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Assessing drinking water quality and health risks of contaminants in the coastal areas of Cambodia

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ABSTRACT

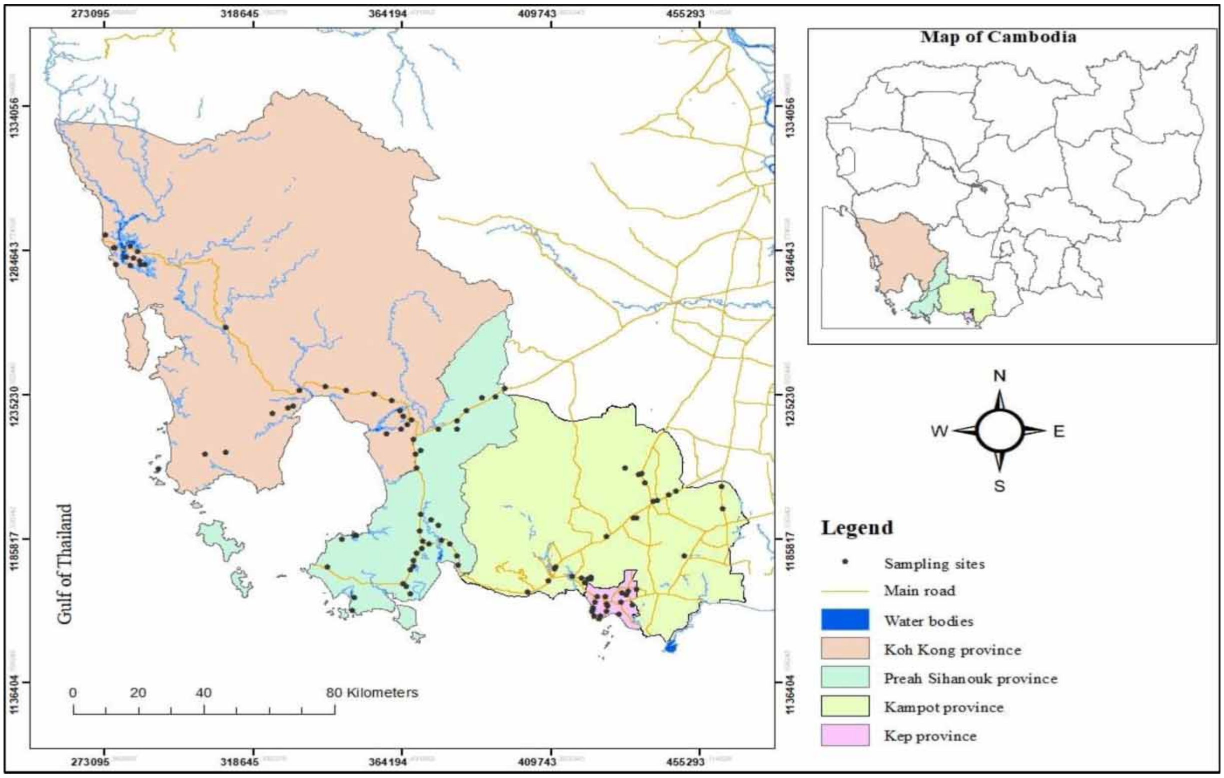
The present study aimed to assess the health risks of chemical contaminants of residents in the coastal areas of Cambodia through their drinking water pathways. Water was sampled from tube wells ($n = 22$), dug wells ($n = 31$), ponds ($n = 11$), canals ($n = 12$) and lakes ($n = 4$) across the Cambodian coastal areas, and measured for the contaminants of health concern (As, Cu, Cr, Cd, F^-, NO_2^-, NO_3^-, Pb, *Escherichia coli* and total coliform) and aesthetic quality following the United States Environmental Protection Agency (USEPA) and standard methods. Analytical results reveal that 9.1% of tube wells and 9.7% of dug wells contained As $>$ 0.01 mg/L. Appropriately, 22.7% of tube wells and 32.3% of dug wells contained Fe $>$ 0.3 mg/L while 100% of tube wells and 80.6% of dug wells contained Mn $>$ 0.1 mg/L. Health risk assessment found that the hazard quotient (HQ) $>$ 1 for children and women. Additionally, the lifetime cancer risk (LCR) was found $>1 \times 10^{-4}$ for As in Cambodian coastal areas. Therefore, a monitoring programme and appropriate treatment to remove contaminants like arsenic, cadmium and fluoride would be required to ensure a safe drinking water supply to Cambodian coastal residents.

