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Toxic and Essential Elements in Household Drinking Water from Kratie Province, Cambodia: Health Risk Assessment Using Survey-Derived Exposure Parameters

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Drinking water contamination by toxic elements poses significant public health risks, particularly in rural communities. This study quantified Pb, Cd, Zn, Cu, and K in 100 household drinking-water samples from Kratie Province, Cambodia, using atomic absorption spectrophotometry following acid digestion. Health risks for children and adults were assessed using exposure parameters obtained from a survey of 147 local participants. Zn and Cu concentrations remained within World Health Organization (WHO) guideline values, whereas Pb and Cd exceeded the applicable limits. Cd exceeded the WHO guideline value by up to 7.5-fold in 69% of samples. K showed the highest concentration among the investigated elements and was considered an indicator of dissolved-ion content. All hazard quotients were below 1 except for Cd. The cumulative hazard index exceeded 1 for children (2.46) and adults (2.07) under a conservative screening scenario, with exceedance persisting across all tested approaches for handling non-detects. The estimated lifetime cancer risk for Cd exceeded 1×10^{-4} across the published range of oral slope factors considered, although these factors were not validated for oral exposure to Cd. These preliminary risk estimates are based on a single sampling round and modelled intake assumptions. Further monitoring and investigation of potential contamination sources are recommended to better understand the extent of the problem.

Keywords: Cadmium, Drinking water, Health risk assessment, Atomic absorption spectrophotometry, Cambodia.

INTRODUCTION

Industrialization and the expansion of agricultural activities have contributed to environmental pollution and the deterioration of water quality [1,2]. Potentially toxic elements are a major concern since they can persist in the environment and accumulate in living organisms over time which may pose risks to human health [2-4]. Drinking water is an important route of human exposure especially when contamination continues over long periods. Therefore, regular monitoring of water quality is essential to detect contamination and assess its potential impact on human health.

Elements such as copper (Cu) and iron (Fe) and zinc (Zn) play important roles in normal physiological processes including enzyme activity and hemoglobin synthesis. However, excessive intake may cause adverse effects [5,6]. In contrast, lead (Pb), cadmium (Cd), and mercury (Hg) have no established beneficial biological function in humans and are of particular toxicological concern [5-7]. Their presence in drinking water may contribute to neurological, cardiovascular, renal and developmental effects, depending on the element, exposure level and duration. Certain elements such as arsenic (As) and cadmium (Cd) are also associated with carcinogenic effects and may increase the risk of cancer following prolonged exposure [3,5,6]. Children and pregnant women may be especially vulnerable since exposure during critical developmental stages can have lasting consequences [4].

Potentially toxic elements enter aquatic environments through natural processes, including rock weathering and soil erosion as well as anthropogenic activities such as mining, industrial discharge, agricultural runoff, and improper waste disposal [6,8]. Once released, these elements may move between water, soil, sediments and biological systems, creating multiple pathways for human exposure [6,9]. Contaminated food may further contribute to exposure when elements accumulate in organisms and enter the food chain [10,11]. The extent of these risks depends on environmental conditions, exposure patterns and individual susceptibility. The WHO has estab-

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lished guideline values for several elements in drinking water to support the protection of public health [12]. However, comparing measured concentrations with guideline values alone does not fully characterize health risks, which also depend on water consumption and body weight.

In Cambodia, households obtain drinking water from groundwater, rainwater, bottled water and locally distributed supplies. These sources may differ in quality due to the geological conditions, agricultural activities, mining, wastewater discharge and water-treatment practices [2]. Such differences make source-specific assessment important for understanding contamination patterns and identifying potentially vulnerable households. Despite the public health importance of safe drinking water, information on potentially toxic elements in household water remains limited in some rural Cambodian settings. The present study addresses the lack of documented data for Kratie Province and incorporates household-specific exposure information obtained through a survey of local participants. Water ingestion rate, body weight and exposure duration were used in the risk calculations rather than relying exclusively on default assumptions. The analytical performance parameters and treatment of non-detectable results are also considered to support transparent interpretation of the estimates. In addition, the study examines whether measured element concentrations are associated with the drinking-water sources reported by participating households.

