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Chemical risks in drinking water of inhabitants in the basin of the Tonle Sap Great Lake

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ABSTRACT

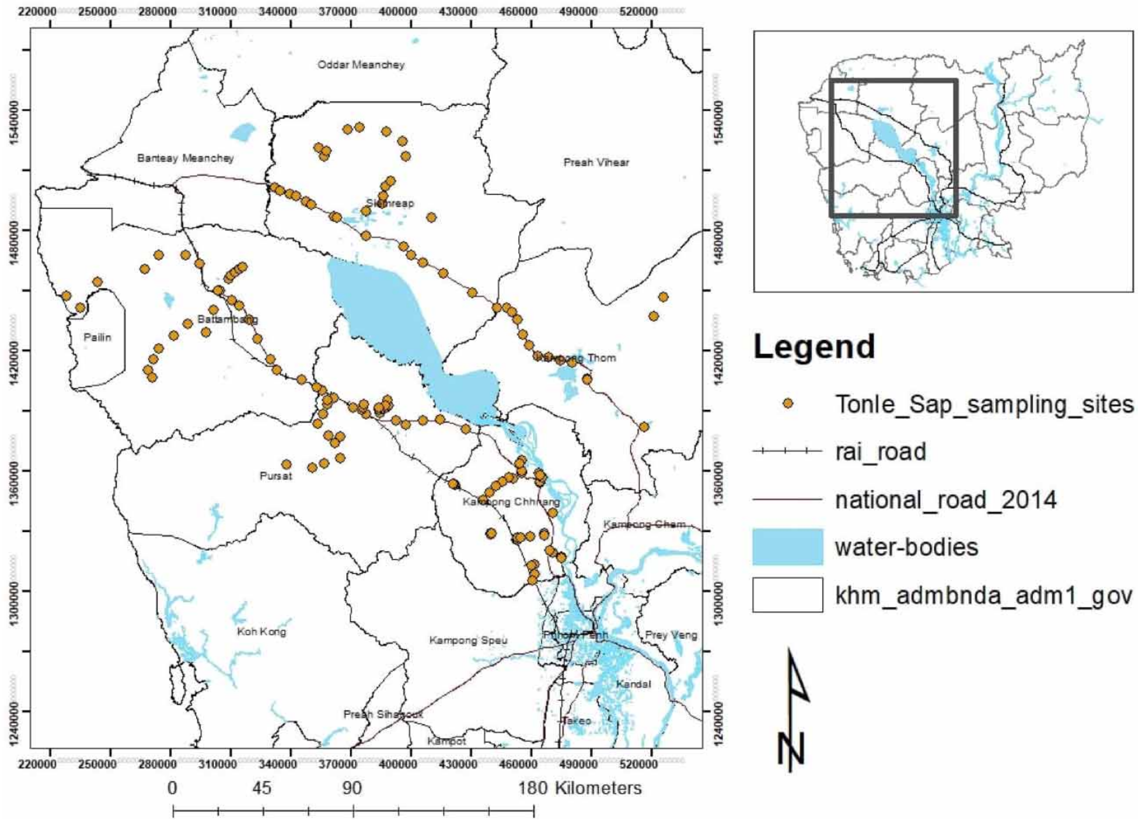
The present study aimed to assess chemical risks in the drinking water of inhabitants in the basin of the Tonle Sap Great Lake. Water samples from tube wells ($n = 52$), dug wells ($n = 13$), stored rain water ($n = 39$), ponds/lakes ($n = 19$), canals/rivers ($n = 24$), and household pipe water ($n = 45$) were collected and analyzed for physicochemical properties, as well as microbial and chemical qualities using standard methods. Analytical results revealed that 42.1% of tube wells had As $> 10\ \mu g\ L^{-1}$ while 8.3% had Cr > 0.05 mg L^{-1}. Concurrently, 55.2 and 11.8% of tube wells had Cd $> 3.00\ \mu g\ L^{-1}$ and Pb $> 10\ \mu g\ L^{-1}$, respectively. Moreover, 35.0% of pipe water had Fe > 0.3 mg L^{-1}, whereas 85.7% of tube wells and 69.2% of dug wells had Mn > 0.1 mg L^{-1}. All water sources including pipe water could pose risks of non-carcinogenic effects of chemical mixtures to all exposure groups through their drinking water pathway. Children were at a higher risk of chemical mixtures in their drinking water than adults. This study suggests that advanced treatment technologies should be applied to the current water treatment plants to provide inhabitants with safe drinking water.

Key words: contaminant of health concern, groundwater, health risk assessment, microbial contaminant, water quality

HIGHLIGHTS

- Analytical results revealed that *Escherichia coli* and coliform were detected in all water sources.
- Elevated As, Ba, Cd, Cr, F^-, NO_3^-, and Pb were detected in some water sources.
- Inhabitants of the Tonle Sap Great Lake basin were exposed to chemicals in drinking water.
- Children were at a higher risk of chemical mixtures in their drinking water than adults.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Cambodia is a tropical country where agriculture is the predominant employment sector for the rural Cambodian population accounting for 57.6% of the 8.8 million-strong labor force and contributing about 32.1% of GDP in 2011 (NCCC 2013). In order to realize a long-term vision of Cambodia to become a high middle-income country by 2030 and high-income country by 2050, the Royal Government of Cambodia has prepared and adopted an Industrial Development Policy (IDP), transforming and modernizing industrial structure from labor intensive industry to a skill-driven one by 2025 (RGC 2015). A general population census of Cambodia 2019 showed that the total population of Cambodia was approximately 15.6 million with a GDP per capita of 1,561$ in 2018 (NIS 2020). The adult mortality rate was 2.5 per 1,000 for women and 4.1 per 1,000 for men (NIS & DGHIM 2011) while the infant mortality rate was 18 per 1,000 live births, 16 in urban areas, and 19 in rural areas (NIS 2020). The Cambodian government has planned that 100% of the rural population will have sustainable access to an improved water supply by 2025 (MRD 2011). By 2020, it has been reported that approximately 73.0% of households had access to clean drinking water, 83.7% in urban areas, and 66.0% in rural areas (NIS 2020). Developments in the Mekong river basin, which might degrade the quality of the water source by nutrient, heavy metal, and pesticide contaminations, were likely to impact the drinking water quality due to the capacities of the available water treatment processes (Vanny *et al.* 2015). The assessment of industrial pollution load in Phnom Penh using an industrial pollution projection system revealed that the basic metal sector generated the most water pollutants in years 1994–2014 (San *et al.* 2018). This study reported that the plastic product and the coke and petroleum refinery sectors were the greatest water polluters in terms of BOD of 111 tonnes (58.47%) and 45 tonnes (23.71%) in 2014, respectively. The basic metal sector contributed the most TSS to water pollution by releasing 10,749 tonnes (65.23%) in 2014 followed by the sporting and athletic goods sector with emissions of 4,880 tonnes (29.61%). The average annual load of total water pollutants was approximately $2,152 \pm 1,083$ tonnes year^{-1} with an annual emission growth rate of 108 ± 195 tonnes year^{-1} (11.11%) (San *et al.* 2018). A previous study on the potential contamination of trace elements in shallow Cambodian groundwater showed that groundwaters from

