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Pollution Evaluation and Risk Assessment of Heavy Metal (Loid)s in Spring Water from the Coastal Areas of Cambodia

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សង្ខិត្តន័យ

លោហៈធ្ងន់ក្នុងប្រភពទឹកគឺជាបញ្ហាទូទាំងពិភពលោក ដែលទាមទារឱ្យមានការវាយតម្លៃហានិភ័យជាប្រចាំ ដើម្បីរកវិធីរារាំងហានិភ័យ ដែលអាចកើតឡើងចំពោះសុខភាពមនុស្ស។ ការវិភាគសំណាកគំរូ ត្រូវបានពិនិត្យស្រាវជ្រាវសម្រាប់ប៉ារ៉ាម៉ែត្ររូបគីមីចំនួន ៦ ប្រភេទ ដែលក្នុងនោះមាន៖ កម្រិត pH សីតុណ្ហភាព (°C) សក្តានុពលអុកស៊ីដកម្មរេដុកម្ម (ORP) អុកស៊ីសែនលាយក្នុងទឹក (DO) ជាតុរឹងសរុបរលាយក្នុងទឹក (TDS) ការចម្លងចរន្តអគ្គិសនី(EC), និងលោហៈធ្ងន់ចំនួន ១២ (ស័ង្កសី (Zn) អាសេនិក (As) សំណ (Pb) ក្រូម (Cr) ទង់ដែង (Cu) ម៉ង់កាណេស (Mn) កាត់ម្យូម (Cd) ដែក (Fe) កូបាល់ (Co) អាលុយមីញ៉ូម (Al) នីកែល (Ni) និងតាល្យូម (Tl) ។ គុណភាពទឹកត្រូវបានវាយតម្លៃតាម ផលប៉ះពាល់ប៉ូកសរុបនៃលោហៈធ្ងន់ ដោយប្រើសន្ទស្សន៍ការបំពុល នៃលោហៈធ្ងន់ (MPI) សន្ទស្សន៍វាយតម្លៃលោហៈធ្ងន់ (HEI) កត្តាចម្លងរោគ (CF) និងកម្រិតចម្លងរោគ (dC) ហើយការវាយ តម្លៃហានិភ័យសុខភាពត្រូវបានធ្វើឡើងដោយប្រៀបធៀបទិន្នន័យ ដែលទទួលបានជាមួយនឹងបទប្បញ្ញត្តិបច្ចុប្បន្នរបស់អង្គការសុខភាព ពិភពលោក (WHO) និងស្តង់ដាគុណភាពនៃទឹកផឹករបស់កម្ពុជា (CDWQS) ព្រមទាំងការប្រើសមីការប៉ាន់ស្មានហានិភ័យ (HQ) និង សមីការប៉ាន់ស្មានហានិភ័យមហារីកសរុប (TCR) ។ ការវិភាគស្ថិតិសម្រាប់ការសិក្សាស្រាវជ្រាវនេះត្រូវបានអនុវត្ត ដោយប្រើកម្មវិធី Minitab 21 និង Microsoft Excel 16។ លទ្ធផលសិក្សាបានបង្ហាញថា កម្រិតកំហាប់លោហៈធ្ងន់មានតម្លៃលំដាប់ដូចតទៅនេះ៖ Fe > Al > Mn > Zn > Cu > Pb > As > Co > Cr > Ni > Cd > Tl។ ជាក់ស្តែងកំហាប់នៃកូបាល់ (KE03) Mn (KE02 និង KE03) អាលុយមីញ៉ូម

(KS03 KP01 KE02 និង KE03) និងដែក (KS02 KS03 KP01 KP02 KE01 KE02 និង KE03) បានលើសពីកម្រិតស្តង់ដាដែលបានកំណត់ដោយ WHO និង CDWQS។ តាមលទ្ធផល នៃ MPI HEI និង dC បានបង្ហាញថា ទឹកធម្មជាតិដែលចេញពីក្រោមដីបានចាប់ផ្តើមក្រខ្វក់ទៅហើយ ហើយថែមទាំងកំពុងស្ថិតក្នុងកម្រិតបំពុលខ្ពស់ទៀតផង។ បើប្រៀបធៀបទៅនឹងកុមារ ហានិភ័យមហារីកបានកើនឡើងរួចទៅហើយចំពោះមនុស្សពេញវ័យ។ ប្រសិនបើនៅតែបន្តទទួលទានទឹកបែបនេះជាប្រចាំ (CDI) ពួកគេនឹង ប្រឈមពេញមួយជីវិតនឹងការកើតមហារីក (ILCR)។ ការស្រាវជ្រាវ នេះមានឥទ្ធិពលយ៉ាងខ្លាំងក្នុងការជំរុញការយល់ដឹងអំពីសុវត្ថិភាព ទឹក និងជាជំហានក្នុងការទទួលស្គាល់គោលដៅនៃការផ្តល់ទឹកស្អាត និងមានសុវត្ថិភាពសម្រាប់មនុស្សគ្រប់រូប។ ដូច្នេះ ទឹកធម្មជាតិដែលចេញពីក្រោមដីអាចមិនសមស្របសម្រាប់ទទួលទានឡើយ ហើយ ទាមទារឱ្យមានការសម្អាតមុនពេលប្រើប្រាស់ ប៉ុន្តែ អាចប្រើសម្រាប់ គោលបំណងផ្សេងៗក្នុងផ្ទះបាន។

Abstract

Heavy metals in water sources are a worldwide issue that requires regular risk assessments to address any possible health risks to humans. The sample analysis was investigated for 6 physicochemical parameters and 12 heavy metal (loid)s comprising (pH, temperature (°C), oxidation-reduction potential (ORP), dissolved oxygen (DO), total dissolved solids (TDS), electrical conductivity (EC), zinc (Zn), arsenic (As), lead (Pb), chromium (Cr), copper (Cu), manganese (Mn), cadmium (Cd), iron (Fe), cobalt (Co), aluminum (Al), nickel (Ni), and thallium (Tl)). Water qualities were evaluated by cumulative impacts of heavy metals with metal pollution index (MPI), heavy metal evaluation index (HEI), contamination degree (CF), and the degree of contamination (dC), and health risk assessment was evaluated by comparing the obtained data with current World Health Organization (WHO) and Cambodian Drinking Water Quality Standard (CDWQS) regulations as well as using the hazard quotient and total cancer risk (HQ and TCR). Statistical analysis was performed with Minitab 21 and Microsoft Excel 16 software. The detection results revealed the following order of heavy metal concentrations: Fe > Al > Mn > Zn > Cu > Pb > As > Co > Cr > Ni > Cd > Tl. Notably, the concentrations of Co (KE03), Mn (KE02 and KE03), Al (KS03, KP01, KE02, and KE03), and Fe (KS02, KS03, KP01, KP02, KE01, KE02, and KE03) exceeded the standard limits set by WHO and CDWQS. From the results of MPI, HER, and dC, the spring water shows that water has started to be contaminated and has reached a high pollution level. Cancer risk was increased in adults compared to children when using chronic daily intake (CDI) and incremental lifetime cancer risk (ILCR). This research helps ensurewater safety in countries that rely mostly on natural sources for water supply by fostering a more sophisticated understanding of water safety and taking a step towards realizing the goal of providing everyone with safe and clean drinking water. Therefore, spring water may not be suitable for drinking; the treatments are required before use but can used for other domestic purposes.