Accordingly, this study aimed to (i) determine the concentrations of Pb, Cd, Zn, Cu and K in household drinking-water samples from Kratie Province; (ii) to assess potential non-carcinogenic and carcinogenic risks associated with relevant elements through drinking-water ingestion; and (iii) examine associations between measured concentrations and reported water sources. Pb and Cd were prioritized due to their toxicological significance, while Zn and Cu were evaluated in relation to applicable drinking-water guidelines and health-based reference doses. Potassium (K) was measured to provide supplementary information on water composition but was excluded from hazard quotient and hazard index calculations. The findings provide baseline evidence to support further water quality monitoring and investigation of potential contamination sources in the study area.

EXPERIMENTAL

Analytical-grade nitric acid (65%) was obtained from Merck, Germany and used for sample preparation and digestion. Elemental calibration curves were prepared using 1000 ppm stock standard solutions obtained from CPAchem, Bulgaria. All samples were analyzed using an atomic absorption spectrophotometer (AAS; AA-7800, Shimadzu, Japan) for elemental quantification. Beakers and volumetric and conical flasks supplied by Isolab, Germany were used during sample preparation

Sample collection: Drinking water samples were collected from 100 households in Phum Thom of Sondan Commune in Sombour District of Kratie Province, Cambodia. Each sample was collected in a 500 mL polyethylene bottle. Before sampling the bottles were cleaned with 10% HNO_3 for 24 h and rinsed three times with deionized water. The collected samples were acidified with HNO_3 for preservation before analysis [2]. During field sampling the samples were stored in an ice box and subsequently transferred to a refrigerator maintained at 4 ºC until analysis.

Sample preparation and analysis: Water samples were digested in duplicate by heating 50 mL of each sample with 2.5 mL of 65% HNO_3 on a hotplate at 90 ± 5 ºC for 1 h. The digested samples were filtered through Whatman filter paper followed by a 0.22 μm nylon membrane filter and diluted to a final volume of 50 mL with deionized water [2]. Calibration solutions of the target elements were prepared by serial dilution of a mixed standard stock solution. Calibration curves were constructed by plotting corrected standard intensities against the corresponding concentrations. The digested samples were analyzed for Cu Zn K Pb and Cd using an atomic absorption spectrophotometer (Shimadzu AA-7800). The calibration curves were constructed separately for each element using all valid replicate standard readings within the prepared concentration range and fitted by ordinary least squares. The calibration ranges and equations together with the coefficients of determination are shown in Table-1. The limits of detection (LOD) and quantification (LOQ) were calculated as 3.3σ/S and 10σ/S respectively where S represents the slope of the calibration curve and σ represents the standard

TABLE-1
LIST OF AAS OPERATING CONDITIONS AND ANALYTICAL VALIDATION PARAMETERS FOR THE DETERMINATION OF DIFFERENT METALS

Parameter	Zn	Pb	Cd	Cu	K
Wavelength (nm)	213.9	283.3	228.8	324.7	766.5
Burner height (mm)	7	7	7	7	7
Lamp mode	BGC-D2	BGC-D2	BGC-D2	BGC-D2	BGC-D2
Flame type	Air-C_2H_2	Air-C_2H_2	Air-C_2H_2	Air-C_2H_2	Air-C_2H_2
Fuel gas (L/min)	2.0	2.0	1.8	2.0	2.0
Support gas (L/min)	15.0	15.0	15.0	15.0	15.0
Calibration range (mg/L)	0.001–0.5	0.01–0.12	0.005–0.08	0.001–0.2	0.1–3.0
Calibration equation	y = 0.5834x + 0.00107	y = 0.0233x − 0.00028	y = 0.4167x − 0.00255	y = 0.1480x − 0.00076	y = 0.2204x + 0.00351
R^2	0.9959	0.9207	0.9797	0.9632	0.9964
LOD (mg/L)	0.0049	0.0156	0.0036	0.0064	0.0929
LOQ (mg/L)	0.0148	0.0473	0.0109	0.0194	0.2816

Note: BGC = background correction using a deuterium lamp

deviation of the *y*-intercept in accordance with ICH Q2(R2) [13].

Results were classified as not detected (ND) when the absorbance was negative or the mean concentration was below the element-specific LOD. Non-detects were excluded from summary statistics without substitution and the number of detections was reported for each element. Results between the LOD and LOQ were considered semi-quantitative while results exceeding the highest calibration standard were reported as above the calibrated range and excluded from mean calculations rather than extrapolated. Substitution using zero LOD/2 or LOD/√2 was considered but rejected because such approaches could strongly influence the estimated mean when detection frequencies were low. Accordingly, the reported concentrations represent the means of detected samples rather than the means across all 100 households.