Kandal and Kraite were enriched in As, Mn, Ba, and Fe (Phan *et al.* 2013). Moreover, the assessment of water quality and trace metal contaminations in Mondolkiri province in the northeastern part of Cambodia revealed that the mean concentrations of Fe and Mn in tube wells and channel water exceeded the Cambodian aesthetic guideline (Phan *et al.* 2019). High arsenic levels (up to 100 $\mu g\ L^{-1}$) were also found in shallow groundwaters from the Tonle Sap Lake and coastal regions of Cambodia (Sovann & Polya 2014). However, it was reported that the shallow aquifer, which was primarily contaminated with pollutants, was chemically less of a health risk than the deep aquifer (Bennett *et al.* 2010). A study on the status of metal levels and their potential sources of contamination in Southeast Asian rivers revealed that the dissolved arsenic concentrations in the Tonle Sap–Bassac rivers were about 2.5 times higher than their background concentrations, the average dissolved metal concentrations of world natural river systems (Chanpiwat & Sthiannopkao 2014). It was reported that the use of rain and surface water from rivers, ponds, and lakes might reduce chronic arsenic poisoning, but they were often supplied without verification of their chemical and microbiological qualities, especially in rural areas (Feldman *et al.* 2007). Because some colorless, odorless, and tasteless contaminants such as arsenic (As), fluoride (F^-), and nitrate (NO_3^-) could not be perceived by householders in their drinking water sources, the only practical way to prevent people from consuming unsafe contamination levels was to test the water quality (Guppy & Shantz 2011). To date, a nationwide water quality monitoring program has not been conducted, thus only a little data are available for health risk assessment and remedial options. Although numerous studies on Cambodian drinking water sources and their health risks have been documented in the Mekong river basin (Phan *et al.* 2010, 2013), the northeastern highland area (Phan *et al.* 2019), and the coastal area (Phan *et al.* 2021, 2023; Sao *et al.* 2023), human health risks of drinking water in the basin of the Tonle Sap Great Lake are little known. The emerging water contaminants described by Kumar *et al.* (2022) are of great importance for water quality assessment and monitoring, but the present study focuses on conventional contaminants because of the limitation of resources and facilities of our local laboratories. In the present study, the qualities of drinking water sources and human health risks of chemical contaminants through the drinking water pathway of inhabitants residing in the basin of the Tonle Sap Great Lake, Cambodia were assessed. The specific objectives were to: (1) determine the physicochemical properties, as well as microbial and chemical qualities of different drinking water sources in the Tonle Sap Great Lake basin; (2) assess the quality of drinking water sources by comparing with the Cambodian drinking water quality standard (CDWQS) and WHO's drinking water quality guidelines; and (3) assess human health risks of chemical contaminants through the drinking water pathway of inhabitants in the basin areas of the Tonle Sap Great Lake.

2. MATERIALS AND METHODS

2.1. Study areas

The present study was designed as a cross-sectional study. Sampling was conducted in the basin of the Tonle Sap Great Lake (Figure 1). This study area is composed of five provinces of Cambodia including Kampong Chhnang, Pursat, Battambang, Siem Reap, and Kampong Thom. The rainfall distribution in Cambodia is strongly influenced by its topography. Seasonal monsoons resulted in the highest rainfall (2,000–3,400 mm) in the southwest of the coastal areas followed by the northeast plateau area (1,800– $>$ 2,200 mm), and the stretches from the northwest to the southeast received an annual rainfall $<$ 1,400 mm (Sok & Chuop 2017).

2.2. Field sampling

Water sampling was conducted in each province of the study area. However, sample collection was dependent on our accessibility to water sources. Water samples from tube wells ($n = 52$), dug wells ($n = 13$), stored rainwater ($n = 39$), ponds/lakes ($n = 19$), and canals/rivers ($n = 24$) were collected. Concurrently, pipe water from the point of use in households ($n = 45$) was also collected after informed consent was obtained. Groundwater was collected from tube wells after 5 min pumping of the standing water in the tube. Dug well water was sampled using a bucket to bring water samples from the well to the ground. Canal/river and lake/pond water were collected using the grab sampling method at a depth of about 0–30 cm. Simultaneously, on-site measurements of water dissolved oxygen (DO) and temperature were measured by using Hanna HI 9147 meter (Hanna, Italy). pH and ORP were measured by using a Hanna pH/ORP meter HI98191 (Hanna, Italy). Electrical conductivity (EC), total dissolved solids (TDS), and salinity were measured by using a Hanna Conductivity/TDS/Salinity meter HI 98192 (Hanna, Italy). Turbidity was measured by a Hach DR850 colorimeter (Hach, USA). A composite sample was filled into three different sampling bottles. Fresh (unfiltered, unacidified) samples were analyzed for physicochemical properties, as well as free Cl_2, F^-, NO_3^-, and NO_2^-. Samples with acidified, filtered (0.45 μm) water samples were analyzed for As, Cu, Cr,

