

## ORIGINAL RESEARCH ARTICLE

# Assessment of surface water quality impacted by upstream artisanal mining in Prek Te area, Cambodia

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**Abstract:** Mining activities can significantly impact water quality by introducing various contaminants into water sources. The purpose of this study is to assess heavy metal concentrations and other elemental contaminants in water from the Prek Te area across two seasons and evaluate the potential health risks associated with drinking contaminated water. Surface water samples were collected twice in 2023: from March 5 – 11 (dry season) to October 20 – 26 (rainy season). A total of 21 surface water samples were collected from different locations along the Prek Te area. On-site measurements included pH, electrical conductivity, dissolved oxygen, and total dissolved solids, while laboratory analyses determined arsenic (As), chromium, nickel (Ni), copper, zinc, cadmium, and lead concentrations using inductively coupled plasma mass spectrometry. The results indicated that most parameters were within the World Health Organization guidelines and Cambodia Drinking Water Quality Standards, except for As and Ni. During the rainy season, the highest As concentration was 58.1 µg/L, followed by 22.0 µg/L and 10.8 µg/L. Health risk assessments revealed that the hazard index and hazard quotient for children exceeded 1, indicating potential non-carcinogenic health risks. In addition, children exhibited the highest lifetime cancer risk for As ( $>1.8 \times 10^{-1}$ ), followed by women ( $>1.2 \times 10^{-1}$ ) and men ( $>1 \times 10^{-1}$ ). These findings suggest that children are more vulnerable to health risks associated with drinking contaminated water compared to adults. To ensure safe drinking water for communities along the Prek Te area, an urgent monitoring program and appropriate water treatment measures—particularly to remove As contamination—are recommended.

**Keywords:** Cambodia; Artisanal gold mining; Heavy metals; Health risk; Prek Te area

## 1. Introduction

Mondulhiri, Cambodia's largest province, is located in the eastern region of the country and shares borders with Vietnam to the east and south, Kratie Province to the west, Stung Treng Province to the northwest, and

Ratanakiri Province to the north. Despite its vast land area, Mondulhiri has the lowest population density in Cambodia. The province is known not only for its potential to attract tourists but also for its abundant mineral resources, including gold deposits. However, gold mining in Mondulhiri is predominantly small-scale,

commonly referred to as artisanal gold mining, which is typically carried out by individuals, families, or small community groups using rudimentary technology and traditional extraction methods. Artisanal gold mining is a major environmental concern due to inefficient and often nonexistent pollution control measures during mineral extraction and processing.<sup>1</sup> Most artisanal gold mining operations take place near water bodies such as rivers and streams, which facilitate the acquisition of alluvial ores and provide water for operational needs.<sup>2</sup> However, runoff from mining activities can degrade water quality by introducing contaminants through processes such as cleaning, dewatering, and acid rock drainage.<sup>3</sup> Among human activities, mining poses a significant threat to surface water quality, particularly affecting rivers, streams, lakes, and rainfall-dependent water sources.<sup>4</sup>

Despite its environmental challenges, artisanal gold mining has made a substantial financial contribution to rural communities by generating income from mineral resources.<sup>5</sup> The Cambodian government recognizes mining as a strategic sector for economic growth, given the country's diverse mineral resources, including gold, copper (Cu), and other base metals, which have the potential to boost economic development if effectively explored and managed.<sup>6</sup> Mining has both positive and negative effects on the environment and society. While it contributes to infrastructure development, economic growth, job creation, and social programs, it also poses severe risks to freshwater ecosystems. These risks include contamination from mine effluent discharge, seepage from tailings and waste rock impoundments, and water-intensive ore processing techniques. The release of hazardous chemicals into rivers, streams, and lakes as a result of mining operations has deteriorated water quality and threatened aquatic life. Consequently, rural communities relying on these water sources face significant health risks.<sup>7</sup>

A combination of factors, including increased sedimentation and its correlation with toxic contaminants such as arsenic (As) and mercury (Hg), further degrades water quality downstream of gold mining activities.<sup>8</sup> Among the most evident risks associated with artisanal mining is the high potential for miners to sustain bodily injuries.<sup>9</sup> The rise in artisanal gold mining has also led to a greater reliance on chemical-based techniques for gold processing and recovery, especially those involving cyanide and Hg, both of which pose serious environmental and public health hazards.<sup>10</sup>