Introduction

Water is crucial to human life since it regulates metabolism, physiological activities, and overall growth (Kavouras & Anastasiou, 2010; Popkin, D'Anci, & Rosenberg, 2010). Safe, clean, and uncontaminated potable water is vital in preserving excellent health and well-being (Edokpayi et al., 2018; Rubino, 2023). The integrity of natural water resources worldwide is at risk due to anthropogenic activity, particularly heavy metal contamination (Briffa, Sinagra, & Blundell, 2020; Edokpayi et al., 2018; P. Zhang et al., 2023). Many publications have recorded health risks associated with heavy metals. Comprehensive risk assessments are essential to diagnose, treat, and prevent possible problems (Ayaz et al., 2023; Eid et al., 2024; Saravanan et al., 2024; Tongprung, Wibuloutai, Dechakhamphu, & Samaneein, 2024) such as Lead (Pb), mercury (Hg), cadmium (Cd), arsenic (As), and chromium (Cr) (Balali-Mood, Naseri, Tahergorabi, Khazdair, & Sadeghi, 2021; Renu et al., 2021; Tchounwou, Yedjou, Anita K Patlolla, & Dwayne, 2012). Even at low levels, these hazardous heavy metals have the potential to cause serious harm to human health, including cancer, neurological disorders, renal impairments, and cardiovascular problems (Jaishankar, Tseten, Anbalagan, Mathew, & Beeregowda, 2014; Jankowski, Floege, Fliser, Böhm, & Marx, 2021; Mitra et al., 2022; Shetty et al., 2023; Tchounwou et al., 2012).

The long-term health of the general people may be at risk due to bioaccumulative consequences of repeated exposure to these pollutants in drinking water (Amit Krishan, Shweta Yadav, & Ankita Srivastava, 2023; Chheang, Thongkon, Sriwiriyarat, & Thanasupsin, 2021a; Kurwadkar et al., 2022; Murphy, Post, Buckley, Lippincott, & Robson, 2012; Sharma & Bhattacharya, 2017). Even though heavy metals naturally occur in the earth's crust, human activities such as mining, farming, industrial processes, and wastewater disposal increase their levels in water bodies (Briffa et al., 2020; Dagdag et al., 2023; Jaishankar et al., 2014; Mitra et al., 2022; Nyiramigisha, Komariah, & Sajidan, 2021).

Economic activities, including mining, agriculture, and the use of chemical fertilizers, have been linked to heavy metal contamination in Cambodia (Alengebawy, Abdelkhalek, Qureshi, & Wang, 2021; Chheang, Limsuwan, Thongkon, Sriwiriyarat, & Thanasupsin, 2023; Chheang, Thongkon, Sriwiriyarat, & Thanasupsin, 2021b; Eliyan et al., 2024; Ministry of Environment Cambodia, 2004). Heavy metal contamination in Cambodia is attributable to economic activities such as mining, agriculture, and chemical fertilizers. In addition, spring water is produced from subsurface water sources that may have been influenced by the dissolving of naturally occurring material carrying heavy metals (Akhtar, Syakir Ishak, Bhawani, & Umar, 2021). Inadequate local awareness, governance, and legislation further exacerbate the risk. A comprehensive assessment of the potential presence of heavy metals in spring water in Cambodia is required in the scenario, followed by a risk assessment for human health (Chheang et al., 2023; Dong, Zhang, & Quan, 2020; Song, Yang, Ramu, & Choi, 2024).

Heavy metal pollution in Cambodia's spring water is the result of a variety of factors. The first issue is the leakage of hazardous refuse from factories into water sources due to unregulated industrialization. For instance, inappropriate iron, lead, and copper disposal can contaminate streams (Adnan et al., 2024; Haghighizadeh et al., 2024; Hossain, Fakhruddin, Chowdhury, & Gan, 2016; Wei et al., 2018). Second, heavy metals leach into groundwater due to mining operations, which affects spring water (Baba & Gündüz, 2017; Haghighizadeh et al., 2024; Wei et al., 2018; W. Zhang, Xin, & Yu, 2023). Unsustainable farming methods that use hazardous fertilizers and pesticides worsen this problem (Chheang et al., 2021b; Rashid et al., 2023; Tudi et al., 2021). The lack of suitable waste management systems consequently speeds up the infiltration of urban garbage into spring water, raising the content of heavy metals in the water (Chheang et al., 2021b; Rashid et al., 2023; Tudi et al., 2021).

Stringent regulations, more effective waste management, and increased public awareness are all necessary to address this multifaceted issue. Risk assessments assess the hazards to human health and the environment, identify potential sources of heavy metal contamination, and analyze the extent of contamination (Ayaz et al., 2023; Carpenter & Bushkin-Bedient, 2013; Hoang et al., 2021; Liang et al., 2017). Assessments like these guide actions to protect our vital water resources and implement necessary safeguards against pollution that could harm people and the environment. Effectively prioritizing stringent risk evaluations can prevent significant damage. Worldwide health standards for safe drinking water follow the World Health Organization (WHO) guidelines. They lay the groundwork scientifically for water safety plans, which include measures to reduce the likelihood of contamination, create easy-to-understand ways to measure water quality and increase water availability. Furthermore, the Safe Drinking Water Act mandates that the US Environmental Protection Agency (EPA) set national standards for drinking water safety. These guidelines specify rigorous treatment processes and maximum contamination levels to restrict the presence of numerous physical, chemical, microbiological, and radioactive contaminants in drinking water substances that potentially pose major dangers to human health (World Health Organization, 2017b).

Considering the variations in regional circumstances, the water supply is guaranteed safe for consumption by the combined criteria set by the USEPA and the WHO. This study aimed to assess spring water quality in Cambodia's coastal areas, focusing on pollution levels and the associated non-carcinogenic and carcinogenic health risks from selected heavy metals. The findings will provide crucial insights to lawmakers and medical groups, allowing them to adopt effective policies to reduce the negative implications on community health.

Materials and Methods

All reagents were of analytical reagent-grade quality. Double-distilled deionized water was used for dilution and washing. HNO_3 (65%; w/w), HCl (37%; w/w), and H_2O_2 (30%; w/w), which were prepared by Merck (Darmstadt, Germany), were of supra pure quality. All polyethylene containers and glassware were cleaned by soaking in dilute HNO_3 (10%; w/w) and rinsed with distilled water before use. A mixed stock of standard solutions of heavy metals was supplied from Agilent Technology and was used to prepare working standard solutions.

This cross-sectional study was conducted across coastal areas, including Kok Kong (KK), Preah Sihanouk (KS), Kampot (KP), and Keb (KE) provinces of Cambodia (See. Figure S1). Spring water samples were collected from 3 locations in each province, with the date and location detail in Table 1. The sampling location map is shown in Figure 1.