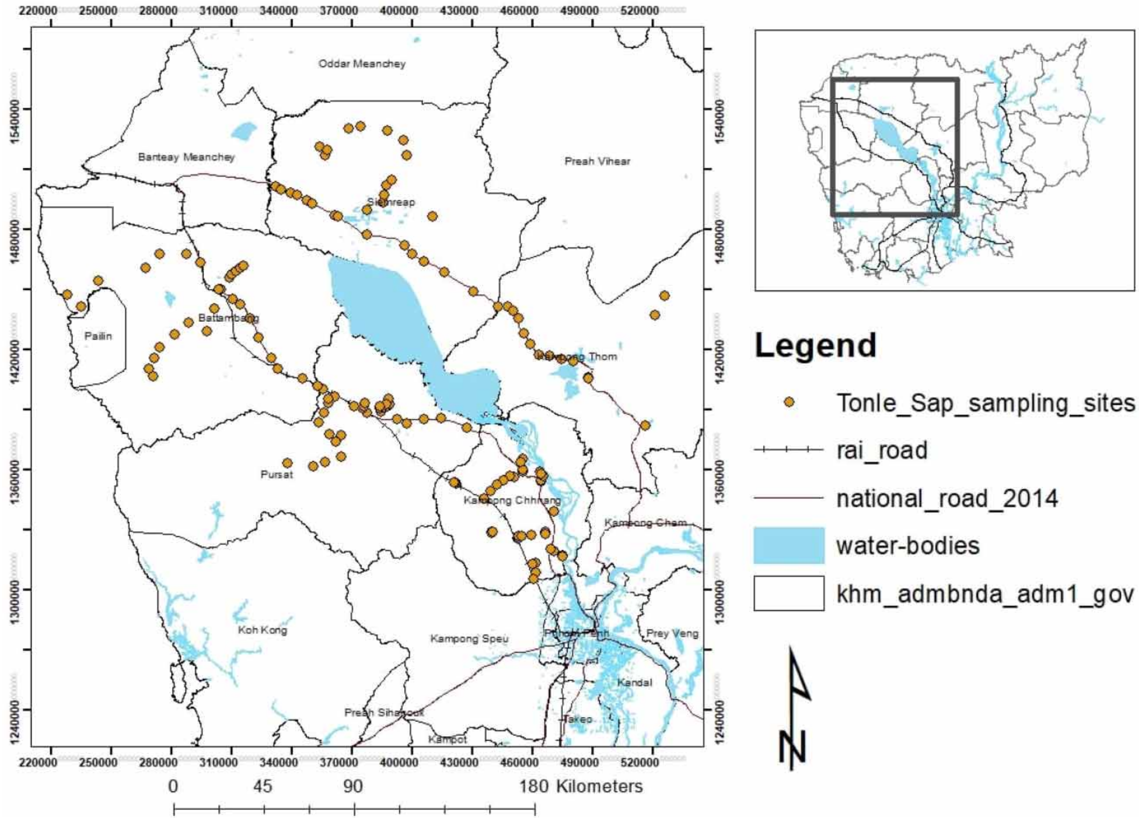


Figure 1 | Map of the sampling area.

Cd, Fe, Mn, Pb, and Zn. The water sample filled in a sterilized bottle was used to test *Escherichia coli* and coliforms. All collected samples were kept in an ice box during field sampling and then were transferred to a refrigerator and stored at 4 °C until analysis.

2.3. Sample preparation and analysis

The measurement of free Cl_2, NO_3^-, and NO_2^- concentrations was conducted by using DR 1900 (Hach, USA) with the respective reagents supplied by Hach. The concentrations of Cu, Cr, Cd, F^-, Fe, Mn, Pb, and Zn were analyzed by colorimetric standard methods (APHA 2017). *E. coli* and coliforms in the water sample were quantified using a modified membrane filtration technique developed by the United States Environmental Protection Agency (USEPA 2002). A 100 mL of water sample is filtered through a 47 mm, 0.45-μm pore size cellulose ester membrane filter, and then, the filter is placed on a 5-mL plate of MacConkey agar. The plate is incubated at 37 °C for up to 24 h. Bacterial colonies that grow on the plate are inspected for the presence of *E. coli* and coliforms with pink and yellow color, respectively. The suspected colonies from McConkey agar were enriched in Tryptic Soy Broth (Sigma Aldrich, US), after which Chromocult® Coliform agar (Merck, Germany) was used to confirm *E. coli* colonies with dark-blue to violet colonies. The concentration was reported as colony-forming units (CFU) per 100 mL of the water sample and all samples were processed in duplicate.

2.4. Health risk assessment

Health risk assessment procedures from the USEPA (1989) were applied to calculate the non-carcinogenic effects of single and mixed contaminants. The average daily dose of a single chemical is calculated from the following Equation (1):

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

where ADD is the average daily dose from ingestion (mg kg^{-1} day^{-1}); C_w is the chemical concentration in water sources (mg L^{-1}); IR is the ingestion rate of water sources (L day^{-1}); EF is the exposure frequency (days $year^{-1}$); ED is the exposure duration (year); BW is the body weight (kg); and AT is the averaging time (d). The summary of parameters used to calculate the ADD of rural Cambodian inhabitants is presented in Table 1. The non-carcinogenic effects of a single chemical, expressed as the hazard quotient (HQ), are computed from Equation (2) whereas the non-carcinogenic effects of mixed chemicals (hazard index) are calculated from Equation (3).

$$HQ = \frac{ADD}{RfD} \quad (2)$$

HQ is the hazard quotient. Non-carcinogenic effects were considered if $HQ > 1$; RfD is the reference dose of a single chemical. The oral reference dose (mg kg^{-1} day^{-1}) of As (3×10^{-4}), Ba (2×10^{-1}), Cd (5×10^{-4}), Cr (3×10^{-3}), Mn (1.4×10^{-1}), Zn (3×10^{-1}), F (6×10^{-2}), NO2 (10^{-1}), NO_3 (16×10^{-1}), and Cl_2 (10^{-1}) was obtained from a database of the Integrated Risk Information System (USEPA 2022).

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

HI is a hazard index that indicates the aggregate risk/risk of mixed chemicals. The non-carcinogenic effects of mixed chemicals are considered to occur in circumstances where HI is greater than one.

2.5. Statistical data analysis

All statistical data analyses were performed by SPSS for Windows (version 15.0). The Mann–Whitney *U* test was used to verify the significant differences in physicochemical properties between tube wells and dug wells and those between pipe water and rainwater. The Kruskall–Wallis test was applied to verify the significant differences in *E. coli* and coliform among all water sources. Significance was considered in circumstances where $p < 0.05$.

3. RESULTS AND DISCUSSION

3.1. Physicochemical and microbial qualities of water sources in the basin of Tonle Sap Lake

The physicochemical properties and microbiological qualities of water sources in the basin of the Tonle Sap Great Lake are presented in Table 2. The pH of tube wells ranged from 4.57 to 7.74 (6.19 ± 0.78) where approximately 61.5% of tube wells had a pH < 6.50. The mean pH of dug wells was 6.36 ± 0.54 where approximately 53.8% of dug wells had a pH < 6.50. It was consistent with the previous report that the pH of shallow groundwater in the Tonle Sap Lake was slightly acidic to circum-neutral, ranging from 5.8 to 7.6 (Sovann & Polya 2014). The mean pH of pond/lake water was 6.91 ± 0.94 (ranged from 4.47 to 9.08) while that of canal/river water was 7.27 ± 0.45 (ranged from 6.24 to 8.26); approximately 31.6% of pond water and 8.3% of canal water had pH < 6.50 while 5.3% of pond water had pH > 8.50. The pH of ponds/lakes was in a wider range than the previous study which reported that the Tonle Sap Lake had a pH that ranged from 7.04 to 8.61 in the dry season while it ranged from 7.91 to 8.40 in the rainy season (Yoshikawa *et al.* 2020). Similarly, the pH of canals/rivers was in a wider range than the previously reported pH of the tributary rivers of the Tonle Sap Lake (ranged from 6.60 to 7.93) (Yoshikawa *et al.* 2020). The pH of pipe water ranged from 5.09 to 9.18 (7.18 ± 0.70) where approximately 15.6% water had pH < 6.50 and 2.2% had pH > 8.50. Stored rainwater had a pH that ranged from 6.34 to 10.74 (7.93 ± 0.92) where approximately 5.1% water had pH < 6.50 and 17.9% had pH > 8.50. The EC of tube wells ranged 22.6–2,503.3 μS cm^{-1} while that of dug wells ranged from 24.1 to 646.9 μS cm^{-1}. Sovann & Polya (2014) reported that the EC of shallow groundwaters from provinces around the Tonle Sap Great Lake, Cambodia ranged from 121 to 3,070 μS cm^{-1}, which was

Table 1 | Summary of parameters used to calculate the ADD of rural Cambodian inhabitants adapted from Phan *et al.* (2010)

	Adults				Children			
	BW (kg)	Age (years)	IR (L day^{-1})	ED (years)	BW (kg)	Age (years)	IR (L day^{-1})	ED (years)
Male	53.5	39	2.0	8	20.4	8	1.1	5
Female	49.4	40	1.7	8	20.0	8	1.0	5

BW, Body Weight (Kg); IR, Ingestion Rate (L d^{-1}); ED, Exposure Duration (y).