Key words: Cambodia, coastal area, contaminants of health concern, drinking water, faecal pollution, heavy metals, risk assessment

HIGHLIGHTS

- Both total coliform and *E. coli* were found in the tube well, dug well, ponds, canals and lakes while the Cambodian Drinking Water Quality Standard for total coliform and *E. coli* is not detectable per 100 mL.
- Health risk assessment revealed that for children and women residing in the coastal areas of Cambodia had HQ $>$ 1.
- Men, women and children residing in the coastal areas of Cambodia are exposed to carcinogenic risk of As through drinking water pathways.

GRAPHICAL ABSTRACT



1. INTRODUCTION

The rapid growth of population, industrial development and agricultural activities may lead to increased production of different wastes containing various chemicals around the world. Health risk management and assessment of contaminants from natural resources including water are important in protecting community health (WHO 1999). Assessment is required for hazardous substances that may enter the body through ingestion or inhalation as well as skin contact. It should be noted that if water is contaminated by chemicals, ingested water can result in potential health risks for consumers (Villanueva *et al.* 2014).

Surface water contamination is often caused by nutrients, pathogens, plastics and chemicals such as antibiotics, heavy metals and pesticides, whereas groundwater is contaminated by naturally occurring processes in the ground. Contamination of pathogenic microorganisms in drinking water sources can be removed by simple methods such as boiling, filtration (ceramic/bio-sand) or disinfection. However, the removal of heavy metals may require advanced water treatment technologies. Some metals like copper (Cu), zinc (Zn), iron (Fe) and magnesium (Mg) are essential for human growth, but some metals such as cadmium (Cd), chromium (Cr), nickel (Ni), arsenic (As) and lead (Pb) are toxic and harmful to humans (Xie *et al.* 2013). Children may be particularly susceptible to neurotoxic substances such as arsenic and manganese as suggested by previous studies on their effects on children's intellectual function (Wasserman *et al.* 2011). Arsenic is a ubiquitous element found in the atmosphere, soil, rocks and natural waters. The introduction of cancer appears to be the most striking long-term effect of chronic exposure to inorganic arsenic. Epidemiological studies have demonstrated an evident causal relationship between environmental, occupational and medical exposure of man to inorganic arsenic and cancer of the skin and lungs (IARC 1980).

In Cambodia, both surface and groundwater are commonly used for drinking, bathing and agricultural activities. Water quality and human health risks caused by chemical contaminants of surface and groundwater in coastal areas in Cambodia have not been properly assessed. In the present study, the non-carcinogenic and carcinogenic health risks of the residents living in Cambodian coastal areas through their drinking pathways are investigated. The objectives of this study were (i) to evaluate the qualities of surface water and groundwater for drinking following the Cambodian Drinking Water Quality

Standard (CDWQS) (MIME 2004) and the guideline of drinking water quality of the World Health Organization (WHO) (WHO 2011) and (ii) to assess non-carcinogenic and carcinogenic health risks constituted by selected trace elements and heavy metals in drinking water sources from both tube wells and dug wells in the coastal areas of Cambodia.

2. MATERIALS AND METHODS

2.1. Study area

This study was designed as a cross-sectional study that was conducted across coastal areas including Koh Kong, Preah Sihanouk, Kampot and Kep provinces of Cambodia (Figure 1).

2.2. Sample collection

Groundwater and surface water samples from tube wells ($n = 22$), dug wells ($n = 31$), ponds ($n = 11$), canals ($n = 12$) and lakes ($n = 4$) were collected across the above-mentioned coastal areas. Groundwater sampling was conducted following a method described by Phan *et al.* (2021). The water from tube wells was sampled after 5–10 min of pumping to flush the standing water out. Grab sampling was used to collect water from the dug wells, ponds, canals and lakes. At each site, water samples were filled in three different bottles for specific analysis purposes. A water sample filled in a sterilized PTFE bottle was used to test *Escherichia coli* and coliforms. Fresh (unfiltered, unacidified) water samples were analyzed for free Cl_2, F^-, NO_3^- and NO_2^- concentrations. And finally, those with acidified, filtered (0.45 µm) water samples were analyzed for As, Cu, Cr, Cd, Fe, Mn, Pb and Zn. The simultaneous on-site measurements were conducted at each site to test physicochemical parameters. pH, temperature and ORP were measured by using a HANNA pH/ORP meter HI98191 (HANNA, Italy), while electrical conductivity (EC), total dissolved solids (TDS) and salinity were measured by using a HANNA Conductivity/TDS/Salinity meter HI 98192 (HANNA, Italy). In addition, dissolved oxygen (DO) was measured by using a HANNA HI 9147 meter (HANNA, Italy) and turbidity was measured at each sampling location by Hach DR850 colourimeter (Hach DR850, USA). All collected samples were kept in an ice box during field sampling and then were transferred to a refrigerator maintained at the temperature of 4 °C until analysis.