Spring water samples were collected from 3 locations from 4 provinces of the coastal area of Cambodia. To date, there have been no previous reports on the levels of potentially toxic metals in spring water of these locations or reports relating to the levels of heavy metals. Triplicate water samples were collected at each location in 500.0 mL polyethylene bottles. These sampling bottles were pre-cleaned with 10% nitric acid for 24 hours and rinsed thrice with deionized water. Before collecting the water samples, the bottles were rinsed three times. The water samples were preserved and acidified with nitric acid (pH ~ 2) before measurement (Chheang et al., 2021b). The simultaneous on-site measurements were conducted at each site to test physicochemical parameters. pH, temperature, and ORP were measured using a HANNA pH/ORP meter HI98191 (HANNA, Italy). The electrical conductivity (EC), total dissolved solids (TDS), and salinity were measured 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

Table 1: Data information of field sampling of spring water samples

No.	*Sample codes*	*Sampling date*	*Locations*	*WGS 1984 Zone 48N*	
				X	*Y*
Koh Kong province					
1	KK01	03-06-2024	Koh Kong district	297107	1280160
2	KK02	04-06-2024	Koh Kong district	295354	1279269
3	KK03	05-06-2024	Botum Sakor district	340532	1254229
Preah Sihanouk province					
4	PS01	06-06-2024	Prey Nob district	361355	1170478
5	PS02	06-06-2024	Stueng Hav district	347857	1180340
6	PS03	07-06-2024	Prey Nob district	364958	1175670
Kampot province					
7	KP01	08-06-2024	Tuek Chhu district	396272	1178375
8	KP02	08-06-2024	Tuek Chhu district	404898	1179717
9	KP03	09-06-2024	Tuek Chhu district	403825	1173461
Keb province					
10	KB01	10-06-2024	Krong Keb	426578	1163642
11	KB02	11-06-2024	Damnak Changaeur district	431158	1164490
12	KB03	12-06-2024	Damnak Changaeur district	432671	1169294

at each sampling location by Hach DR850 colorimeter (Hach DR850, USA). All collected samples were kept in an ice box during field sampling and then transferred to a refrigerator at 4°C until analysis (Chand & Prasad, 2013; Khamlerd, Tengjaroenkul, & Neeratanaphan, 2019; Rajeshkumar & Li, 2018; Sriuttha et al., 2017).

Over 50.0 mL of water samples (triplicate) were digested with 2.5 mL of 69% nitric acid at 90 ± 5°C on a hotplate for 1-hour. The digested samples were filtered through Whatman filter papers and again through 0.2 µm nylon membrane filters, followed by a volume adjustment to 50.0 mL with deionized water (Chheang et al., 2021b). Calibrated solutions of the target metal ions were prepared from a mixed standard stock solution by serial dilution. The calibration curve for each metal was prepared by plotting the corrected intensity of standards against their concentrations. The acidified water samples were analyzed for the presence of Zn, As, Pb, Cr, Cu, Mn, Cd, Fe, Co, Al, Ni, and Tl, respectively, using an inductively coupled plasma-optical emission spectrometry (ICP-OES, manufactured by Perkin Elmer and referred to as the Optima 8000 DV).

The pollution state of selected samples can be estimated by different indexes of pollution, of which the metal pollution index, MPI can be used as an indicator of the overall water quality related to heavy metals content, and it is calculated by the following Eq. 1 (Shehu & Vasjari, 2016; Shehu et al., 2022):

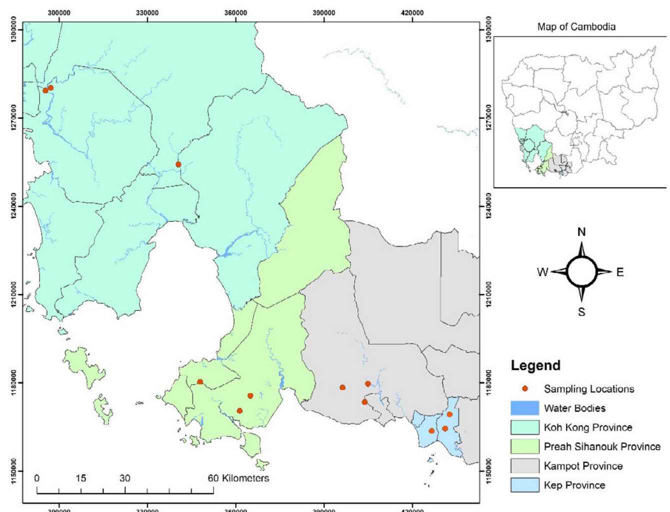

Figure 1: Map of the sampling locations

$$\text{MPI} = \sum_{m=1}^{n} \frac{C_m}{MAC_m} \quad (1)$$

Where Cm is the measured concentration of each metal, and MACm is the maximum permissible concentration of the mth metal. MPI values above 1 represent a threshold warning (Shehu & Vasjari, 2016; Shehu et al., 2022). The MPI classification for water used for drinking and domestic purposes were very pure I (MPI < 0.3), pure II (0.3 < MPI < 1.0), slightly affected III (1.0 < MPI < 2.0), moderately affected IV (2.0 < MPI < 4.0), Seriously affected V (4.0 < MPI < 6.0), and seriously affected VI (6.0 < MPI) (Shehu & Vasjari, 2016; Shehu et al., 2022). The HEI is another approach to assessing the quality of water impacted by heavy metals. It uses the same calculation as MPI but a different classification (Eq. 2).

$$\mathrm{HEI} = \sum_{m=1}^{n} \frac{H_C}{H_{MAC}} \qquad (2)$$

The monitored heavy metal concentrations and maximum acceptable concentrations are the Hc and H MAC, respectively. There are three classifications for HEI. When HEI > 5 is low, 5 < HEI < 20 is middle, and HEI > 20 is high polluted (Boateng, Opoku, Acquaah, & Akoto, 2015; Hamidu et al., 2021).

For calculating the multiple effects of heavy metals on human health, the degree of contamination (dC) was calculated. In this function, the contamination factor (CF) should be computed. Conversely, the Cf depends on the concentration of heavy metals in water (Cm) and the maximum acceptable concentration (MACm) of the element in water (Eq. 3 and Eq. 4). This investigation evaluated heavy metals, including Zn, As, Pb, Cr, Cu, Mn, Cd, Fe, Co, Al, Ni, and Tl.

$$\mathrm{CF} = \frac{C_m}{MAC_m} - 1 \qquad (3)$$

$$\mathrm{dC} = \sum_{m=1}^{n} CF \qquad (4)$$

Interpretation of contamination degree is based on three classifications: high (Cd > 3), medium (1 < Cd < 3), and (Cd < 1) low degree of contamination (Boateng et al., 2015; Hamidu et al., 2021).

To assess both non-cancer and cancer risks for children and adults, the chronic daily intake (CDI) of Heavy metals, which represents the lifetime average daily dose (LADD) of exposure to a contaminant, was used (Bamuwamye, Ogwok, Tumuhairwe, Eragu, & Nakisozi, 2017; Chidiebere, Ignatius, Stephen, & Ikechukwu, 2022; Yu, Wang, & Zhou, 2014). The CDI of the Heavy metals via oral ingestion was calculated using Eq. 5:

$$\mathrm{CDI} = \frac{(C \text{ x } IR \text{ x } EF \text{ x } ED)}{(BW \text{ x } AT)} \qquad (5)$$

Where, CDI is the chronic daily intake (mg/Kg/day); C is the concentration of the contaminant in a water sample (mg/L); IR is the ingestion rate per unit time (1 L/day for a child and 2.2 L/day for an adult) (Chidiebere et al., 2022; Yu et al., 2014); ED is the exposure duration (6 years for a child and 30 years for an adult); EF is the exposure frequency (365 days/year); BW is body weight (15 Kg for a child and 70 Kg for an adult); AT is the average exposure time (for carcinogens, AT = 70 × 365 = 25550 days for both children and adults; for non-carcinogens, AT = ED × 365 = 2190 days and 10950 days for children and adults, respectively) (Chidiebere et al., 2022; Yu et al., 2014).