Furthermore, gold mining operations can significantly elevate the concentrations of heavy

metals associated with gold deposits, including Cu, zinc (Zn), As, cadmium (Cd), Hg, and lead (Pb), in the surrounding environment. This contamination affects soil, sediments, surface water, and groundwater, posing serious risks to human and animal health.<sup>11</sup> Due to their high mobility and persistence, these heavy metals can be easily dispersed, absorbed by plants and animals, and bioaccumulated in humans through the food chain.<sup>12</sup>

This study aims to:

- (i) Evaluate the levels of heavy metals and other elemental contaminants in drinking water sources in the Prek Te area throughout the year, in accordance with the Cambodian Drinking Water Quality Standard (CDWQS)<sup>13</sup> and the World Health Organization (WHO) drinking water quality guidelines.<sup>14</sup>
- (ii) Assess the non-carcinogenic and carcinogenic health risks posed by selected trace elements in drinking water sources.

## 2. Materials and methods

### 2.1. Study area

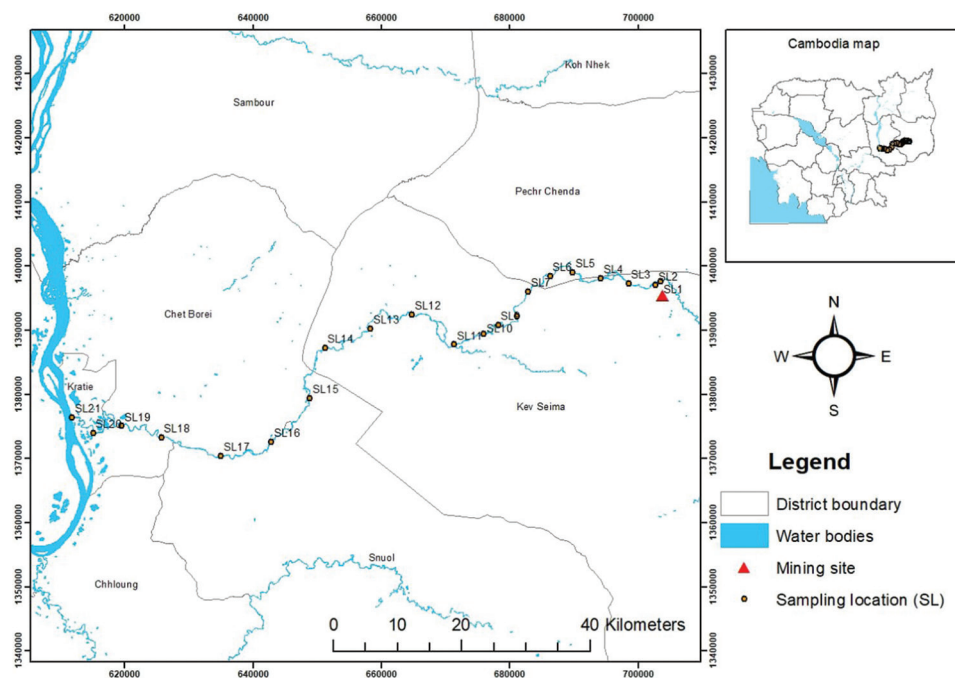
This cross-sectional survey involved the sampling of surface water along Prek Te, a tributary of the Mekong River, extending from Chong Phlah Commune, Keo Seima District, Mondulkiri Province, to Sangkat Roka Kandal, Kratie City, Kratie Province (Figure 1). Cambodia experiences two distinct seasons: the dry season (November–April) and the rainy season (May–October). During the dry season, temperatures can reach up to 40°C in April, whereas in the rainy season, temperatures drop to around 22°C, with high humidity.

The water level in Prek Te is significantly impacted by the flow of the Mekong River. During the rainy season, the water level can exceed 10 m, whereas in the dry season, it typically ranges from 1 to 3 m.