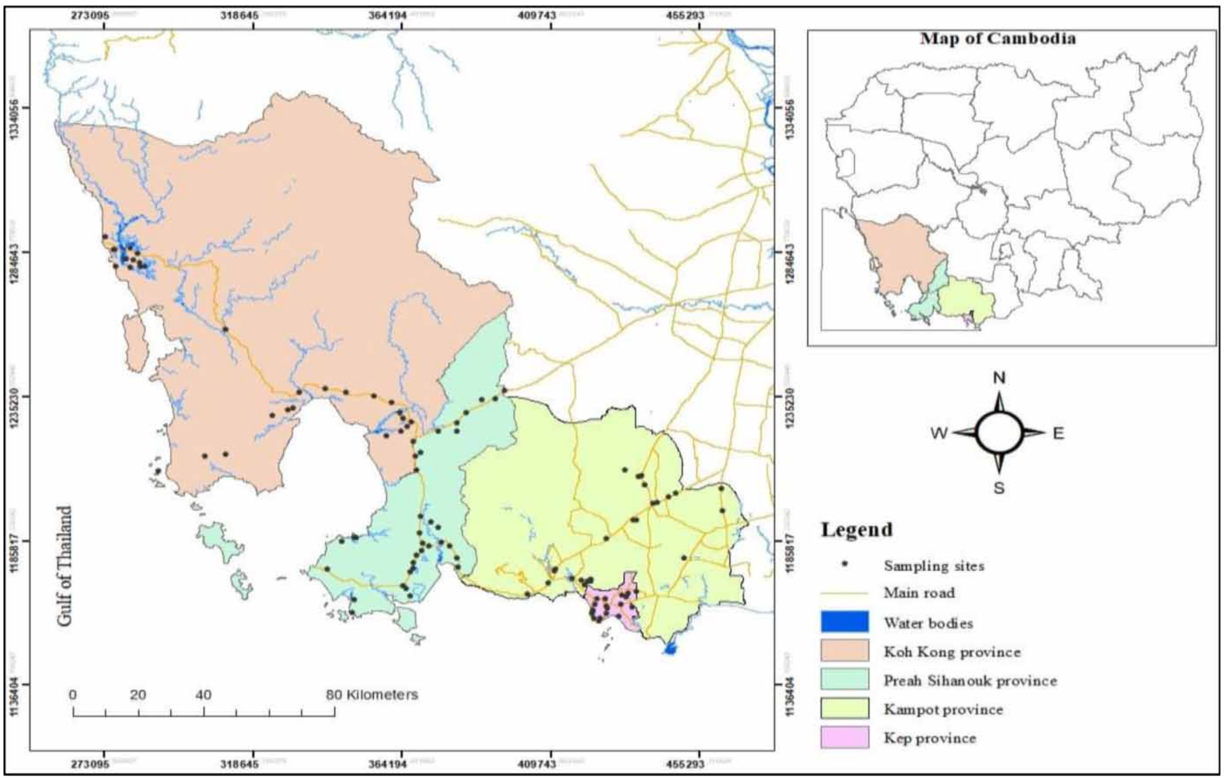


Figure 1 | Map of the study coastal area.

2.3. Sample preparation and analysis

The measurements of free Cl_2, NO_3^- and NO_2^- concentrations were 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 colourimetric standard methods (APHA 2017). Standard reference materials were measured in the same manner as the samples to certify the accuracy of each analytical method. *E. coli* and coliforms in the water sample were quantified using a modified membrane filtration technique developed by the United States Environmental Protection Agency (USEPEA) (USEPA 2002). 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. The bacterial colonies grown on the plate are inspected for the presence of *E. coli* and coliforms with pink and yellow colour, respectively. The count number of bacteria is reported as colony-forming units (CFU) per 100 mL of water sample, and all samples were processed in duplicate.

2.4. Health risk assessment

Human health risk assessment of heavy metals through drinking water was carried out to estimate the non-carcinogenic and lifetime cancer risk (LCR) of residents in the coastal areas. To estimate the non-carcinogenic risk, the following equations were used (USEPA 2009):

$$HQ = \frac{ADD}{RfD}, \text{ and}$$

$$ADD = \frac{C \times IR \times EF \times ED}{BW \times AT},$$

where HQ is the hazard quotient (therefore, $HQ < 1$ suggests unlikely adverse health effects and $HQ > 1$ indicates the probability of adverse health effects (Watts 1998)), ADD is the average daily dose (mg/kg day), C is the average concentration of heavy metals in water, IR is the ingestion rate of drinking water per capita, EF is the exposure frequency, ED is the exposure duration, BW is the body weight, and AT is the average time $= ED \times 365$ (Mesdaghinia *et al.* 2016). Table 1 shows the summary of exposure assumptions used to calculate risk assessment.