Non-cancer risks due to non-carcinogenic effects of Heavy metals in drinking water were determined by the non-cancer hazard quotient using Eq. 6 (Chidiebere et al., 2022; Yu et al., 2014):

$$\mathrm{HQ} = \mathrm{CDI}/\mathrm{RfD} \qquad (6)$$

Where: HQ is the non-cancer hazard quotient; CDI is the chronic daily intake (mg metal/Kg/day); and RfD represents the chronic oral reference dose that approximates the human population's daily oral exposure level, plus delicate subpopulation which is probably to be without a significant risk of harmful effect through a lifetime (Bamuwamye, Ogwok, & Tumuhairwe, 2015; Bamuwamye et al., 2017). Potential risks to human health posed by exposure to multiple heavy metals were measured by the chronic hazard index (HI), the sum of all HQ calculated for each heavy metal (Bamuwamye et al., 2015, 2017; Chidiebere et al., 2022; Yu et al., 2014), and the value of HQ or HI. RfD (mg/Kg/day) is 0.3, 0.0003, 0.036, 1.5, 0.037, 0.14, 0.0005, 0.7, 0.02, 1.0, and 0.02 for Zn, As, Pb, Cr, Cu, Mn, Cd, Fe, Co, Al, and Ni respectively.

Cancer risk is the hazard from a lifetime average dose exposure to 1-mg/Kg body weight/day of a pollutant. Cancer risk was expressed in terms of incremental lifetime cancer risk (ILCR), which is the probability that one may develop cancer over a 70-year lifetime due to a 24-hour exposure to a potential carcinogen (Eliyan et al., 2024). Cancer risk was calculated as the product of CDI (mg/Kg/day) and cancer slope factor (CSF) measured in (mg/Kg/day) (see Eq. 7) (Bamuwamye et al., 2015, 2017; Chidiebere et al., 2022):

$$\mathrm{ILCR} = \mathrm{CDI} \text{ x } \mathrm{CSF} \qquad (7)$$

Where: ILCR = incremental life cancer risk; CDI = chronic intake (mg/kg/BW/day); CSF = cancer slope factor. The total cancer risk (TCR) from exposure to multiple contaminants due to consumption of a particular type of water was assumed to be the sum of each metal incremental risk (ΣILCR). The United States Environmental Protection Agency (USEPA) considers the minimum or acceptable cancer risk for regulatory purposes within the range of 1×10^{-6} to 1×10^{-4} (Bamuwamye et al., 2015, 2017; Chidiebere et al., 2022).

The statistical analysis was done using Excel 16 and Minitab 21- analysis of variance (ANOVA), which was used to test whether significant differences existed between groups. Statistical significance was considered at p <0.05.

Results and Discussion

Physicochemical properties of springwater

The physicochemical characteristics of spring water from the coastal areas are presented in Table 2. These parameters significantly affect the water quality. pH quantifies the acidity or alkalinity of the water. The average pH was 6.7, acceptable for Cambodia's water quality guidelines and the WHO (Chheang et al., 2021a; Radfard et al., 2019; P. Zhang et al., 2023). The temperature values ranged from 24 to 32.5°C, slightly lower and higher than the WHO guidelines due to the measurement time. Hence, the average temperature is still within the WHO guidelines and lower than Cambodia's standard. Water temperature significantly influences various properties of water, including the types of organisms that can thrive in it. Temperature changes can impact the ecosystem, making it a crucial factor in determining water quality. Oxidation-reduction potential (ORP) measures a water body's ability to naturally self-purify or break down waste materials, such as contaminants and dead plants or animals (Rostom, Shalaby, Issa, & Afifi, 2017). ORP values typically fall between −78.5 and 89.1 mV, but when the ORP value is negative, it signals a critical imbalance in the water. This negative value indicates that reducing agents (electrons) far outweigh oxidizing agents like oxygen. Such conditions often result from severe water pollution, excessive fertilization leading to eutrophication, or prolonged stagnation. These situations pose a serious threat to water quality and the overall health of the ecosystem. DO refers to the dissolved oxygen in the water. It is a vital indicator of the viability of aquatic life. The average DO was 5.3, above Cambodia's allowable limits for the protected public water areas. Relatively high DO levels were observed at all locations because they are far from water-polluting activities (Chheang et al., 2021a). TDS (total dissolved solids) includes any minerals, salts, metals, cations, or anions dissolved in water (Radfard et al., 2019). Electrical conductivity (EC) measures water's ability to conduct electricity, which is directly influenced by the concentration of ions present (Radfard et al., 2019). It is often used as a quick method to estimate total dissolved solids (TDS). In this study, the average TDS was 133.6 mg/L, and the average EC was 267.6 µS/cm. Both TDS and EC levels were lower than expected and within the acceptable limits set by the World Health Organization (WHO) (Boateng et al., 2015; Radfard et al., 2019; Rostom et al., 2017; World Health Organization, 2017a) and the Cambodian Drinking Water Quality Standard (CDWQS) (MIME, 2004) guidelines for safe drinking water.

Concentration of heavy metals in spring water

Studies have shown that concentrations of heavy metals in the spring water vary based on climate, region, geology, and anthropogenic activities within the watershed (Chheang et al., 2023, 2021a). The average concentrations of heavy metals in the spring water samples were as follows: Zn (21.987 ± 7.809 µg/L), As (2.825 ± 1.205 µg/L), Pb (2.922 ± 1.386 µg/L), Cr (2.165 ± 1.941 µg/L), Cu (8.690 ± 3.442 µg/L), Mn (217.238 ± 526.8 µg/L), Cd (0.069 ± 0.060 µg/L L), Fe (1389.037± 2738.9 µg/L), Co (2.192 ± 3.157 µg/L), Al (368.047 ± 622.21 µg/L), Ni (2.081 ± 0.819 µg/L), and Tl (ND). These concentrations are ranked in descending order as follows: Fe > Al > Mn > Zn > Cu > Pb > As > Co > Cr > Ni > Cd > Tl. Notably, the concentrations of Co (KE03), Mn (KE02 and KE03), Al (KS03, KP01, KE02, and KE03), and Fe (KS02, KS03, KP01, KP02, KE01, KE02, and KE03) exceeded the standard limits set by WHO (Boateng et al., 2015; World Health Organization, 2017a) and CDWQS (MIME, 2004), while concentrations of the other heavy metals and their location remained within limits, as shown in Table 3 and Table S1. The concentrations of Co, Mn, Al, and Fe in spring water from the coastal areas of Cambodia were higher than the WHO standards for drinking water, which can be caused by Geological Factors when the local geology impacts the composition of spring water. Rocks and soils can release heavy metals into the water through weathering processes (Baba & Gündüz, 2017; Haghighizadeh et al., 2024; Wei et al., 2018; W. Zhang et al., 2023). Another reason is that coastal locations frequently serve as hubs for industry, contributing to the pollution caused by industrial and mining activity. Heavy metals may be present in the wastes produced by these companies, which have the potential to contaminate groundwater and lead to increased concentrations of Co, Mn, Al, Fe, and other heavy metals (Adnan et al., 2024; Haghighizadeh et al., 2024; Hossain et al., 2016; Wei et al., 2018). Inadequate waste disposal and agricultural runoff are other reasons agricultural activities consistently employ pesticides and fertilizers to safeguard crops and achieve greater yields. These substances frequently contain heavy metals, which can percolate into the groundwater and contaminate it with heavy metals (Chheang et al., 2021a; Rashid et al., 2023; Tudi et al., 2021). Acid rain and oceanic influence are also the reasons for causing heavy metal; specific coastal regions may exhibit elevated element concentrations due to the influence of tidal and sea spray, which can elevate trace metal concentrations in spring water. Acid rains, a consequence of air pollution, can cause heavy metals to leach from the soil into the groundwater (Hamid, Bhat, & Jehangir, 2020; Payus, Jikilim, & Sentian, 2020).