Table 2 | Summary of the physicochemical properties and microbial qualities of water sources in the basin of the Tonle Sap Great Lake of Cambodia

Water sources	Statistics	DO (mg L^{-1})	Temp (°C)	pH	ORP (mV)	EC (μS cm^{-1})	TDS (mg L^{-1})	Sal (ppt)	Turb (NTU)	*E. coli LogCFU 100* mL^{-1}	Coliform *LogCFU 100* mL^{-1}
Tube well	Mean	3.8	28.4	6.19	269.3	523.0	261.8	0.18	11.8	3.0	3.5
(n = 52)	Median	3.2	28.7	6.30	265.8	285.3	142.8	0.07	2.0	3.3	3.8
	SD	2.0	1.7	0.78	65.8	591.7	296.1	0.24	37.2	1.3	0.9
	Min	1.1	24	4.57	63.7	22.6	11.3	0	0	0.0	1.7
	Max	10.3	33.1	7.74	391	2503.3	1252.7	1.12	254	4.6	5.1
Dug well	Mean	3.4	28.8	6.36	250.7	258.6	129.4	0.07	11.8	2.9	3.5
(n = 13)	Median	3.2	28.9	6.49	233.0	160.0	79.9	0.01	10.0	2.8	3.5
	SD	1.3	1.3	0.54	56.5	215.7	108.0	0.09	8.6	0.7	0.6
	Min	1.2	26.1	5.47	193.1	24.1	12.1	0	1	2.0	2.6
	Max	6	30.2	7.03	355.5	646.9	323.8	0.23	29	4.1	4.4
Pipe water	Mean	5.8	28.8	7.18	262.6	180.2	90.2	0.02	4.9	2.0	3.1
(n = 45)	Median	6.1	28.1	7.25	275.0	129.3	64.5	0.00	2.0	2.3	3.2
	SD	1.4	2.3	0.70	49.0	154.4	77.2	0.06	6.6	1.3	0.9
	Min	1.5	25.2	5.09	39.3	20.6	10.3	0	0	0.0	0.0
	Max	8.3	38.1	9.18	327.1	800.3	400.2	0.34	21	4.3	4.7
Rain water	Mean	5.8	28.8	7.93	257.6	170.5	85.2	0.03	1.1	3.1	3.6
(n = 39)	Median	6.1	28.0	7.81	253.8	117.9	59.0	0.00	0.0	3.3	3.5
	SD	0.9	2.4	0.92	45.6	192.1	96.1	0.08	2.7	0.7	0.7
	Min	1.8	25.2	6.34	141.3	33.4	16.7	0	0	0.7	2.4
	Max	6.9	36.9	10.74	368.1	981.2	490.7	0.43	16	4.3	4.9
Pond water	Mean	5.2	30.3	6.91	261.2	188.1	94.1	0.02	9.7	3.4	3.8
(n = 19)	Median	5.4	30.2	6.86	242.2	141.0	70.8	0.00	5.0	3.4	3.9
	SD	1.5	2.9	0.94	49.8	117.9	59.0	0.03	11.0	0.6	0.9
	Min	2.6	25.9	4.47	185.5	59.1	29.6	0	0	2.3	2.0
	Max	8.4	35.8	9.08	351.9	413.5	206.8	0.12	33	4.5	5.0
Canal water	Mean	5.7	28.7	7.27	255.8	119.7	59.7	0.01	97.3	3.1	3.9
(n = 24)	Median	6.0	27.9	7.26	261.0	60.9	30.0	0.00	26.0	3.1	4.0
	SD	1.4	2.0	0.45	46.5	141.9	71.1	0.03	229.2	1.0	0.8
	Min	2.4	26.7	6.24	177.6	10.6	5.3	0	0	1.0	1.8
	Max	8.1	32.6	8.26	325.5	550.3	275.3	0.12	1,137	5.2	5.1

comparable to the present study. Out of all water sources, tube wells had the highest mean TDS of 261.8 ± 296.1 mg L^{-1}, followed by dug wells which had a mean TDS of 129.4 ± 108.0 mg L^{-1}. Although the mean TDS of tube wells was lower than 800 mg L^{-1}, approximately 9.6% of tube wells had TDS greater than the CDWQS (MIME 2004). Stored rainwater had the lowest mean turbidity of 1.1 ± 2.7 NTU whereas canal/river had the highest mean turbidity of 97.3 ± 229.2 NTU. The turbidity of pipe water ranged from 0 to 21 NTU with a mean of 4.9 ± 6.6 NTU. Approximately 28.8% of tube wells, 69.2% of dug wells, 26.7% of pipe water, 2.6% of rainwater, 42.1% of ponds, and 79.2% of canals had turbidity greater than 5 NTU, exceeding CDWQS (MIME 2004). Although DO, temperature, pH, EC, TDS, salinity, and turbidity were significantly different among all types of water sources (Kruskall–Wallis test, $p < 0.05$), except turbidity, they did not significantly differ between tube wells and dug wells (Mann–Whitney U test, $p > 0.05$). Further comparison showed that pipe water and rainwater were not significantly different in DO, temperature, ORP, EC, TDS, and salinity (Mann–Whitney U test, $p >$ 0.05), but pH and turbidity were significantly different (Mann–Whitney U test, $p < 0.05$).

E. coli and coliform were detected in all water sources, but ponds/lakes had the highest mean logCFU of *E. coli* (Figure 2). Since *E. coli* is an indicator organism for fecal contamination, the presence of other pathogens transmitted by the oral-fecal route is not unconsidered and there might potentially be higher risks to the health of inhabitants who drink the surface waters (Widmer *et al.* 2013). A recent study revealed that fecal sludge in Phnom Penh is a pollution source that needs to be treated before discharging it into the natural environment, to reduce potential health and environmental consequences (Eliyan *et al.* 2022). Pipe water collected from the point of use in the present study, which is believed to be treated, contained *E. coli* and