To estimate the lifetime cancer risk (LCR), the following equations were used (USEPA 2009):

$$LCR = LADD \times CSF, \text{ and}$$

$$LADD = \frac{CW \times IR \times EF \times ED}{BW \times AT},$$

where LCR is greater than 10^{-4} and will be deemed as a clearly unacceptable risk, but the acceptable LCR will range from 10^{-6} to 10^{-4}. Calculation for the lifetime average daily dose (LADD) is similar to that for the ADD, except the average time (AT). The AT for carcinogen is 70 years, which is equivalent to 25,550 days. Table 2 shows the reference dose (RfD) and cancer slope factor (CSF) of parameters used to calculate the risk assessment.

Table 1 | Summary of exposure assumptions used for health risk assessment

		Values		
Risk exposure factors	**Unit**	**Men**	**Women**	**Children**
Ingestion Rate (IR)	L/day	2	2	1
Exposure Frequency (EF)	Days/year	365	365	365
Exposure Duration (ED)	Years	20	20	20
Average Time (AT) for non-carcinogenic	Years	7.300	7.300	7.300
Average Time (AT) for carcinogenic	Day	25,550	25,550	25,550
Average Body Weight (BW)	Kg	70	60	20

Table 2 | The summary of RfD and CSF used for health risk assessment

Parameters	Unit	RfD/CSF Factors	
		RfD	CSF
Arsenic	mg/kg-day	3×10^{-4}	1.5
Chlorine	mg/kg-day	1×10^{-1}	NA
Copper	mg/kg-day	4×10^{-2}	NA
Chromium	mg/kg-day	3×10^{-3}	NA
Cadmium	mg/kg-day	5×10^{-4}	NA
Fluoride	mg/kg-day	6×10^{-2}	NA
Iron	mg/kg-day	7×10^{-1}	NA
Manganese	mg/kg-day	1.4×10^{-1}	NA
Nitrate	mg/kg-day	1.6	NA
Lead	mg/kg-day	3.5×10^{-3}	NA
Zinc	mg/kg-day	3×10^{-1}	NA

USEPA (2009), Maleki & Jari (2021).

Note: USEPA, United States Environmental Protection Agency; RfD, oral reference dose; CSF, cancer slope factor; NA, not applicable.

2.5. Data analysis

Data obtained from the survey were analyzed by using Microsoft Excel and presented as descriptive statistics in the form of tables. The water quality data from the experiment were compared with the corresponding values of the CDWQS (MIME 2004) and WHO (WHO 2011).

3. RESULTS AND DISCUSSION

3.1. Groundwater quality

Table 3 shows the summary of water quality of tube wells and dug wells in Cambodian coastal areas. The results indicate that 45.5% of tube wells and 74.2% of dug wells had pH $<$ 6.5, which is lower than the pH in CDWQS (MIME 2004) and the guidelines of drinking water quality of the WHO (WHO 2011) ranging from 6.5 to 8.5. Approximately 85% of tube wells and 76% of dug wells in Koh Kong had pH $<$ 6.5 (Phan *et al.* 2021). Both tube wells and dug wells often contained high levels of TDS, which is an indication of salt content. Normally, fresh water is defined by salinity of less than 1,000 mg/L or slightly saline if salinity is from 1,000 to 3,000 ppm (USGS 2019). The Agency for Toxic Substances and Disease Registry (ATSDR) classified arsenic as the top substance on its list of 275 substances present in the environment that pose the most significant potential threat to human health (ATSDR 2011). Arsenic concentration in groundwater was found to be $>$0.01 mg/L, a guideline value of the WHO guidelines (WHO 2011). However, it was lower than 0.05 mg/L, a regulation limit of the Cambodia Drinking Water Quality Standard (MIME 2004). Approximately 9.1% of tube wells and 9.7% of dug wells contained As greater than 0.01 mg/L. Analytical results showed that the concentration of As in Cambodian groundwater samples in the Mekong River basin ranged from 0.03 to 1,841.50 μg/L, where Kandal province was found to have the highest concentration of As (Phan *et al.* 2010). It should be noted that the contamination of arsenic in groundwater is a form of groundwater pollution that is naturally occurring in deep groundwater. Estimates using groundwater quality and population data for Kandal province of Cambodia suggested that over 100,000 people are at high risk of chronic exposure to groundwater with arsenic levels exceeding 50 μg/L (Sampson *et al.* 2008). Exposure to high arsenic could cause pigmentation, hyperkeratosis, ulceration, skin cancer and also affect liver, kidney, heart, and lungs (Sun *et al.* 2019). The concentration of F^- in water from tube wells ranges from 0.09 mg/L to 2.31 mg/L, and from 0.12 mg/L to 1.71 mg/L for dug wells. This exceeds the value of 1.5 mg/L of CDWQS and WHO. About 9% of tube wells and 9.7% of dug wells contained F^- greater than 1.5 mg/L. A similar case was observed in Bangladesh, where the fluoride concentration in the groundwater of Bangladesh's coastal areas varied widely from 0.01 to 15 mg/L (wet season) and 0.01 to 16.11 mg/L (dry season), which was within the standard limits set in Bangladesh of 1.0 mg/L (Rahman *et al.* 2020). Natural occurrence of iron (Fe) and manganese (Mn) is often found dissolved in groundwater at a high concentration which caused groundwater to be unusable due to