### 2.2. Samples collection

Surface water quality sampling was conducted twice: the first from March 5 to 11, 2023 (dry season), and the second from October 20 to 26, 2023 (rainy season). A total of 21 surface water samples were collected from different locations along Prek Te. Sampling locations were selected based on accessibility, as some sites were situated in dense forest areas with no access routes. The distance between sampling locations ranged from 5 to 10 km, covering a total stretch of 145 km. The first sampling site was located at an artisanal mining site, while the final site (21<sup>st</sup> location) was at the confluence

## Water quality impact from mining in Prek Te



**Figure 1. Map of surface water sampling locations**

of Prek Te and the Mekong River. Surface water samples were collected at a depth of approximately 0 – 30 cm.<sup>15</sup> Sterilized polytetrafluoroethylene bottles were used to store 100 mL of each water sample. To preserve the samples, nitric acid ( $\text{HNO}_3$ ) was added, and they were stored in an ice box during field sampling. Subsequently, the samples were transferred to a refrigerator set at 4°C for storage until analysis for As, chromium (Cr), Ni, Cu, Zn, Cd, and Pb.<sup>16</sup>

Physicochemical parameters were measured on-site at each sampling location. pH was measured using a HANNA pH/ORP meter HI98191 (HANNA, Italy), while electrical conductivity (EC) and total dissolved solids (TDS) were determined using a HANNA Conductivity/TDS/Salinity meter HI 98192 (HANNA, Italy). In addition, dissolved oxygen (DO) was measured with a HANNA HI 9147 meter (HANNA, Italy).

### 2.3. Samples preparation and analysis

Prior to instrumental analysis, filtration was carried out to evaluate the dissolved fraction of the water samples. Sartorius filter papers (0.45  $\mu\text{m}$  pore size) were used for filtration, and 50 mL of filtered water was extracted for analysis.

Filtering water samples is a standard procedure that enhances precision, sensitivity, and reliability in analytical measurements. It minimizes instrument blockages, reduces contamination, improves analytical

sensitivity, and guarantees consistency in the detection of heavy metals and trace elements in water samples. The concentrations of As, Cr, Ni, Cu, Zn, Cd, and Pb were determined using an inductively coupled plasma mass spectrometry (ICP-MS; 8990 GC System, Agilent, United States). Calibration standards of 1  $\mu\text{g/L}$ , 5  $\mu\text{g/L}$ , 10  $\mu\text{g/L}$ , 20  $\mu\text{g/L}$ , 50  $\mu\text{g/L}$ , and 100  $\mu\text{g/L}$  were prepared from a stock multielement standard solution for ICP (Sigma-Aldrich, Switzerland) in 2%  $\text{HNO}_3$ .

For quality control, a certified reference material (CRM), River Thames water (LGC6019, LGC Standards, United Kingdom), was used to ensure accuracy and precision in the measurements. After every 10 sample analyses, the CRM sample was run to verify the ICP-MS accuracy. If the recovery rate fell outside the recommended range (80 – 120%), a new calibration curve was applied before further analysis.

### 2.4. Health risk assessment

Health risk assessment is a systematic process used to evaluate the potential adverse health effects resulting from exposure to environmental hazards. It is a widely adopted tool used by regulatory agencies, health organizations, and industries to ensure that activities such as mining, manufacturing, and waste disposal do not pose significant health risks to human populations. In this study, water samples from residential areas along Prek Te were analyzed to assess lifetime cancer risk

(LCR) and non-carcinogenic health risks associated with heavy metal exposure.

The non-carcinogenic risk was determined using Equations I–II:<sup>17</sup>

$$ADD = \frac{C \times IR \times EF \times ED}{BW \times AT} \quad (I)$$

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

Where *HQ* is the hazard quotient ( $HQ < 1$  suggests unlikely adverse health effects, while  $HQ > 1$  indicates a higher probability of adverse health effects<sup>18</sup>), *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 exposure frequency, *ED* is exposure duration, *BW* is body weight, and *AT* is averaging time, calculated as  $ED \times 365$ .<sup>19</sup> Table 1 shows the summary of exposure assumptions used to calculate the health risk assessment.

The hazard index (HI), which represents the combined risk from multiple substances, is given by:

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

Where  $HI > 1$  suggests that the combined exposure to multiple contaminants may cause non-carcinogenic effects.