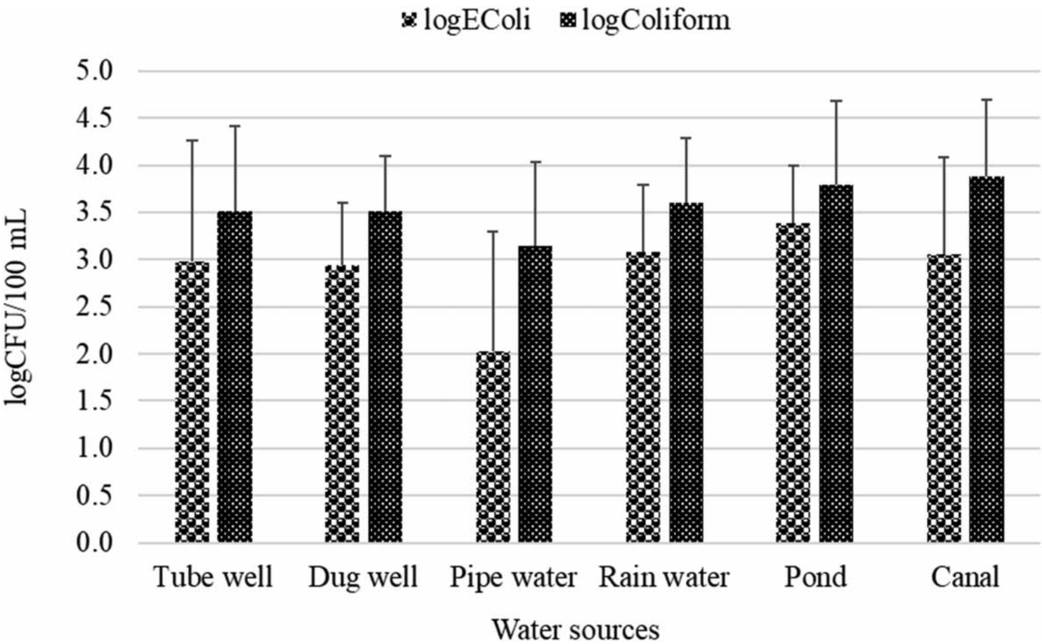


Figure 2 | Distribution of *Escherichia coli* and coliform in different water sources in the basin of the Tonle Sap Great Lake.

coliform exceeding the CDWQS (MIME 2004). A comparison indicated that *E. coli* and coliform were significantly different among all types of water sources (Kruskall–Wallis test, $p < 0.05$). However, *E. coli* and coliform of tube wells and dug wells were not significantly different (Mann–Whitney *U* test, $p > 0.05$). A previous study reported that microbial contamination was considerable for shallow wells with mean *E. coli* loads of 10^3 CFU/100 mL (Bennett *et al.* 2010). Further comparison revealed that *E. coli* and coliform of pipe water were significantly different from their water sources including pond/lake (Mann–Whitney *U* test, $p < 0.05$) and canal/river (Mann–Whitney *U* test, $p < 0.05$). The detection of microbial contamination in pipe water indicated that water treatment processes might not effectively remove microorganisms from water sources or secondary contamination at the point of use might occur. Recently, it has been reported that the increase in coliform and *E. coli* between the point of collection and the point of use indicated that water contamination mostly occurred within the household (Poirot *et al.* 2020). However, our field visit to typical rural water supply facilities in Kampong Thom and Kampong Chhang provinces noted that pipe water was treated with simple treatment processes consisting of coagulation and sand filtration with unmonitored chlorination. It might not effectively disinfect microorganisms from moderate to highly contaminated water sources. A nationwide water quality monitoring program should be implemented to ensure that clean and safe water is supplied across the country.

3.2. Chemical qualities of drinking water sources in the basin of the Tonle Sap Great Lake

The chemical qualities of drinking water sources in the basin of the Tonle Sap Lake are presented in Table 3. The concentrations of As, Ba, Cl_2, Cr, Cu, Fe Mn, and Zn were significantly different among all types of water sources in the present study area (Kruskall–Wallis test, $p < 0.05$). A further comparison revealed that As in tube wells significantly differed from pipe water (Mann–Whitney *U* test, $p < 0.05$), but it was not significantly higher than dug wells, stored rain water, ponds/lakes, and canals/rivers (Mann–Whitney *U* test, $p > 0.05$). Approximately, 15.8% of tube wells had As > 50 μg L^{-1}, CDWQS (MIME 2004), while 42.1% had As > 10 μg L^{-1}, WHO's drinking water quality guideline (WHO 2017). Tube wells were detected with the highest As concentration (240 μg L^{-1}) among all types of water sources in the basin of the Tonle Sap Great Lake. This was comparable to a previous study which found that As levels ranged from 0.1 to 101 μg L^{-1} in shallow groundwaters from the Tonle Sap Great Lake (Sovann & Polya 2014). As distribution in water sources in the basin of the Tonle Sap Great Lake was lower than that of the Mekong river basin which has been previously documented (Kim *et al.* 2011; Phan *et al.* 2013; Murphy *et al.* 2018). Arsenicosis symptoms were found to rapidly develop in the Kandal province of Cambodia (Sampson *et al.* 2008), which might be likely due to high As in blood through oral ingestion

Table 3 | Summary of contaminants of health concern and other chemical qualities of water sources in the basin of the Tonle Sap Great Lake of Cambodia

Water sources	Statistics	As (mg L^{-1})	Ba (mg L^{-1})	Cl_2 (mg L^{-1})	Cu (mg L^{-1})	Cr (mg L^{-1})	Cd (μg L^{-1})	F- (mg L^{-1})	Fe (mg L^{-1})	Mn (mg L^{-1})	NO_2^- (mg L^{-1})	NO_3^- (mg L^{-1})	Pb (μg L^{-1})	Zn (mg L^{-1})
Tube well	Mean	0.040	1.53	0.04	0.04	0.03	8.281	0.23	0.65	0.66	0.15	7.43	6.10	0.17
(n = 52)	Median	0.005	1.00	0.03	0.02	0.01	4.800	0.17	0.11	0.43	0.01	4.00	3.50	0.05
	SD	0.071	2.00	0.05	0.08	0.04	14.036	0.29	1.12	0.79	0.95	12.55	7.95	0.40
	Min	0.000	0.00	0.00	0.00	0.00	0.200	0.00	0.00	0.00	0.00	0.00	0.17	0.00
	Max	0.240	8.00	0.25	0.48	0.14	77.000	1.45	5.70	4.07	6.90	82.80	25.58	2.58
Dug well	Mean	0.006	1.33	0.05	0.10	0.06	5.682	0.31	0.37	0.31	0.02	8.69	3.00	0.04
(n = 13)	Median	0.000	0.00	0.04	0.06	0.06	4.591	0.16	0.34	0.30	0.02	5.30	3.00	0.03
	SD	0.015	3.28	0.04	0.10	0.05	5.249	0.46	0.31	0.26	0.01	11.06	2.47	0.02
	Min	0.000	0.00	0.01	0.01	0.01	0.545	0.04	0.02	0.00	0.00	1.30	1.25	0.01
	Max	0.047	10.00	0.12	0.29	0.14	13.000	1.81	0.97	0.89	0.03	39.30	4.75	0.08
Pipe water	Mean	0.007	0.53	0.04	0.07	0.13	5.530	0.21	0.29	0.28	0.12	4.71	14.38	0.14
(n = 45)	Median	0.000	0.00	0.03	0.03	0.11	5.200	0.21	0.10	0.14	0.02	3.25	3.50	0.09
	SD	0.017	0.86	0.08	0.10	0.13	4.037	0.11	0.39	0.28	0.68	4.60	31.13	0.19
	Min	0.000	0.00	0.00	0.00	0.00	0.000	0.00	0.00	0.02	0.00	0.00	0.08	0.01
	Max	0.065	3.00	0.54	0.45	0.55	15.286	0.41	1.83	0.90	4.60	23.50	117.25	1.13
Rain water	Mean	0.044	0.83	0.01	0.02	0.01	4.428	0.29	0.05	0.39	0.26	4.34	3.53	0.33
(n = 39)	Median	0.010	1.00	0.01	0.01	0.01	2.250	0.24	0.03	0.45	0.01	4.00	1.80	0.16
	SD	0.079	0.99	0.02	0.02	0.01	6.049	0.21	0.08	0.24	0.89	2.43	5.48	0.54
	Min	0.000	0.00	0.00	0.00	0.00	0.000	0.03	0.00	0.00	0.00	0.00	0.17	0.01
	Max	0.232	3.00	0.13	0.06	0.01	25.867	0.97	0.35	0.80	3.94	10.60	19.22	2.79
Pond water	Mean	0.033	1.89	0.12	0.04	0.03	3.088	0.38	0.83	0.40	0.34	4.30	8.33	0.20
(n = 19)	Median	0.005	1.00	0.11	0.03	0.01	1.429	0.30	0.64	0.30	0.01	3.10	6.42	0.07
	SD	0.059	1.54	0.11	0.05	0.06	3.546	0.33	0.81	0.32	0.96	4.32	8.74	0.24
	Min	0.000	0.00	0.00	0.00	0.00	0.000	0.06	0.00	0.02	0.00	0.00	1.83	0.00
	Max	0.120	5.00	0.49	0.20	0.18	11.000	1.05	2.60	1.30	3.07	18.20	23.08	0.71
Canal	Mean	0.004	0.88	0.09	0.08	0.11	3.479	0.21	1.54	0.90	0.03	4.15	1.84	0.10
water	Median	0.000	0.50	0.07	0.05	0.11	2.643	0.17	1.41	0.29	0.03	2.50	1.84	0.06
(n = 24)	SD	0.008	1.15	0.08	0.08	0.08	2.516	0.17	1.58	1.68	0.04	4.29	2.35	0.20
	Min	0.000	0.00	0.00	0.01	0.01	0.000	0.01	0.01	0.00	0.00	0.00	0.17	0.00
	Max	0.030	3.00	0.33	0.24	0.30	9.571	0.61	7.30	6.88	0.20	12.80	3.50	0.99