Table 2: Physicochemical parameters of spring water samples

Parameters	*KK*			*KS*			*KP*			*KE*			*Min*	*Max*	*Aver.*	*CDWQS*	*WHO*
	01	*02*	*03*	*01*	*02*	*03*	*01*	*02*	*03*	*01*	*02*	*03*					
pH	6.68	6.5	7.4	6.8	6.75	6.6	6.7	5.7	6.3	7.3	7.6	6.3	5.7	7.6	6.7	6.5 - 8.5	6.5 - 8.5
Temp. (°C)	30.1	29	27.3	28.4	32.5	31.9	24	28.5	27.7	30.7	32.1	31.6	24	32.5	29.5	< 45	25 - 30
ORP (mV)	20.2	29.5	20	6.5	36	23.7	88.8	79.4	45.5	-78.5	-38.3	89.1	-78.5	89.1	26.8	-	-
DO (mg/L)	7.8	5.7	6.5	4.15	5.5	4.5	3.5	3.9	4.7	7.2	5.42	4.4	3.5	7.8	5.3	2	-
TDS (mg/L)	162.9	11.76	8.3	124.1	14.6	102.7	80.5	35.7	102	364.1	190.6	406.4	8.3	406.4	133.6	-	1000
EC (µs/cm)	324.5	23.5	16.5	248.5	29.3	204.2	160.8	71.3	211	726.7	381.9	812.7	16.5	812.7	267.6	800	1000

Table 3: Heavy metal concentrations in spring water samples

Locations	*Mean Concentrations of Heavy Metals (µg/L) in Spring water Samples*											
	Zn	*As*	*Pb*	*Cr*	*Cu*	*Mn*	*Cd*	*Fe*	*Co*	*Al*	*Ni*	*Tl*
KK01	29.752^{b}	2.012^{f}	4.293^{b}	0.923^{e,f}	10.780^{c}	21.301^{e,f}	0.051^{f}	147.342^{g,h}	1.060^{d}	132.976^{e,f}	1.811^{f,g}	ND
KK02	13.048^{h}	3.340^{c}	1.501^{f}	0.909^{e,f}	7.993^{e}	10.170^{f,g}	0.045^{g}	153.730^{g,h}	1.005^{d,e}	121.336^{f}	1.399^{h}	ND
KK03	14.879^{g}	2.291^{e,f}	1.868^{e}	0.940^{e,f}	8.809^{d}	11.276^{e,f,g}	0.037^{h}	228.242^{g,h}	0.959^{d,e}	70.151^{g,h}	1.708^{g}	ND
KS01	19.965^{e}	1.597^{g}	2.874^{c}	0.769^{f}	4.964^{g}	22.947^{e}	0.068^{d}	288.278^{f,g,h}	1.005^{d,e}	71.508^{g,h}	1.106^{i}	ND
KS02	16.975^{f}	1.612^{g}	2.950^{c}	0.754^{f}	3.591^{h}	36.109^{d}	0.046^{g}	960.775^{d}	1.312^{c}	149.431^{e}	2.021^{e}	ND
KS03	11.505^{i}	2.048^{f}	2.112^{d,e}	1.913^{d}	4.538^{g}	22.862^{e,f}	0.025^{i}	1847.692^{b}	0.847^{e}	963.501^{b}	1.117^{i}	ND
KP01	38.045^{a}	2.340^{e}	2.713^{c}	1.945^{d}	12.786^{b}	37.202^{d}	0.009^{j}	702.454^{d,e}	1.314^{c}	244.282^{d}	2.128^{d,e}	ND
KP02	22.066^{c,d}	2.648^{d}	2.021^{d,e}	2.370^{c}	7.844^{e}	38.424^{d}	0.008^{j}	523.536^{e,f}	1.109^{d}	49.617^{h}	2.169^{d}	ND
KP03	23.252^{c}	2.083^{e,f}	4.334^{b}	1.055^{e}	6.772^{f}	7.637^{g}	0.206^{a}	113.272^{h}	1.105^{d}	67.987^{g,h}	2.553^{c}	ND
KE01	30.956^{b}	4.517^{b}	2.280^{d}	6.461^{a}	12.042^{b}	87.285^{c}	0.145^{b}	401.835^{f,g}	0.986^{d,e}	87.107^{g}	1.861^{f}	ND
KE02	22.383^{c,d}	5.173^{a}	6.254^{a}	5.776^{b}	14.619^{a}	472.550^{b}	0.061^{e}	9914.006^{a}	3.687^{b}	2176.503^{a}	3.207^{b}	ND
KE03	21.021^{d,e}	4.236^{b}	1.868e	2.165^{c}	9.543^{d}	1839.087^{a}	0.131^{c}	1387.287^{c}	11.919^{a}	282.165^{c}	3.888^{a}	ND
Average ± SD	21.987 ± 7.809	2.825 ± 1.205	2.922 ± 1.386	2.165 ± 1.941	8.690 ± 3.442	217.238 ± 526.8	0.069 ± 0.060	1389.037± 2738.9	2.192 ± 3.157	368.047 ± 622.21	2.081 ± 0.819	-
WHO^{a} (µg/L)	5000	10	10	50	2000	400	3	300	4	200	70	2
EU^{b} (µg/L)	5000	10	10	50	2000	50	5	200	100	200	20	2
USEPA^{c} (µg/L)	5000	10	15	100	1000	50	5	300	100	200	100	2
CDWQS^{d} (µg/L)	3000	50	10	50	1000	100	3	300	4	200	20	2

Data are presented as the average values; SD means standard deviation, ND means not detected, Values with similar letters refer to "not significantly different", where a, b, c, d, e, f, g, h, i, j refer to "significantly different" ($p < 0.05$) with the following order: a > b > c > d > e > f > g > h > i > j (Minitab 21 ANOVA one-way test), [a]Guidelines for Drinking-Water Quality 2017 (Boateng et al., 2015; Radfard et al., 2019; Rostom et al., 2017; World Health Organization, 2017a). [b]European Union (EU) permissible limit (Bamuwamye et al., 2017). [c]United States Environmental Protection Agency (USEPA) permissible limit (Bamuwamye et al., 2017; Rostom et al., 2017). [d]Cambodian drinking water quality standard (CDWQS) (MIME, 2004).

Spring water quality assessment based on MPI, HEI, and dC values

MPI values revealed that none of the samples exhibited "very Prue I and Prue II" quality, i.e. with the values of MPI < 0.3 and 0.3 < MPI < 1.0 (Table 4). Tap water collected at KK02, KK03, and KP03 exhibited "slightly affected III (1.0 < MPI < 2.0)". KK01, KS01, KP02, and KE01 were classified as "moderately affected IV (2.0 < MPI < 4.0)". KS02 and KP01 were classified as "seriously affected V", with MPI 4-6 values. The samples from locations KS03, KE02, and KE03 were classified as "seriously affected VI (6.0 < MPI)". Also, the mean HEI values of all locations in this study are shown in Table 4. Based on HEI classification (HEI > 5 is low, 5 ≤ HEI < 20 is middle, and HEI ≥ 20 is highly polluted), the higher values of HEI were in KE02 and KE03 reached the high level (HEI ≥ 20), and KS03 was in middle level (5 ≤ HEI < 20) and besides these 3 locations were in the lower level (HEI > 5). The degree of contamination considers the number of parameters that exceed the upper permissible limit or guide values of potentially harmful elements and the concentration exceeding these limit values. The observation of this study about the cumulative effect of heavy metals is also summarised in Table 4. The results showed the highest contamination degree of parameters was 37.368, which was higher than 3, which supports the high degree of heavy metals pollution. Only three locations (KS03, KE02, and KE03) dC was higher, while other locations were lower than 1, which supports the low pollution of heavy metals. KS03, KE02, and KE03 were more polluted by heavy metals from agricultural activity that used pesticides and fertilizers in that area to protect crops and increase production. It is near industrial areas with canals that collect the wastewater and connect with the spring water (Chheang et al., 2021a; Rashid et al., 2023; Tudi et al., 2021).