Table 3 | Summary of water quality of tube well and dug well in coastal areas

	Tube well ($n = 22$)				Dug well ($n = 31$)					
Parameters	**Mean**	**Min**	**Max**	**SD**	**Mean**	**Min**	**Max**	**SD**	**CDWQS**	**WHO**
pH	6.52	4.29	9.05	1.06	5.80	4.04	7.68	0.94	6.5–8.5	6.5–8.5
Temperature (°C)	30.02	26.60	39.10	2.41	30.44	27.90	33.10	1.44	–	–
DO (mg/L)	3.46	1.00	7.40	1.67	2.88	1.20	5.90	1.34	–	–
ORP (mV)	307.67	242.87	409.00	44.49	317.94	251.43	410.00	35.08	–	–
EC (μS/cm)	415.67	17.36	1,954.00	453.97	382.94	6.85	6,875.00	1,224.94	–	–
TDS (mg/L)	207.08	8.70	974.40	226.32	191.52	3.44	3,438.67	612.68	800	1.000
Salinity (ppt)	0.20	0.01	0.97	0.23	0.15	0.00	3.27	0.59	–	–
Turbidity (NTU)	9.61	0.00	102.00	21.83	11.10	0.00	87.00	17.83	5	5
As (mg/L)	0.01	0.00	0.03	0.01	0.01	0.00	0.02	0.01	0.05	0.01
Free Cl_2 (mg/L)	0.05	0.00	0.17	0.04	0.07	0.00	0.40	0.08	–	5
Cu (mg/L)	0.05	0.00	0.18	0.05	0.02	0.00	0.05	0.02	1	2
Cr (mg/L)	0.05	0.00	0.19	0.07	0.01	0.00	0.03	0.02	0.05	0.05
Cd (μg/L)	3.85	0.33	10.78	3.28	2.40	0.27	6.75	2.03	3	3
F^- (mg/L)	0.76	0.09	2.31	0.56	0.68	0.12	1.71	0.52	1.5	1.5
Fe (mg/L)	0.40	0.00	2.35	0.68	0.54	0.01	4.10	0.97	0.3	0.3
Mn (mg/L)	0.38	0.10	1.10	0.26	0.46	0.02	1.40	0.35	0.1	0.1
NO_2-N (mg/L)	0.003	0.000	0.009	0.002	0.002	0.000	0.011	0.003	3	3
NO_3-N (mg/L)	1.15	0.00	2.97	0.76	1.48	0.00	5.20	1.13	50	50
Pb (μg/L)	5.33	1.40	10.40	2.71	3.74	0.44	10.80	2.88	10	10
Zn (mg/L)	0.12	0.00	0.62	0.14	0.07	0.00	0.72	0.17	3	5
Log *E. coli* (CFU/100 mL)	2.43	0.00	4.02	1.04	3.11	1.83	4.41	0.70	0	0
Log Coliform (CFU/100 mL)	3.61	1.78	4.79	0.84	3.28	1.78	5.03	0.81	0	0

Note: SD, standard deviation; Min, minimum; Max, Maximum; CDWQS, Cambodian Drinking Water Quality Standard; WHO, World Health Organization.

its aesthetic properties. In the case of Mn, a potential health concern (Podgorski *et al.* 2022) is observed. In our study, analytical results showed that approximately 22.7% of tube wells and 32.3% of dug wells contained Fe > 0.3 mg/L, while 100% of tube wells and 80.6% of dug wells contained Mn > 0.1 mg/L. This exceeded the aesthetic value set by CDWQS and WHO. Groundwater has been considered as a water source being non-contaminated by microbiological such as total coliform and *E. coli*. However, our results revealed the presence of both total coliform and *E. coli* in tube wells and dug wells. That is likely caused by improper maintenance, cleaning and rainfall which could accelerate the infiltration of contaminants from the surface into the groundwater.