The LCR was estimated using Equations IV and V:

$$LCR = LADD \times CSF \quad (IV)$$

$$LADD = \frac{CW \times IR \times EF \times ED}{BW \times AT} \quad (V)$$

Where  $LCR > 10^{-4}$  is deemed an unacceptable risk, while an acceptable range falls between  $10^{-6}$  and  $10^{-4}$ . Lifetime average daily dose is calculated similarly to ADD, except for AT. AT for carcinogenic risk is set as 70 years, equivalent to 25,550 days.

Table 2 presents the reference dose (RfD) and cancer slope factor used in the health risk assessment.

## 2.5. Statistical analysis

Statistical analyses were performed using SPSS for Windows (version 21). The Mann–Whitney U test was used to determine whether there were significant differences in water quality between the dry and rainy seasons along the Prek Te area.

**Table 1. Summary of exposure assumptions used for health risk assessment**

Risk exposure factors	Unit	Values		
		Men	Women	Children
Ingestion rate	L/day	2	2	1
Exposure frequency	Days/year	365	365	365
Exposure duration	Years	20	20	20
Average time (AT) for non-carcinogenic	Day	7.300	7.300	7.300
AT for carcinogenic	Day	25,550	25,550	25,550
Average body weight	Kg	70	60	20

**Table 2. Summary of RfD and CSF used for health risk assessment<sup>17</sup> and<sup>20</sup>**

Parameters	Unit	RfD/CSF factors	
		RfD	CSF
Arsenic	mg/kg/day	$3 \times 10^{-4}$	1.5
Copper	mg/kg/day	$4 \times 10^{-2}$	NA
Chromium	mg/kg/day	$3 \times 10^{-3}$	NA
Cadmium	mg/kg/day	$5 \times 10^{-4}$	NA
Lead	mg/kg/day	$3.5 \times 10^{-3}$	NA
Zinc	mg/kg/day	$3 \times 10^{-1}$	NA
Nickel	mg/kg/day	$2 \times 10^{-2}$	NA

Abbreviations: CSF: Cancer slope factor; NA: Not applicable; RfD: Oral reference dose; USEPA: United States Environmental Protection Agency.

## 3. Results and discussion

### 3.1. Water quality in dry and rainy seasons

Table 3 summarizes the water quality parameters observed during the dry and rainy seasons. Surface water is essential for ecological, commercial, drinking, irrigation, and societal purposes, encompassing rivers, lakes, streams, canals, ponds, wetlands, and reservoirs. However, mining activities can significantly impact water quality by disturbing soil and rock, leading to increased erosion and sedimentation in nearby water sources.<sup>21</sup> Contaminated sediment can degrade water quality by smothering aquatic habitats, reducing light penetration, and diminishing water clarity. In addition, sediment particles can act as carriers for contaminants such as heavy metals.

**Table 3. Summary of water quality in dry and rainy seasons along Prek Te**

Parameters	Dry season (n=21)				Rainy season (n=21)				CDWQS	WHO
	Mean	Min	Max	SD	Mean	Min	Max	SD		
pH	6.64	6.0	7.20	0.33	7.41	6.9	7.70	0.21	6.5 – 8.5	6.5 – 8.5
DO (mg/L)	5.58	4.07	6.47	0.68	6.40	5.38	7.17	0.62	-	-
EC (µS/cm)	95.5	32.8	589	129	92.6	56.1	142	22.6	-	-
TDS (mg/L)	5.58	4.07	6.47	0.68	6.40	5.39	7.17	0.62	800	1000
As (µg/L)	1.23	0.92	2.88	0.42	8.53	1.01	58.1	12.1	50	10
Cu (µg/L)	1.06	0.78	2.82	0.43	26.5	17.6	34.7	4.64	1000	2000
Cr (µg/L)	0.40	0.29	1.05	0.16	1.63	0.16	11.5	2.44	50	50
Cd (µg/L)	ND	ND	ND	ND	0.04	0.03	0.07	0.01	3	3
Pb (µg/L)	0.28	0.22	0.64	0.09	0.42	0.22	1.32	0.26	10	10
Zn (µg/L)	1.18	0.81	3.20	0.52	84.8	10.6	356	91.07	3000	5000
Ni (µg/L)	0.36	0.27	0.88	0.13	8.30	1.51	45.8	11.5	20	70

Abbreviations: As: Arsenic; CDWQS: Cambodian Drinking Water Quality Standard; Cu: Copper; Cd: Cadmium; Cr: Chromium; DO: Dissolved oxygen; EC: Electrical conductivity; ND: Non-detected; Ni: Nickel; Pb: Lead; SD: Standard deviation; TDS: Total dissolved solid; WHO: World Health Organization; Zn: Zinc.