Health risk assessment

Table 5 displays the results for the chronic daily intake (CDI) (The average daily intake dose, ADI) for the ingestion pathway in the spring water for adults and children. The results showed that the CDI values were slightly above the reference dose USEPA or other international bodies recommended for As (KE01 and KE02). The CDI for Fe was highest in the spring water samples collected from the coastal areas for adults and children but still lower than the reference dose recommended by USEPA or other international bodies. The CDI values of minors were generally higher than those of adults exposed to the same drinking water sources. For the adult and children's populations, the average CDI value indices for the heavy metals in the study areas were as follows: Fe > Al > Mn > Zn > Cu > Pb > As > Co > Cr > Ni > Cd. Even though most CDI values were lower than the reference dose, the concentration of heavy metals in some locations exceeded the WHO and CDWQS standards or guidelines for drinking water, which might have a long-term effect on the customers regarding bioaccumulation (Munene, Hashim, & Ambusso, 2023; S. Zhang et al., 2023).

Table 6 shows the results of non-carcinogen risk assessment through oral route by HQ calculation. The HQ for heavy metals in various water sources was also higher in children than adults. The HQ was >1 in the spring water for As from locations KE01 and KE02 in the study. The HQ indices >1 calculated for all these 2 locations samples present an unacceptable risk for non-carcinogenic adverse effects, especially concerning As. HQ of As > 1 or As levels in water exceeding the World Health Organization's recommendation threshold of 10 μg/L can have serious health consequences. Chronic arsenic exposure in drinking water can cause a variety of cancers, including skin, bladder, and lung cancer. It can also cause skin lesions, cardiovascular and nervous system damage, issues with cognitive development, and poor reproductive outcomes. It can also affect the immune system and raise the chance of developing diabetes. Furthermore, arsenic hurts a child's IQ and development (Martinez, Vucic, Becker-Santos, Gil, & Lam, 2011; Smith & Smith, 2004; Uppal, Zheng, & Le, 2019). The hazard quotient (HQ) for the children's group exceeded one, indicating potential health risks according to WHO guidelines. Since children consume more air, water, and food relative to their body size than adults, they are often more exposed to environmental toxins (Badeenezhad et al., 2021; Mastorci, Linzalone, Ait-Ali, & Pingitore, 2021; Suk, Murray, & Avakian, 2003). Children's behavior, i.e., playing on the ground, heightens their exposure to potential toxins. Moreover, their vulnerability to environmental risks is greater because their developing immune systems are not yet equipped to efficiently metabolize, detoxify, and eliminate harmful substances. Environmental concerns for children include asthma exacerbating air pollution, lead-based paint in older homes, treatment-resistant microorganisms in drinking water, and persistent chemicals that may cause cancer or induce reproductive or developmental harm (Carroquino, Posada, & Landrigan, 2012; Mastorci et al., 2021; Perlroth & Castelo Branco, 2017). When the cumulative effects of parameters were calculated, the results showed that the HI in the adult group had a value of more than one in location KE02 and min = 0.204 and max = 1.196. In the children's group, there was more than one value in location (KE01, KE02, and KE03) with min = 0.433 and max = 2.538 (Table 6).

Various contaminants, including chemical, physical, and microbiological contaminants, can compromise the protection of potable water and result in severe health issues for humans (Yilkal, Zewge, & Chandravanshi, 2019). This study performed a human health risk assessment to compare the effects of carcinogens and non-carcinogens on chemical parameters. The target population was divided into two subgroups: adults and children. The

Table 4: Value of MPI, HEI, and dC in spring water samples

Locations	MPI/HEI Value	MPI characteristics class	HEI characteristics class	dC Value	dC characteristics class
KK01	2.178	Moderately affected IV (2.0 < MPI < 4.0)		-7.822	
KK02	1.940	Slightly affected III (1.0 < MPI < 2.0)		-8.060	
KK03	1.859	Slightly affected III (1.0 < MPI < 2.0)	HEI > 5 is low	-8.141	low degree (Cd < 1)
KS01	2.135	Moderately affected IV (2.0 < MPI < 4.0)		-7.865	
KS02	4.889	Seriously affected V (4.0 < MPI < 6.0)		-5.111	
KS03	11.729	Seriously affected VI (6.0 < MPI)	5 < HEI < 20 is middle	1.729	medium (1 < Cd < 3)
KP01	4.576	Seriously affected V (4.0 < MPI < 6.0)	HEI > 5 is low	-5.424	
KP02	2.923	Moderately affected IV (2.0 < MPI < 4.0)		-7.077	low degree (Cd < 1)
KP03	1.789	Slightly affected III (1.0 < MPI < 2.0)	HEI > 5 is low	-8.211	
KE01	3.135	Moderately affected IV (2.0 < MPI < 4.0)		-6.865	
KE02	47.368	Seriously affected VI (6.0 < MPI)	HEI > 20 is high	37.368	high degree (Cd > 3)
KE03	14.374	Seriously affected VI (6.0 < MPI)		4.374	

Table 5: Chronic daily intake (CDI) or average daily intake (ADI) dose in spring water samples (mg/Kg/day)

Locations	Mean chronic daily intake (CDI) of Heavy Metals in Spring water Samples ([Conc.] x 10^{-4})										
	Zn	As	Pb	Cr	Cu	Mn	Cd	Fe	Co	Al	Ni
Adults											
KK01	9.351	0.632	1.349	0.290	3.388	6.695	0.016	46.3074	0.333	41.793	0.569
KK02	4.101	1.050	0.472	0.286	2.512	3.196	0.014	48.315	0.316	38.134	0.440
KK03	4.676	0.720	0.587	0.295	2.769	3.544	0.012	71.733	0.302	22.048	0.537
KS01	6.275	0.502	0.903	0.242	1.560	7.212	0.021	90.602	0.316	22.474	0.348
KS02	5.335	0.507	0.927	0.237	1.129	11.349	0.014	301.958	0.412	46.964	0.635
KS03	3.616	0.644	0.664	0.601	1.426	7.185	0.008	580.703	0.266	302.815	0.351
KP01	1.196	0.735	0.853	0.611	4.019	11.692	0.003	220.771	0.413	76.774	0.669
KP02	6.935	0.832	0.635	0.745	2.465	12.076	0.003	164.540	0.349	15.594	0.682
KP03	7.308	0.655	1.362	0.332	2.128	2.400	0.065	35.600	0.347	21.368	0.802
KE01	9.729	1.420	0.717	2.030	3.785	27.432	0.045	126.291	0.310	27.377	0.585
KE02	7.035	1.626	1.966	1.815	4.595	148.516	0.019	3115.830	1.159	684.044	1.008
KE03	6.607	1.331	0.587	0.680	2.999	577.999	0.041	436.004	3.746	88.680	1.222