3.2. Surface water quality

Surface water is the water above the ground which includes rivers, streams, lakes, canals, ponds, wetlands and reservoirs. Surface water is an important source for drinking and irrigation of farmland. In a previous study, surface water was dominated by equilibrium with atmospheric carbon dioxide, whose pH value was often around 6 (Phan *et al.* 2021). In the current study, the summary of water quality data from ponds, canals and stream in coastal areas is presented in Table 4. Approximately 63.6% of ponds had pH of less than 6.50 while 9.1% had a pH exceeding 8.5. Approximately 58.3% of the canals had a pH of less than 6.5 while none of them had a pH > 8.5. pH values of water from lakes ranged between 6.5 and 8.5, which was within recommended limits (WHO 2011). About 54.5% of ponds, 75.0% of canals and 100% of lakes had turbidity > 5 NTU, exceeding the CDWQS and the guideline of drinking water quality of WHO. Erosion, runoff, debris or discharge of wastewater was likely the sources resulting in an increase of turbidity in surface water. The mean concentration of As in ponds, canals and lakes was lower than CDWQS, 0.05 mg/L. However, the upper range of As in ponds and canals was equal to 0.01 mg/L, WHO's Drinking Water Quality Guideline (WHO 2011). Analytical results showed that

Table 4 | Summary of water quality of pond, canal and lake water in the Cambodian coastal areas

	Pond ($n = 11$)				Canal ($n = 12$)				Lake ($n = 4$)					
Parameters	**Mean**	**Min**	**Max**	**SD**	**Mean**	**Min**	**Max**	**SD**	**Mean**	**Min**	**Max**	**SD**	**CDWQS**	**WHO**
pH	6.29	4.39	9.04	1.21	6.15	4.36	7.54	0.88	7.08	6.91	7.37	0.20	6.5–8.5	6.5–8.5
Temp (°C)	31.36	28.10	34.40	1.75	31.20	28.00	35.90	2.38	31.98	30.90	32.80	0.89	–	–
DO (mg/L)	5.29	3.90	6.20	0.68	4.69	1.30	7.70	1.78	4.88	4.10	5.80	0.85	–	–
ORP (mV)	326.18	259.53	406.00	39.14	283.03	244.50	348.27	38.14	327.99	316.10	341.87	11.60	–	–
EC (μS/cm)	66.15	8.49	230.60	73.22	103.11	10.00	319.83	80.97	73.19	50.07	95.65	22.22	–	–
TDS (mg/L)	33.23	4.41	115.23	36.48	51.62	5.00	160.00	40.47	36.63	25.07	47.86	11.10	800	1.000
Salinity (ppt)	0.01	0.00	0.04	0.01	0.01	0.00	0.10	0.03	0.00	0.00	0.00	0.00	–	–
Turbidity (NTU)	16.70	1.00	100.33	28.51	20.50	0.00	71.00	23.23	15.50	9.00	24.00	6.41	5	5
As (mg/L)	0.01	0.00	0.01	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.05	0.01
Free Cl_2 (mg/L)	0.07	0.00	0.32	0.09	0.10	0.02	0.30	0.08	0.16	0.09	0.24	0.07	–	5
Cu (mg/L)	0.02	0.00	0.05	0.02	0.11	0.01	0.38	0.18	0.12	0.03	0.35	0.15	1	2
Cr (mg/L)	0.02	0.00	0.05	0.02	0.03	0.02	0.04	0.01	0.04	0.03	0.05	0.01	0.05	0.05
Cd (μg/L)	4.92	1.18	9.67	4.29	1.43	0.78	1.75	0.46	3.28	0.78	5.22	2.29	3	3
F^- (mg/L)	0.51	0.18	0.91	0.30	1.06	0.16	1.97	0.67	0.42	0.28	0.72	0.20	1.5	1.5
Fe (mg/L)	0.70	0.12	2.71	0.72	0.86	0.02	2.06	0.73	0.79	0.36	1.52	0.51	0.3	0.3
Mn (mg/L)	0.52	0.10	1.90	0.49	0.46	0.20	1.60	0.38	0.32	0.27	0.40	0.06	0.1	0.1
NO_2-N (mg/L)	0.01	0.00	0.05	0.02	0.01	0.00	0.10	0.03	0.12	0.04	0.19	0.06	3	3
NO_3-N (mg/L)	1.48	0.47	3.37	0.97	1.13	0.10	2.40	0.69	0.63	0.40	0.90	0.22	50	50
Pb (μg/L)	5.42	3.78	8.22	2.12	2.62	1.50	3.18	0.97	0.00	0.00	0.00	0.00	10	10
Zn (mg/L)	0.06	0.01	0.013	0.05	0.08	0.01	0.19	0.06	0.11	0.09	0.16	0.03	3	5
Log *E. coli* (CFU/100 mL)	3.48	1.98	4.33	0.69	3.04	1.38	3.95	0.68	2.22	1.81	2.69	0.44	0	0
Log Coliform (CFU/100 mL)	3.97	3.52	4.90	0.40	4.10	2.58	4.85	0.70	3.29	2.82	3.63	0.34	0	0

Note: SD, standard deviation; Min, minimum; Max, Maximum; CDWQS, Cambodian Drinking Water Quality Standard; WHO, World Health Organization.