(Phan *et al.* 2014). Generally, drinking water contains an average of 2 μg L^{-1} of As, but long-term oral exposure to low levels of inorganic As might cause dermal effects, peripheral neuropathy, and increased risks of skin cancer, bladder cancer, and lung cancer (ATSDR 2007). Approximately 8.3% of tube wells and 50.0% of dug wells had Cr $>$ 0.05 mg L^{-1}. The distribution of Cd and Pb in different types of water sources in the basin of the Tonle Sap Great Lake is presented in Figure 3. About 55.8% of all tube wells (n = 52) were detected with Cd. While approximately 55.2% of the detected tube wells had Cd $>$ 3.00 μg L^{-1}, elevated Cd was also found in other water sources in the basin of the Tonle Sap Great Lake. Cd and Pb in pipe water were not significantly different from those in tube wells, dug wells, stored rainwater, ponds/lakes, and canals/rivers (Mann–Whitney U test, $p > 0.05$). It was found that approximately 11.8% of tube wells had Pb $>$ 10 μg L^{-1}. Elevated Pb concentrations were also found in pipe water and stored rainwater. Approximately 36.5% of tube wells, 61.6% of dug wells, and 35% of pipe water had Fe $>$ 0.3 mg L^{-1} whereas 85.7% of tube wells and 69.2% of dug wells had Mn $>$ 0.1 mg L^{-1}. Elevated F concentrations were found in dug wells whereas elevated NO_3^- concentrations were found in tube wells.

3.3. Exposure assessment

The average daily dose of a single chemical for adults is presented in Table 4 and for children is presented in Table 5. It is reported that approximately 55% of urban and 16% of rural residents have access to a safely managed drinking water service at their homes (MRD 2019). Our field observation revealed that rural inhabitants, who had access to either a tube well or a dug well, have used them in combination with rainwater. The exposure frequency of rainwater is about six months

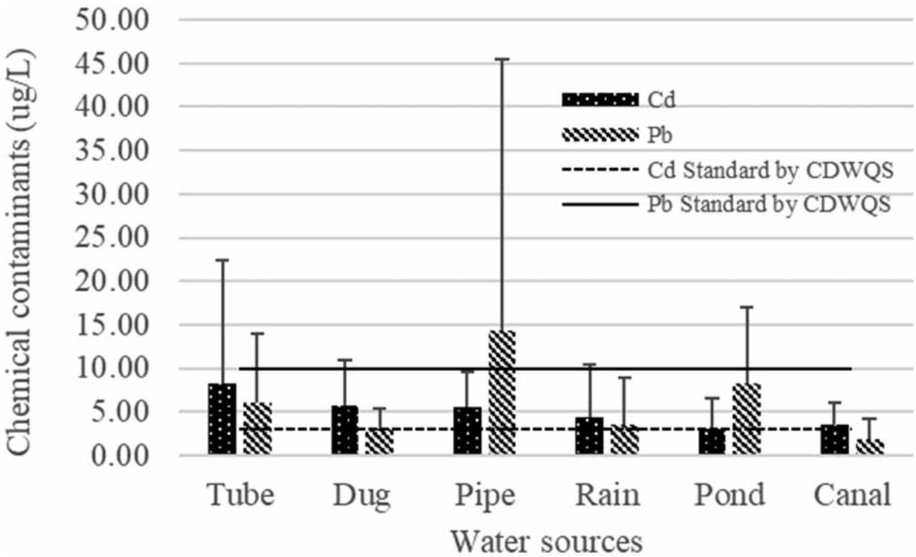


Figure 3 | Distribution of Cd and Pb in different water sources in the basin of the Tonle Sap Great Lake.

Table 4 | Summary of the average daily dose (mg kg^{-1} day^{-1}) of a single chemical through drinking pathway of adult inhabitants in the basin of the Tonle Sap Great Lake of Cambodia

	Male adults					**Female adults**				
	Mean	**Median**	**SD**	**Min**	**Max**	**Mean**	**Median**	**SD**	**Min**	**Max**
As	0.00045	0.00000	0.00102	0.00000	0.00447	0.00041	0.00000	0.00094	0.00000	0.00412
Ba	0.01425	0.00000	0.03231	0.00000	0.18692	0.01312	0.00000	0.02974	0.00000	0.17206
Cl_2	0.00151	0.00074	0.00258	0.00000	0.02019	0.00139	0.00068	0.00238	0.00000	0.01858
Cr	0.00193	0.00037	0.00322	0.00000	0.02056	0.00178	0.00034	0.00296	0.00000	0.01893
Cd	0.00014	0.00009	0.00017	0.00000	0.00142	0.00013	0.00008	0.00016	0.00000	0.00131
F	0.00658	0.00485	0.00677	0.00000	0.03912	0.00605	0.00446	0.00623	0.00000	0.03601
Mn	0.01392	0.00796	0.02730	0.00000	0.25712	0.01282	0.00733	0.02513	0.00000	0.23669
NO_2^-	0.00414	0.00024	0.02045	0.00000	0.17193	0.00381	0.00022	0.01882	0.00000	0.15827
NO_3^-	0.13017	0.08163	0.17347	0.00000	1.52653	0.11982	0.07515	0.15969	0.00000	1.40524
Zn	0.00459	0.00205	0.00798	0.00000	0.05144	0.00422	0.00188	0.00735	0.00000	0.04735

SD, standard deviation; Min, minimum; Max, maximum.