The analytical results reveal that, except for As and Ni, most quality parameters were within the WHO guidelines and the CDWQS. During the rainy season, the highest As concentration among all sampling locations was 58.1 µg/L at Sampling Location 1, followed by 21.96 µg/L at Sampling Location 2 and 10.8 µg/L at Sampling Location 3. The concentration at Sampling Location 1 exceeded both the CDWQS limit (50 µg/L) and the WHO guideline (10 µg/L), while the concentrations at Sampling Locations 2 and 3 exceeded only the WHO guideline. These sampling locations are in proximity to the mining site. However, the mean As concentration across all sampling locations was  $8.5 \pm 12.1$  µg/L, which remains below both CDWQS and WHO limits. In contrast, during the dry season, all trace element concentrations were below both CDWQS and WHO limits, likely due to the absence of mining runoff.

During the rainy season, the highest Ni concentration among all sampling locations was 45.8 µg/L at Sampling Location 1, followed by 25.4 µg/L at Sampling Location 2, 24.4 µg/L at Sampling Location 3, and 23.8 µg/L at Sampling Location 4. These values exceeded the CDWQS limit of 20 µg/L but remained below the WHO guideline of 70 µg/L. However, the mean Ni concentration across all sampling locations was  $8.30 \pm 11.5$  µg/L.

Arsenic and Ni are naturally occurring elements found in various minerals, including sulfide ores, which are frequently targeted in mining operations for commodities such as gold, Cu, and Pb-Zn.<sup>22,23</sup> A

previous study reported As concentrations of up to 15.3 mg/L near a mining site, with levels decreasing downstream.<sup>1</sup> In the present study, trace element concentrations were lower in the dry season compared to the rainy season, indicating improved water quality during the dry season. Increased runoff during the rainy season likely mobilizes contaminants from mining tailings or other sources, transporting them into nearby water sources. Conversely, the dry season is characterized by reduced precipitation and runoff, limiting pollutant transport and resulting in improved water quality.

Similar trends have been observed in other mining-affected regions. For instance, a study conducted in Wonogiri, an artisanal gold mining area in Indonesia, reported elevated heavy metal concentrations both at mining sites and in surrounding communities.<sup>24</sup> The levels of heavy metals such as As, Pb, and Cd have increased in artisanal mining communities, surpassing naturally occurring background levels.<sup>25</sup> Populations residing downstream, where metals have been inappropriately disposed of, as well as those living in close proximity to mining sites, face increased exposure to these contaminants through drinking water and food consumption.

To mitigate these environmental and public health risks, stringent laws or regulations should be enacted to prevent small-scale illegal mining and protect water quality. Effective implementation of these regulations requires targeted training and educational initiatives for miners and other pertinent stakeholders.

### 3.2. Influence of seasonal impact on water quality

Table 4 presents the influence of seasonal impact on water quality along Prek Te. Statistical analysis indicates that all measured parameters, including pH, DO, EC, TDS, and the concentrations of As, Cu, Cr, Cd, Pb, Zn, and Ni, exhibited significant differences ( $p < 0.05$ ) between the rainy and dry seasons. A  $p < 0.05$  suggests that the likelihood of these differences occurring by chance is  $< 5\%$ , providing strong evidence of seasonal impact on water quality.

The observed significant differences suggest that seasonal factors (rainy and dry seasons), such as variations in precipitation and hydrological conditions, influence water quality. During the rainy season, increased precipitation leads to higher runoff, which transports pollutants into water bodies, leading to elevated concentrations of dissolved metal and other contaminants. Seasonal variations in water quality are critical considerations for effective water resource management and environmental protection.