18.18% of pond water and 50.0% of lake water had Cd > 3 μg/L of CDWQS and WHO. The maximum concentrations of F^- in pond and lake water were lower than CDWQS and WHO's drinking water quality guideline value, 1.5 mg/L; but 25.0% of F^- concentration in canals was higher than CDWQS, 1.5 mg/L. The presence of Fe in natural water can be attributed to the weathering of rocks and minerals, acidic mine drainage, landfill, leachates, sewage effluents and iron-related industries (James 1977). Analytical results showed that 81.8% of ponds, 66.7% of canals and 100% of lakes had Fe > 0.3 mg/L, a regulation limit of CDWQS and WHO. Similarly, all ponds, canals and lake waters had Mn > 0.1 mg/L, a regulation limit of CDWQS and WHO. Total coliforms are the group of bacteria commonly found in environments such as water and soil exposed to waste pollution. *E. coli* is a member of the total coliform group that is highly specific for faecal excreta from animals and humans. The presence of coliform bacteria in water indicates recent faecal contamination which implies the possible presence of other pathogens like bacteria, viruses and parasites. CDWQS for total coliform and *E. coli* are none detectable per 100 mL. Analytical results showed that both total coliform and *E. coli* were found in ponds, canals and lakes.

3.3. Human health risk assessment

The assessment of human health risks was conducted for three target groups: men, women and children. The calculation was performed based on the average consumption rate and frequency. The calculations of non-carcinogenic risks by drinking water from tube wells are presented in Table 5 while those from dug wells are presented in Table 6. The calculation of non-carcinogenic risks of Free Cl_2, Cu, Cr, Cd, F^-, Fe, Mn, NO_3^-, Pb and Zn among men, women and children revealed that HQ was less than one unit, indicating that there are no potential non-carcinogenic health risks associated with their drinking water. The HQ of As was higher than one unit for women and children which indicated that there are potential non-carcinogenic health risks associated with As in their drinking water. It should be noted that HQ values for children were higher than those for men and women, indicating that children were more susceptible to non-carcinogenic risk from the contaminants, respectively. Moreover, HQ values in tube wells were higher than those in dug wells, suggesting that tube wells pose higher health risks than dug wells. HQ is taken into consideration for oral toxicity reference doses for trace metals that humans can be exposed to (Luvhimbi *et al.* 2022). Health risks associated with heavy metal exposure through ingestion depends on sex, age, weight, consumption duration and volume of water consumed by an individual. For groundwater, the mean values of HQ of As for both children and adults were above 1, indicating a sign of adverse effects and non-carcinogenic risks to human health (Tong *et al.* 2021). Thus, the residents in the studied coastal areas should be aware of the health risks caused by drinking their groundwater. We suggest proper treatment as an immediate solution before using groundwater in the Cambodian coastal areas, specifically those water sources containing a high concentration of As.

Table 5 | Non-carcinogenic risk calculation by ingestion from tube well

	Tube well (n = 22)						
		Men		Women		Children	
Parameters	Mean concentration (mg/L)	ADD	HQ	ADD	HQ	ADD	HQ
As	0.01	0.00029	0.952	0.00033	**1.111**	0.00050	**1.667**
Free Cl_2	0.05	0.00143	0.014	0.00167	0.017	0.00250	0.025
Cu	0.05	0.00143	0.036	0.00167	0.042	0.00250	0.063
Cr	0.05	0.00143	0.476	0.00167	0.556	0.00250	0.833
Cd	0.00385	0.00011	0.220	0.00013	0.257	0.00019	0.385
F^-	0.76	0.02171	0.362	0.02533	0.422	0.03800	0.633
Fe	0.40	0.01143	0.016	0.01333	0.019	0.02000	0.029
Mn	0.38	0.01086	0.078	0.01267	0.090	0.01900	0.136
NO_3^-	1.15	0.03286	0.021	0.03833	0.024	0.05750	0.036
Pb	0.00533	0.00015	0.044	0.00018	0.051	0.00027	0.076
Zn	0.12	0.00343	0.011	0.00400	0.013	0.00600	0.020

Note: ADD, average daily dose; HQ, hazard quotient.

