H., Sao, V., Hashim, J. H., Mohamed Yasin, M. S. & Aljunid, S. M. 2010 Health risk assessment of inorganic arsenic intake of Cambodia residents through groundwater drinking pathway. *Water Res* **44**, 5777–5788.

Phan, K., Phan, S., Huoy, L., Suy, B., Wong, M. H., Hashim, J. H., Mohamed Yasin, M. S., Aljunid, S. M., Sthiannopkao, S. & Kim, K. W. 2013 Assessing mixed trace elements in groundwater and their health risk of residents living in the Mekong River basin of Cambodia. *Environ Pollut* **182**, 111–119.

Sander, S. G., Anderson, B., Reid, M. R., Kim, J. P. & Hunter, K. A. 2013 Trace metal chemistry in the pristine freshwater Lake Hauroko, Fiordland, New Zealand. *Microchemical Journal* **111**, 74–81.

Sok, C. & Chuop, S. 2017 Climate change and groundwater resources in Cambodia. *J. GW Sci. Eng* **4** (2), 31–43.

USEPA 1989 *Risk Assessment Guidance for Superfund, Human Health Evaluation Manual, Vol. 1, Part A*. United States Environmental Protection Agency (USEPA), Washington DC.

USEPA 2014a *Integrated Risk Information System*. United States Environmental Protection Agency (USEPA). http://www.epa.gov/iris/ and http://cfpub.epa.gov/ncea/iris/index.cfm?fuseaction=iris.showSubstanceList. Date accessed: July 10, 2014

USEPA 2014b *Risk Based Concentration Tables*. Regional Screening Level (RSL) Summary Table (TR = 1E-6, HQ = 1) May 2014. http://www.epa.gov/reg3hwmd/risk/human/rb-concentration_table/Generic_Tables/docs/master_sl_table_run_MAY2014.pdf Date accessed: July 10, 2014

USEPA 2014c *Water: Drinking Water Contaminants*. National primary drinking water regulations. http://water.epa.gov/drink/contaminants/ Date accessed: July 10, 2014

WHO 2011 *Guideline for Drinking Water Quality*, 4th edn. World Health Organization (WHO), Geneva.

Wu, B., Zhao, D. Y., Jia, H. Y., Zhang, Y., Zhang, X. X. & Cheng, S. P. 2009 Preliminary risk assessment of trace metal pollution in surface water from Yangtze River in Nanjing Section, China. *Bull Environ Contam Toxicol* **82**, 405–409.

First received 28 August 2022; accepted in revised form 26 March 2023. Available online 10 April 2023