In addition, seasonal fluctuations in river flow, particularly under the influence of the monsoon, may contribute to variations in water quality.<sup>26</sup> Increased rainfall during the rainy season can result in higher discharge rates and greater transport of total suspended solids, thereby affecting the overall water quality of the Mekong River.<sup>27</sup> These seasonal variations can have detrimental effects on the water quality.<sup>28</sup>

### 3.3. Human health risk assessment

#### 3.3.1. Non-carcinogenic risk assessment

Non-carcinogenic risk assessment is a critical process in environmental health used to evaluate the potential

adverse health effects of exposure to chemical substances that do not cause cancer. This assessment typically focuses on risks such as organ damage, developmental toxicity, and neurological effects. The process integrates data from exposure assessment and dose-response analysis to estimate the potential risks associated with chemical exposure through drinking water.

A key metric in non-carcinogenic risk assessment is the HQ, which is calculated by dividing the estimated exposure dose by the RfD.  $HQ > 1$  indicates a potential risk of adverse health effects, whereas  $HQ < 1$  suggests that non-carcinogenic health risks are unlikely.<sup>29</sup> The human health risk assessment was conducted for three demographic groups: men, women, and children. The non-carcinogenic risk was calculated based on ADD and the frequency of water consumption. Table 5 presents the non-carcinogenic risk calculations for the dry season, while Table 6 provides the corresponding values for the rainy season. During the dry season, the HQ levels for As, Cu, Cr, Cd, Pb, Zn, and Ni remained below 1 across all groups, indicating that drinking water posed no potential non-carcinogenic health risks. In contrast, in the rainy season, the HQ of As exceeded 1 for children, indicating potential non-carcinogenic risks associated with As in their drinking water. Notably, children exhibited higher HQ values compared to women and men, highlighting their increased vulnerability to water contaminants.

Further analysis revealed that HQ values for As exceeded 1 at Sampling Locations 1, 2, and 3 across all groups, suggesting that drinking water from these

**Table 4. Influence of seasonal impact on water quality along Prek Te**

Parameters	Dry season (n=21)				Rainy season (n=21)				Mann–Whitney U test (p-value)
	Mean	Min	Max	SD	Mean	Min	Max	SD	
pH	6.64	6.0	7.20	0.33	7.41	6.90	7.70	0.21	0.001*
DO (mg/L)	5.58	4.07	6.47	0.68	6.40	5.38	7.17	0.62	0.001*
EC ( $\mu$ S/cm)	95.5	32.8	589	128	92.6	56.1	142.5	22.6	0.001*
TDS (mg/L)	5.58	4.07	6.47	0.68	6.40	5.39	7.17	0.62	0.001*
As ( $\mu$ g/L)	1.23	0.92	2.88	0.42	8.53	1.01	58.1	12.1	0.001*
Cu ( $\mu$ g/L)	1.06	0.78	2.82	0.43	26.5	17.6	34.7	4.64	0.001*
Cr ( $\mu$ g/L)	0.4	0.29	1.05	0.16	1.63	0.16	11.5	2.44	0.001*
Cd ( $\mu$ g/L)	ND	ND	ND	ND	0.04	0.03	0.07	0.01	0.001*
Pb ( $\mu$ g/L)	0.28	0.22	0.64	0.09	0.42	0.22	1.32	0.26	0.005*
Zn ( $\mu$ g/L)	1.18	0.81	3.20	0.52	84.8	10.6	356	91.1	0.001*
Ni ( $\mu$ g/L)	0.36	0.27	0.88	0.13	8.30	1.51	45.8	11.5	0.001*

Note: \*Significant difference at  $p < 0.05$ .

Abbreviations: As: Arsenic; Cu: Copper; Cd: Cadmium; Cr: Chromium; DO: Dissolved oxygen; EC: Electrical conductivity; ND: Non-detected; Ni: Nickel; Pb: Lead; SD: Standard deviation; TDS: Total dissolved solid; Zn: Zinc.