Table 6 | Non-carcinogenic risk calculation by ingestion from dug well

	Dug well ($n = 31$)						
		Men		Women		Children	
Parameters	Mean concentration (mg/L)	ADD	HQ	ADD	HQ	ADD	HQ
As	0.01	0.00029	0.952	0.00033	**1.111**	0.00050	**1.667**
Free Cl_2	0.07	0.00200	0.020	0.00233	0.023	0.00350	0.035
Cu	0.02	0.00057	0.014	0.00067	0.017	0.00100	0.025
Cr	0.01	0.00029	0.095	0.00033	0.111	0.00050	0.167
Cd	0.0024	0.00007	0.137	0.00008	0.160	0.00012	0.240
F^-	0.68	0.01943	0.324	0.02267	0.378	0.03400	0.567
Fe	0.54	0.01543	0.022	0.01800	0.026	0.02700	0.039
Mn	0.46	0.01314	0.094	0.01533	0.110	0.02300	0.164
NO_3-N	1.48	0.04229	0.026	0.04933	0.031	0.07400	0.046
Pb	0.00374	0.00011	0.031	0.00012	0.036	0.00019	0.053
Zn	0.07	0.00200	0.007	0.00233	0.008	0.00350	0.012

Note: ADD, average daily dose; HQ, hazard quotient.

Table 7 shows the carcinogenic risks calculated through drinking water from tube wells and dug wells. The calculation of LCR of As among men and women found that they were equal to 1×10^{-4}, indicating that there are potential carcinogenic health risks associated with drinking from either tube wells or dug wells while children are at higher LCR as LCR is greater than 1×10^{-4}. It should be noted that other heavy metals such as Cu, Cr, Cd and Pb were not assigned by the US Environmental Protection Agency as oral ingestion. Inorganic arsenic is a confirmed carcinogen and it is the most significant chemical contaminant in drinking water globally (Taiwo *et al.* 2012). Exposure to cadmium may cause adverse health effects like lung cancer, kidney damage and bone fracture (Akoto *et al.* 2019). Drinking water with a concentration of As, Pb, Cr and Cd could potentially enhance the risk of cancer in humans. Long-term of exposure to low concentrations of hazardous chemicals may result in various types of cancer years later (Luvhimbi *et al.* 2022).

4. CONCLUSIONS

In conclusion, it was found that 9.1% of tube wells and 9.7% of dug wells contained As greater than 0.01 mg/L. This exceeds the value set in WHO's Drinking Water Quality Guidelines, which suggests health risk considerations. Approximately 36.4% of tube wells and 16.1% of dug wells contained Cd greater than the minimum standard (3 μg/L). Out of the total number of tube wells and dug wells, approximately 9.1% of tube wells and 9.7% of dug wells contained F^- greater than the minimum standard (1.5 mg/L). Approximately, 22.7% of tube wells and 32.3% of dug wells contained Fe greater than the minimum standard (0.3 mg/L), while 100% of tube wells and 80.6% of dug wells contained Mn greater than the minimum standard (0.1 mg/L). Similarly, in surface water it is also found that some parameters exceed the minimum standard such as turbidity, As, Cd, Fe, Mn, *E. coli* and coliform, respectively. Risk assessment showed that Free Cl_2, Cu, Cr, Cd, F^-, Fe, Mn, NO_3^-, Pb and Zn among

Table 7 | Carcinogenic risk calculation by ingestion from tube well and dug well

	Tube well ($n = 22$)						
		Men		Women		Children	
Parameters	Mean concentration (mg/L)	LADD	LCR	LADD	LCR	LADD	LCR
As	0.01	8.2×10^{-5}	1×10^{-4}	9.5×10^{-5}	1×10^{-4}	1.4×10^{-4}	2×10^{-4}
	Dug well ($n = 31$)						
As	0.01	8.2×10^{-5}	1×10^{-4}	9.5×10^{-5}	1×10^{-4}	1.4×10^{-4}	2×10^{-4}

Note: LADD, lifetime average daily dose; LCR, lifetime cancer risk.

men, women and children were HQ < 1, indicating that there are no potential non-carcinogenic health risks associated with their drinking water. However, As that had HQ > 1 for women and children indicated that there are potential non-carcinogenic health risks associated with their drinking water. Children are more susceptible to non-carcinogenic risk than women and men from the study contaminants. The residents must be aware of the health risks resulting from groundwater consumption. Therefore, groundwater in Cambodian coastal areas should be treated by removing As, Cd, and F^- before drinking.

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DECLARATION OF COMPETING INTEREST

The authors declare no competing interest or personal relationships that could have appeared to influence this paper.

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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