Children											
KK01	19.834	1.341	2.862	0.615	7.187	14.201	0.034	98.228	0.707	88.651	1.207
KK02	8.699	2.227	1.001	0.606	5.329	6.780	0.030	102.487	0.670	80.891	0.932
KK03	9.919	1.528	1.245	0.627	5.873	7.517	0.025	152.161	0.640	46.768	1.139
KS01	13.310	1.065	1.916	0.512	3.310	15.298	0.046	192.186	0.670	47.672	0.738
KS02	11.317	1.075	1.967	0.502	2.394	24.073	0.031	640.517	0.875	99.621	1.347
KS03	7.670	1.365	1.408	1.275	3.025	15.241	0.017	1231.795	0.565	642.334	0.748
KP01	25.363	1.560	1.809	1.297	8.524	24.801	0.006	468.302	0.876	162.855	1.419
KP02	14.711	1.765	1.347	1.580	5.229	25.616	0.006	349.024	0.739	33.078	1.446
KP03	15.502	1.389	2.889	0.703	4.515	5.091	0.137	75.514	0.737	45.325	1.702
KE01	20.637	**3.011**	1.520	4.307	8.028	58.190	0.096	267.890	0.657	58.072	1.240
KE02	14.922	**3.448**	4.169	3.850	9.746	315.033	0.041	6609.337	2.458	1451.002	2.138
KE03	14.014	2.824	1.245	1.443	6.362	1226.058	0.087	924.858	7.946	188.100	2.592

Table 6: Hazard quotient and Hazard index in spring water sample

Locations	*Mean Hazard Quotient (HQ) of Heavy Metals in Spring water Samples*										*Hazard index (HI)*
	Zn	*As*	*Pb*	*Cr**	*Cu*	*Mn*	*Cd*	*Fe*	*Co*	*Al*	*Ni*	
Adults												
KK01	0.003	0.211	0.004	0.002	0.009	0.005	0.003	0.007	0.002	0.004	0.003	0.250
KK02	0.001	0.350	0.001	0.002	0.007	0.002	0.003	0.007	0.002	0.004	0.002	0.379
KK03	0.002	0.240	0.002	0.002	0.007	0.003	0.002	0.010	0.002	0.002	0.003	0.272
KS01	0.002	0.167	0.003	0.002	0.004	0.005	0.004	0.013	0.002	0.002	0.002	0.204
KS02	0.002	0.169	0.003	0.002	0.003	0.008	0.003	0.043	0.002	0.005	0.003	0.240
KS03	0.001	0.215	0.002	0.004	0.004	0.005	0.002	0.083	0.001	0.030	0.002	0.345
KP01	0.004	0.245	0.002	0.004	0.011	0.008	0.001	0.032	0.002	0.008	0.003	0.316
KP02	0.002	0.277	0.002	0.005	0.007	0.009	0.001	0.024	0.002	0.002	0.003	0.328
KP03	0.002	0.218	0.004	0.002	0.006	0.002	0.013	0.005	0.002	0.002	0.004	0.258
KE01	0.003	0.473	0.002	0.014	0.010	0.020	0.009	0.018	0.002	0.003	0.003	0.543
KE02	0.002	0.542	0.005	0.012	0.012	0.106	0.004	0.445	0.006	0.068	0.005	**1.196**
KE03	0.002	0.444	0.002	0.005	0.008	0.413	0.008	0.062	0.019	0.009	0.006	0.973
Children												
KK01	0.007	0.447	0.008	0.004	0.019	0.010	0.007	0.014	0.004	0.009	0.006	0.531

KK02	0.003	0.742	0.003	0.004	0.014	0.005	0.006	0.015	0.003	0.008	0.005	0.804
KK03	0.003	0.509	0.003	0.004	0.016	0.005	0.005	0.022	0.003	0.005	0.006	0.578
KS01	0.004	0.355	0.005	0.003	0.009	0.011	0.009	0.027	0.003	0.005	0.004	0.433
KS02	0.004	0.358	0.005	0.003	0.006	0.017	0.006	0.092	0.004	0.010	0.007	0.510
KS03	0.003	0.455	0.004	0.009	0.008	0.011	0.003	0.176	0.003	0.064	0.004	0.731
KP01	0.008	0.520	0.005	0.009	0.023	0.018	0.001	0.067	0.004	0.016	0.007	0.670
KP02	0.005	0.588	0.004	0.011	0.014	0.018	0.001	0.050	0.004	0.003	0.007	0.695
KP03	0.005	0.463	0.008	0.005	0.012	0.004	0.027	0.011	0.004	0.005	0.009	0.547
KE01	0.007	**1.004**	0.004	0.029	0.022	0.042	0.019	0.038	0.003	0.006	0.006	**1.151**
KE02	0.005	**1.149**	0.012	0.026	0.026	0.225	0.008	0.944	0.012	0.145	0.011	**2.538**
KE03	0.005	0.941	0.003	0.010	0.017	0.876	0.017	0.132	0.040	0.019	0.013	2.064

Table 7: Incremental Life Cancer Risk (ILCR) and Total Cancer Risk (TCR) in spring water samples

Locations	*Mean incremental lifetime cancer risk (ILCR) of HMs in Spring Water Samples ([ILCR] x10^{-5})*										*TCR x10^{-4}*	
	As		*Pb*		*Cr*		*Cd*		*Co*			
	Adults	*Children*	*Adults*	*Children*	*Adults*	*Children*	*Adults*	*Children*	*Adults*	*Children*	*Adults*	*Children*
KK01	4.065	1.724	0.049	0.021	0.621	0.264	0.434	0.184	13.994	5.937	1.916	0.813
KK02	6.749	2.863	0.017	0.007.	0.612	0.260	0.386	0.164	13.262	5.626	2.102	0.892
KK03	4.629	1.964	0.021	0.009	0.633	0.269	0.317	0.134	12.664	5.373	1.826	0.775
KS01	3.227	1.369	0.033	0.014	0.518	0.220	0.580	0.246	13.264	5.627	1.762	0.748
KS02	3.257	1.382	0.034	0.014	0.508	0.215	0.389	0.165	17.316	7.346	2.150	0.912
KS03	4.137	1.755	0.024	0.010	1.288	0.547	0.213	0.090	11.183	4.744	1.685	0.715
KP01	4.727	2.005	0.031	0.013	1.310	0.556	0.077	0.032	17.350	7.361	2.349	0.997
KP02	5.349	2.269	0.023	0.100	1.596	0.677	0.071	0.030	14.639	6.211	2.168	0.920
KP03	4.208	1.785	0.050	0.021	0.710	0.301	1.750	0.742	14.584	6.187	2.130	0.904
KE01	9.126	3.872	0.026	0.011	4.351	1.846	1.228	0.521	13.010	5.519	2.774	1.177
KE02	10.451	4.434	0.072	0.030	3.890	1.650	0.517	0.220	48.667	**20.646**	6.360	2.689
KE03	8.558	3.631	0.021	0.009	1.458	0.619	1.113	0.472	157.325	66.744	16.848	7.147

results of the carcinogenic risk due to heavy metals exposure in spring water are presented in Table 7. According to this table, the highest CDI result for ILCR (10.451×10^{-5} or 1.451×10^{-4}) in the adult group indicated a carcinogen risk equal to or greater than 10^{-4}, significantly higher than the USEPA standard (acceptable values (10^{-6}-10^{-4}). In our study, the adult group's TCR had a higher carcinogen risk than the children group. The results were calculated based on the amount of water ingestion rate (IR) (adult = 2.2 L/day, children = 1 L/day), the average exposure time for carcinogen (AT) (70x365= 25550 days), exposure duration (ED) (adult = 30 years, children = 6 years), average body weight (Bw) (adult = 70 Kg children = 15 Kg). An ecological risk assessment was done in the coastal area of Cambodia, and the concentration of heavy metals was evaluated. The total cancer risk (TCR) for the adult group across all locations, as well as for the children's group in locations KE01, KE02, and KE03, exceeds 10^{-4}, indicating a potential carcinogenic risk from consuming spring water. Although the timing of cancer development is not accounted for, the incremental lifetime cancer risk (ILCR) assesses the increased risk over a lifetime for exposed populations (Charnley & Putzrath, 2001). Using consistent factors in risk calculations also shows that the level of carcinogenic and non-carcinogenic hazards is directly linked to the concentrations of heavy metals in the spring water samples. Along with limiting water consumption, preventive measures should be taken to reduce both immediate and long-term exposure to carcinogenic substances to help prevent cancer in the future (Carpenter & Bushkin-Bedient, 2013).