(EF = 180 days $year^{-1}$) in the rainy season (May to November). Tube wells and/or dug wells were used for another six-month period (EF = 180 days $year^{-1}$) in the dry season. Inhabitants who had pipe water connected at home or had access to other surface water sources, such as ponds and/or canals, used them year-round (EF = 365 days $year^{-1}$). The average daily dose of As up to 6.5×10^{-3} mg kg^{-1} day^{-1} was found in the basin of the Tonle Sap Great Lake. Previous studies had reported that the average daily dose of As was 3×10^{-7}–10.75×10^{-3} mg kg^{-1} day^{-1} in the Mekong river basin of Cambodia (Phan *et al.* 2013) and 1.1×10^{-3}–4.3×10^{-3} mg kg^{-1} day^{-1} in the Ha Nam province of Vietnam (Nguyen *et al.* 2009). The average daily dose of As in the basin of the Tonle Sap Great Lake was lower than in the Mekong River basin, but it was higher than that of the Ha Nam province of Vietnam.

3.4. Risk characterization

The risks of non-carcinogenic effects of chemical mixtures in adults and children are presented in Figure 4. All exposure groups (male and female adults and children) were at risk of chemical mixtures in their water sources. This was consistent

Table 5 | Summary of the average daily dose of a single chemical through the drinking pathway of children inhabitants in the basin of the Tonle Sap Great Lake of Cambodia

	Male children					Female children				
	Mean	**Median**	**SD**	**Min**	**Max**	**Mean**	**Median**	**SD**	**Min**	**Max**
As	0.00064	0.00000	0.00147	0.00000	0.00645	0.00059	0.00000	0.00134	0.00000	0.00590
Ba	0.02055	0.00000	0.04660	0.00000	0.26961	0.01879	0.00000	0.04261	0.00000	0.24652
Cl_2	0.00218	0.00106	0.00373	0.00000	0.02912	0.00199	0.00097	0.00341	0.00000	0.02662
Cr	0.00279	0.00053	0.00464	0.00000	0.02966	0.00255	0.00049	0.00424	0.00000	0.02712
Cd	0.00020	0.00013	0.00025	0.00000	0.00205	0.00018	0.00012	0.00023	0.00000	0.00187
F	0.00948	0.00700	0.00977	0.00000	0.05643	0.00867	0.00640	0.00893	0.00000	0.05160
Mn	0.02008	0.01148	0.03938	0.00000	0.37088	0.01836	0.01050	0.03600	0.00000	0.33911
NO_2^-	0.00597	0.00035	0.02949	0.00000	0.24799	0.00546	0.00032	0.02697	0.00000	0.22675
NO_3^-	0.18775	0.11775	0.25021	0.00000	2.20187	0.17167	0.10766	0.22878	0.00000	2.01328
Zn	0.00662	0.00295	0.01151	0.00000	0.07419	0.00605	0.00270	0.01052	0.00000	0.06784

SD, standard deviation; Min, minimum; Max, maximum.

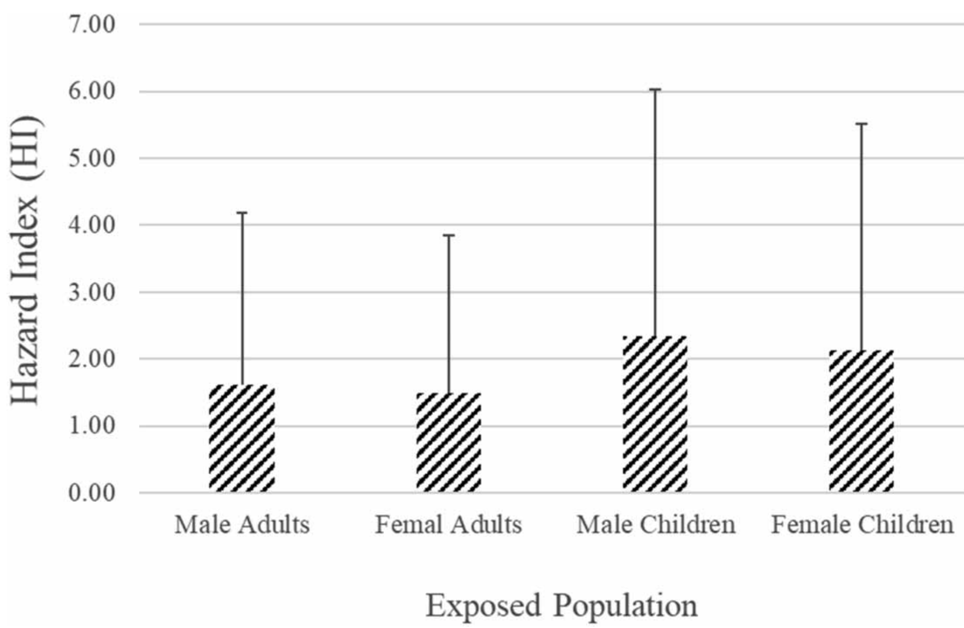


Figure 4 | Hazard index of chemical mixtures in all water sources of inhabitants in the basin of the Tonle Sap Great Lake.

with the human health risk assessment of groundwater in the rural areas of Jashore, Bangladesh which indicated that residents across all age groups (infants, children, and adults) face a significant non-carcinogenic health risk (Chakraborty *et al.* 2022). A comparison of the hazard index among all exposure groups revealed that children were at a higher risk of chemical mixtures than adults while men were at higher risk than women. Numerous studies have reported that children were at a higher risk of chemical mixtures than adults (Xiao *et al.* 2019; Varol 2020). The risks of non-carcinogenic effects of a single chemical in adults and children are presented in Figure 5. A comparison shows that only the mean HQ of As was greater than 1. This was consistent with our previous study on the health risk assessment of contaminants in drinking water sources in the coastal areas of Cambodia (Sao *et al.* 2023). However, the HQ of As in the present study was much lower than the HQ of As of water resources contaminated by agricultural activities in Korkuteli, Turkey which were