**Table 5. Non-carcinogenic risk assessment for the dry season**

Parameters	Dry season (n=21)						
	Mean concentration (µg/L)	Men		Women		Children	
		ADD	HQ	ADD	HQ	ADD	HQ
As	1.23	0.04	0.12	0.04	0.14	0.06	0.21
Cu	1.06	0.03	0.00	0.03	0.00	0.05	0.00
Cr	0.40	0.01	0.00	0.01	0.00	0.02	0.01
Cd	ND	0.00	0.00	0.00	0.00	0.00	0.00
Pb	0.28	0.01	0.00	0.01	0.00	0.01	0.00
Zn	1.18	0.03	0.00	0.04	0.00	0.06	0.00
Ni	0.36	0.01	0.00	0.01	0.00	0.02	0.00

Abbreviations: ADD: Average daily dose; As: Arsenic; Cu: Copper; Cd: Cadmium; Cr: Chromium; HQ: Hazard quotient; ND: Non-detected; Ni: Nickel; Pb: Lead; Zn: Zinc.

**Table 6. Non-carcinogenic risk assessment for the rainy season**

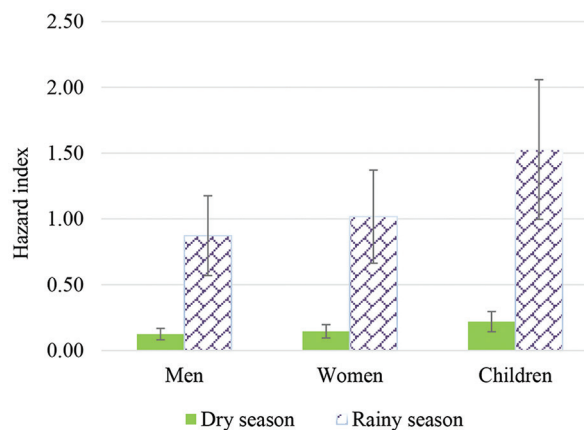
Parameters	Rainy Season (n=21)						
	Mean concentration (µg/L)	Men		Women		Children	
		ADD	HQ	ADD	HQ	ADD	HQ
As	8.53	0.24	0.81	0.28	0.95	0.43	1.42
Cu	26.5	0.76	0.02	0.88	0.02	1.33	0.03
Cr	1.63	0.05	0.01	0.05	0.02	0.08	0.03
Cd	0.04	0.00	0.00	0.00	0.00	0.00	0.00
Pb	0.42	0.01	0.00	0.01	0.00	0.02	0.01
Zn	84.8	2.42	0.01	2.83	0.01	4.24	0.01
Ni	8.30	0.24	0.01	0.28	0.01	0.41	0.02

Abbreviations: ADD: Average daily dose; As: Arsenic; Cu: Copper; Cd: Cadmium; Cr: Chromium; HQ: Hazard quotient; ND: Non-detected; Ni: Nickel; Pb: Lead; Zn: Zinc.

locations may pose non-carcinogenic health risks. Multiple studies have confirmed that children are more susceptible to contaminants in drinking water than adults.<sup>30-32</sup>

Figure 2 illustrates the HI, which represents the cumulative non-carcinogenic risk from combined chemical contaminants across different seasons for males, women, and children. During the rainy season, HI values exceeded 1 for children and women, indicating potential non-carcinogenic risks associated with the drinking water of Prek Te. In contrast, during the dry season, HI values remained below 1 for all groups, suggesting no significant non-carcinogenic risks from drinking water consumption.

Similarly, elevated HI values (>1) were observed among children, women, and men in various drinking water sources within the Tonle Sap Great Lake basin.<sup>33</sup> In addition, oral HI values for both adults and children exceeded the safe thresholds (HI > 1), classifying



**Figure 2. Hazard index of combined chemical contaminants in drinking water across different seasons for men, women, and children**

them within a high-risk category for non-carcinogenic impact.<sup>34</sup>

**Table 7. Carcinogenic risk assessment (arsenic exposure) for the dry and rainy seasons in Prek Te**

Season	Mean concentration ( $\mu\text{g/L}$ )	Men		Women		Children	
		LADD	LCR	LADD	LCR	LADD	LCR
Dry Season ( $n=21$ )	1.235	$1.0 \times 10^{-2}$	$1.5 \times 10^{-2}$	$1.2 \times 10^{-2}$	$1.8 \times 10^{-2}$	$1.8 \times 10^{-2}$	$2.6 \times 10^{-2}$
Rainy Season ( $n=21$ )	8.531	$6.9 \times 10^{-2}$	$1 \times 10^{-1}$	$8.1 \times 10^{-2}$	$1.2 \times 10^{-1}$	$1.2 \times 10^{-1}$	$1.8 \times 10^{-1}$

Abbreviations: As: Arsenic; LADD: Lifetime average daily dose; LCR: Lifetime cancer risk.