Conclusion

This study assessed the pollution levels and associated health risks of heavy metals in spring water from Cambodia's coastal areas. The findings indicate that key heavy metals— Fe, Al, Mn, and Co-exceeded the permissible limits set by WHO and the CDWQS in multiple locations. The pollution indices (MPI, HEI, and dC) suggest that contamination levels are significant, with some sites classified as highly polluted. Additionally, the health risk assessment highlights increased carcinogenic and non-carcinogenic risks, particularly for adults, based on CDI and ILCR calculations. Given these results, it is evident that untreated spring water in these areas is not suitable for direct consumption. Implementing effective water treatment strategies and regular monitoring is essential to ensure water safety for communities relying on these natural sources.

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Declaration of Competing Interest

The authors have no competing interests to declare. All authors have read and approved the final, published version of the manuscript.

Credit Authorship Contribution Statement

CHHEANG Lita conducted all experiments, analyzed the data, developed the methodology, conceptualized, planned, designed, drafted the original version, and reviewed and edited the final version. THANASUPSIN Sudtida Pliankarom wrote, reviewed, and edited the final version of the manuscript. SAO Vibol map design discussed results, reviewed, and directed the project. CHEY Thavy reviewed and discussed the results. All authors have read and agreed to the published version of the manuscript.

Data Availability Atatement

Not available.

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Sumplementary Material

Figure S1: Realtime images of springwater

Table S1: Heavy metal concentrations in springwater samples with standard deviation (SD) and % relative standard deviation (%RSD)

Parameters	*Mean Concentrations (µg/L) in Spring Water Samples*																	
	KK01			*KK02*			*KK03*			*KS01*			*KS02*			*KS03*		
	Conc.	*SD*	*%RSD*	*Conc.*	*SD*	*%RSD*	*Conc.*	*SD*	*%RSD*	*Conc.*	*SD*	*%RSD*	*Conc.*	*SD*	*%RSD*	*Conc.*	*SD*	*%RSD*
Zn	29.752	1.333	4.482	13.048	0.567	4.347	14.879	0.104	0.702	19.965	0.837	4.194	16.975	0.347	2.044	11.505	0.557	4.839
As	2.012	0.086	4.250	3.340	0.121	3.637	2.291	0.004	0.181	1.597	0.073	4.601	1.612	0.041	2.526	2.048	0.045	2.197
Pb	4.293	0.232	5.402	1.501	0.073	4.867	1.868	0.018	0.956	2.874	0.177	6.162	2.950	0.110	3.722	2.112	0.011	0.535
Cr	0.923	0.005	0.516	0.909	0.006	0.693	0.940	0.013	1.402	0.769	0.021	2.687	0.754	0.006	0.805	1.913	0.043	2.266
Cu	10.780	0.727	6.746	7.993	0.342	4.280	8.809	0.441	5.005	4.964	0.253	5.096	3.591	0.159	4.422	4.538	0.123	2.713
Mn	21.301	0.876	4.112	10.170	0.106	1.045	11.276	0.353	3.130	22.947	0.192	0.839	36.109	0.329	0.911	22.862	0.431	1.886
Cd	0.051	0.002	4.088	0.045	0.002	3.485	0.037	0.001	3.005	0.068	0.001	1.376	0.046	0.002	3.663	0.025	0.001	3.070
Fe	147.342	1.462	0.992	153.730	2.717	1.767	228.242	6.423	2.814	288.278	12.194	4.230	960.775	12.535	1.305	1847.692	87.753	4.749
Co	1.060	0.025	2.318	1.005	0.039	3.885	0.959	0.059	6.138	1.005	0.056	5.542	1.312	0.019	1.442	0.847	0.027	3.217
Al	132.976	7.563	5.688	121.336	3.643	3.003	70.151	1.326	1.890	71.508	1.767	2.471	149.431	7.023	4.700	963.501	40.329	4.186
Ni	1.811	0.067	3.720	1.399	0.041	2.925	1.708	0.032	1.895	1.106	0.045	4.066	2.021	0.034	1.696	1.117	0.053	4.786
Tl	ND	-	-	ND	-	-	ND	-	-	ND	-	-	ND	-	-	ND	-	-
Parameters	*KP01*			*KP02*			*KP03*			*KE01*			*KE02*			*KE03*		
	Conc.	*SD*	*%RSD*	*Conc.*	*SD*	*%RSD*	*Conc.*	*SD*	*%RSD*	*Conc.*	*SD*	*%RSD*	*Conc.*	*SD*	*%RSD*	*Conc.*	*SD*	*%RSD*
Zn	38.045	0.696	1.828	22.066	0.402	1.821	23.252	0.870	3.741	30.956	1.100	3.554	22.383	0.483	2.160	21.021	1.477	7.028
As	2.340	0.133	5.669	2.648	0.120	4.535	2.083	0.006	0.300	4.517	0.084	1.869	5.173	0.395	7.632	4.236	0.332	7.841
Pb	2.713	0.012	0.439	2.021	0.096	4.727	4.334	0.085	1.973	2.280	0.024	1.053	6.254	0.446	7.135	1.868	0.183	9.778
Cr	1.945	0.016	0.841	2.370	0.057	2.406	1.055	0.027	2.554	6.461	0.221	3.419	5.776	0.363	6.286	2.165	0.041	1.906
Cu	12.786	0.652	5.101	7.844	0.254	3.240	6.772	0.209	3.091	12.042	0.504	4.189	14.619	0.922	6.309	9.543	0.293	3.066
Mn	37.202	1.565	4.206	38.424	0.187	0.487	7.637	0.512	6.706	87.285	1.504	1.723	472.550	7.237	1.531	1839.087	25.105	1.365
Cd	0.009	0.000	4.065	0.008	0.000	1.159	0.206	0.001	0.310	0.145	0.002	1.248	0.061	0.001	1.553	0.131	0.002	1.247
Fe	702.454	35.470	5.049	523.536	6.871	1.312	113.272	7.780	6.868	401.835	14.665	3.650	9914.006	543.551	5.483	1387.287	114.418	8.248
Co	1.314	0.028	2.145	1.109	0.025	2.231	1.105	0.065	5.838	0.986	0.032	3.278	3.687	0.030	0.809	11.919	0.382	3.204
Al	244.282	14.302	5.855	49.617	1.147	2.311	67.987	2.180	3.206	87.107	2.527	2.902	2176.503	25.732	1.182	282.165	12.681	4.494
Ni	2.128	0.014	0.652	2.169	0.008	0.368	2.553	0.031	1.197	1.861	0.063	3.369	3.207	0.207	6.465	3.888	0.167	4.298
Tl	ND	-	-	ND	-	-	ND	-	-	ND	-	-	ND	-	-	ND	-	-

ND means not detected