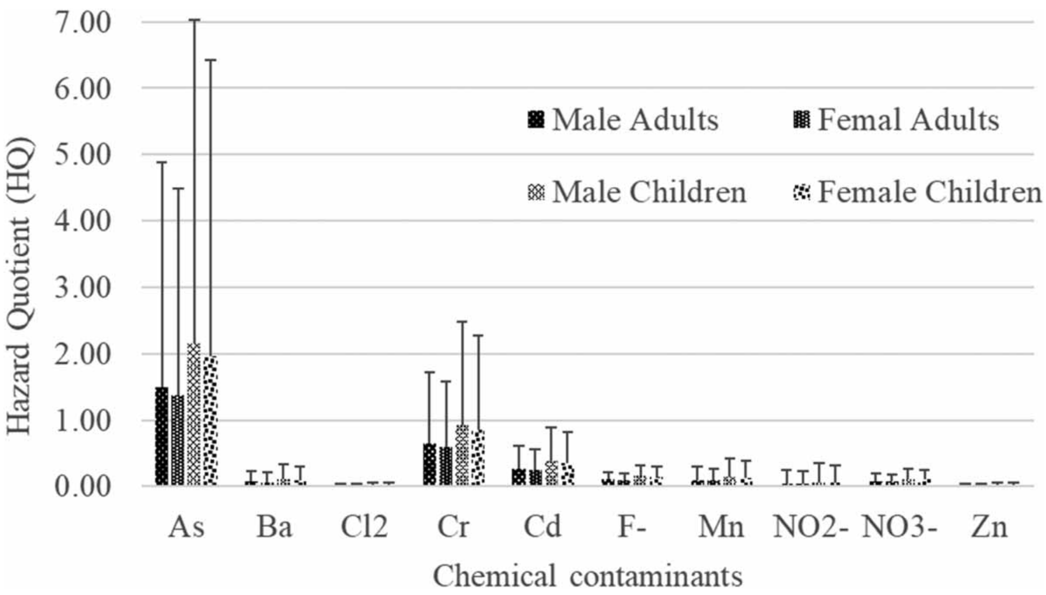


Figure 5 | Hazard quotient of a single chemical in drinking water sources of inhabitants in the basin of the Tonle Sap Great Lake.

between 7.62 and 16.19 in the dry season and 8.72–16.44 in the wet season (Varol & Şekerci 2018). The upper range HQ of Cr, Cd, Mn, NO_2^- of adults and the upper range of HQ of Ba, Cr, Cd, Mn, NO_2^-, and NO_3^- of children were greater than 1 indicating some adults and children in the basin of the Tonle Sap Lake were at the risk of single contaminants in their drinking water sources. It has been reported that none of the inhabitants in the Mekong river basin of Cambodia were at risk of non-carcinogenic effects from Ag, Ba, Cd, Co, Cr, Cu, Mn, Ni, Se, U, and Zn alone. However, 98.7 and 12.4% of inhabitants in the study areas of Kandal and Kraite, respectively, were at risk of non-carcinogenic effects of As (Phan *et al.* 2013). The risks of non-carcinogenic effects of chemical mixtures in adults and children by different water sources are presented in Figure 6. All types of water sources, including pipe water, could pose risks of non-carcinogenic effects of chemical mixtures to all exposure groups through their drinking water pathway. It was consistent with a previous study which reported that approximately 98.7 and 12.4% of inhabitants in the study areas of Kandal and Kraite,

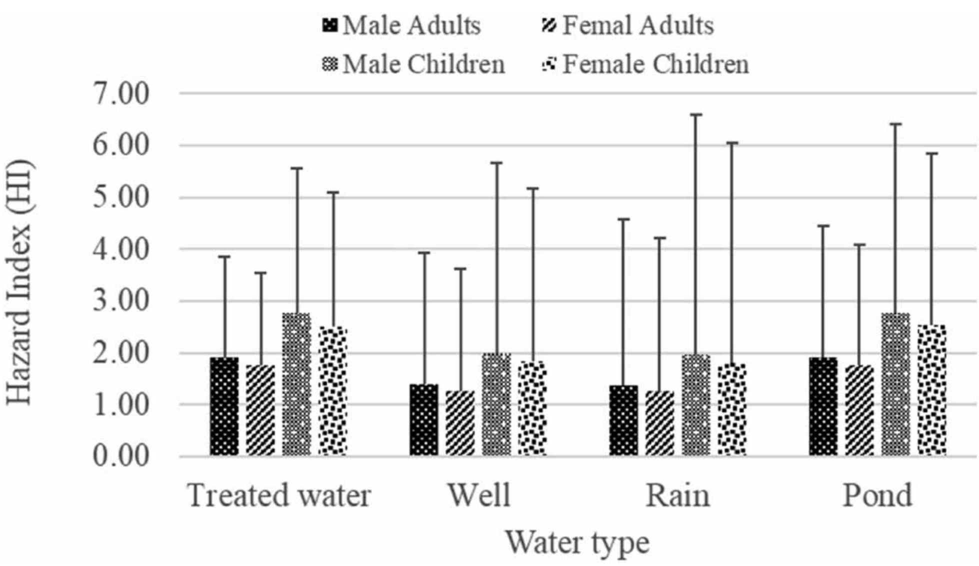


Figure 6 | Hazard index of chemical mixtures in different water sources of inhabitants in the basin of the Tonle Sap Great Lake.

respectively, were at risk of non-carcinogenic effects of mixed trace elements through their groundwater pathway (Phan *et al.* 2013).

4. CONCLUSIONS

Six different types of water sources, including pipe water from the point of use in the basin of the Tonle Sap Great Lake of Cambodia, were investigated on their qualities, and human health risks of chemicals through the drinking water pathway were assessed. Analytical results revealed that *E. coli* and coliform were detected in all water sources whereas pond/lake had the highest mean logCFU of *E. coli*. The concentrations of As, Ba, Cl_2, Cr, Cu, Fe, Mn, and Zn were significantly different among all types of water sources in the present study area. As distribution in water sources in the basin of the Tonle Sap Great Lake was comparable to a previous study, but it was lower than that of the Mekong river basin. Elevated Pb concentrations were found in tube wells, pipe water, and stored rainwater, whereas elevated Cd was found in all types of water sources. Elevated F^- concentrations were found in dug wells whereas elevated NO_3^- concentrations were found in tube wells. The health risk assessment revealed that some inhabitants residing in the basin of the Tonle Sap Great Lake are exposed to chemical contaminants through the drinking water pathway. Children are at a higher risk of chemical mixtures in their drinking water than adults. This study suggests that a nationwide water quality monitoring program should be regularly conducted. Moreover, drinking water should be properly treated based on the qualities of their sources and the best available water treatment technologies should be applied to prevent health risks of chemical contaminants to all consumers. Further studies on emerging water contaminants in various drinking water sources are warranted to better characterize health risks in order to prevent and/or minimize public health concerns in Cambodia.

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CONSENT TO PARTICIPATE

Pipe water from the point of use in households was collected after informed consent was obtained.

CONSENT TO PUBLISH

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

AUTHOR CONTRIBUTIONS

K.P., V.S., and C.O.C. conceptualized and wrote the manuscript. T.S. and V.S. reviewed and revised the manuscript. K.P., S.H., S.P., and N.T. performed sample and data analyses and graphing. C.O.C. approved the submission of the manuscript.

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AVAILABILITY OF DATA AND MATERIAL

All data are presented in this manuscript.

COMPETING INTERESTS

The authors have no conflict of interest to declare.

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.

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