### 3.3.2. Carcinogenic risk assessment

The carcinogenic risks associated with drinking water during the rainy and dry seasons are presented in Table 7. The LCR of As for men, women, and children in the dry season was calculated as  $1.5 \times 10^{-2}$ ,  $1.8 \times 10^{-2}$ , and  $2.6 \times 10^{-2}$ , respectively. These values indicate that for every 10,000 individuals exposed to As in drinking water over their lifetime, approximately 150, 180, and 260 cases of cancer may develop in men, women, and children, respectively.

In the rainy season, the LCR of As increased to  $1 \times 10^{-1}$ ,  $1.2 \times 10^{-1}$ , and  $1.8 \times 10^{-1}$  for men, women, and children, respectively. These values indicate that for every 100 exposed individuals, approximately 10, 12, and 18 cases of cancer could be expected due to As contamination in drinking water. The United States Environmental Protection Agency does not classify several metals—including Cu, Cr, Cd, Pb, Zn, and Ni—as carcinogenic through oral exposure. However, LCR values are essential for assessing As-related risks among different demographic groups. Higher LCR values indicate an increased risk of developing cancer from As exposure, highlighting the need for effective mitigation strategies to minimize exposure, especially among vulnerable populations such as children.

Inorganic arsenic is one of the most prevalent chemical contaminants in drinking water worldwide and is a confirmed human carcinogen.<sup>35</sup> Prolonged exposure to low concentrations of heavy metals may lead to the development of various cancers years after initial exposure.<sup>36</sup> Contaminated drinking water containing heavy metals (Pb, Cr, Cd, and Ni) has been associated with an increased risk of cancer in humans.<sup>37</sup> Given that As concentrations in drinking water exceeded acceptable limits, particularly for children, urgent interventions are necessary to mitigate public health risks.<sup>38</sup>

## 4. Conclusion

This study investigated the seasonal variations in surface water quality and the associated human health risks due to chemical contamination from upstream artisanal mining activities along Prek Te. The analytical results revealed that most water quality parameters complied

with the WHO guidelines and CDWQS, except for As and Ni.

Arsenic concentrations reached a maximum of  $58.1 \mu\text{g/L}$ , exceeding both the CDWQS limits of  $50 \mu\text{g/L}$  and the WHO guideline of  $10 \mu\text{g/L}$ . Additional recorded values of  $21.9 \mu\text{g/L}$  and  $10.8 \mu\text{g/L}$  also surpassed the WHO guideline. Ni concentrations were found at a maximum of  $45.8 \mu\text{g/L}$ , with other recorded values of  $25.4 \mu\text{g/L}$ ,  $24.4 \mu\text{g/L}$ , and  $23.8 \mu\text{g/L}$ . These concentrations exceeded the CDWQS limit of  $20 \mu\text{g/L}$  but remained below the WHO guideline of  $70 \mu\text{g/L}$ . Contaminant concentrations were generally lower in the dry season compared to the rainy season, indicating better water quality during the dry season.

Statistical analysis revealed a significant seasonal difference ( $p < 0.05$ ) in all assessed water quality parameters, including pH, DO, EC, TDS, As, Cu, Cr, Cd, Pb, Zn, and Ni. The health risk assessment indicated that residents along Prek Te are exposed to chemical contaminants primarily through the drinking water pathway. HQ and HI values were higher in children than in women and men, indicating that children are more susceptible to non-carcinogenic risks from waterborne contaminants. Furthermore, LCR analysis showed that children face a higher risk of As-related health effects compared to adults. These findings highlight the urgent need for a regular water quality monitoring program. In addition, the implementation of appropriate drinking water treatment methods, particularly for As removal, is critical to ensuring safe drinking water for residents in the Prek Te area.

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## Conflict of interest

The authors declare there is no conflict of interest.

## Author contributions

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## Availability of data

All relevant data are included in the paper.

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