This distinction is particularly important for Pb which was detected in only 10 of the 100 samples. The mean concentration among detected samples was 0.0349 mg/L whereas assigning zero to all non-detects across the full dataset resulted in a mean of 0.0035 mg/L. One Pb result was classified as non-detectable owing to negative absorbance. The hazard index remained above unity across all four treatments, ranging from 1.43 to 2.46 for children and 1.21 to 2.07 for adults. Cadmium was the predominant contributor to the hazard index under all treatments [14].

Assessment of human health risk: Health risk assessment evaluates the potential non-carcinogenic and carcinogenic risks associated with exposure to toxic elements under different exposure conditions and across population groups [2]. In this study, health risks from drinking-water ingestion were assessed for children and adults. Pb and Cd were detected in only 10% and 69% of samples, respectively; therefore, no individual household in the survey necessarily had the combined concentration profile used in the assessment.

Chronic daily intake: Chronic daily intake (CDI) was calculated to estimate daily exposure to heavy metals through drinking-water ingestion in children and adults over the specified exposure period [15]. As shown in eqn. 1, CDI was determined using the measured metal concentration (C), ingestion rate (IR), exposure frequency (EF) and exposure duration (ED), normalized by body weight (BW) and averaging time (AT). For non-carcinogenic risk assessment, AT was defined as the exposure duration multiplied by the number of days per year. For carcinogenic risk assessment, AT was set to a 70-year lifetime (25,550 days), while ED remained specific to each population group. CDI was expressed in milligrams per kilogram of body weight per day (mg/kg·day) (eqn. 1) and the exposure data is shown in Table-2.

$$CDI = \frac{C \times IR \times EF \times ED}{BW \times AT} \quad (1)$$

Hazard quotient (HQ): The HQ was calculated to assess the potential non-carcinogenic health risk associated with exposure to individual elements. It was defined as the ratio of chronic daily intake (CDI) to the corresponding reference dose (RfD), which represents an estimate of daily exposure unlikely to cause appreciable adverse health effects over a specified period. The RfD values used for Cd, Cu, Zn and Pb were 0.0005, 0.037, 0.3 and 0.0035 mg/kg·day, respectively. For Cd, the value of 0.0005 mg/kg·day was selected based on the US EPA IRIS assessment for drinking water exposure; the higher value of 0.001 mg/kg·day applies to dietary exposure and was there-fore not used for the ingestion pathway evaluated in this study [2,16]. An HQ > 1 indicates that appreciable non-carcinogenic effects are not expected under the assessed exposure conditions, whereas an HQ of 1 or higher indicates a potential health concern requiring further evaluation [2,17]. HQ was calculated using eqn. 2:

TABLE-2
List of exposure parameter values used for estimating drinking water intake and exposure among adults and children in Cambodia

Parameter	Unit	General	Cambodia	
			Adult	Children
IR	L/day	2	2.19	1.10
EF	days/year	350	365	365
ED	years	70	48.92	9.43
BW	kg	70	58.60	24.78
AT	days	25,550	17,855.80	3,441.95

Note: IR, EF, ED, BW, & AT refer to the intake rate of drinking water, exposure frequency, exposure duration, body weight, & exposure average time, respectively. All parameter values were derived from data gathered through survey responses. Adult body weight is the mean of the 88 adults for whom weight was recorded; exposure duration is the mean age of the 100 enrolled adults, assuming residency since birth.

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

Hazard index (HI): The HI was calculated to evaluate the cumulative non-carcinogenic health risk resulting from simultaneous exposure to multiple heavy metals. The HI was calculated by summing the HQs for all analyzed metals in each exposure group. An HI value < 1 indicates an acceptable level of combined exposure, whereas an HI value of 1 or higher indicates a potential health concern due to the additive effects of multiple contaminants [17]. HI was calculated according to eqn. 3:

$$HI = \Sigma HQ \quad (3)$$

Lifetime cancer risk (LCR): The LCR was estimated to assess the probability of developing cancer over a lifetime as a result of exposure to carcinogenic heavy metals. The LCR is considered for highly toxic metals, including Cd and Pb, which are recognized as carcinogens. Carcinogenic risk was assessed using the lifetime average daily dose (LADD), calculated by applying the survey-derived exposure duration for each population group (9.43 years for children and 48.92 years for adults) over a 70-year averaging period. Cancer risk was estimated separately for childhood and adult exposure and as an age-adjusted lifetime value obtained by summing the contributions from both exposure stages for a single resident, following US EPA guidance [16,18]. The US EPA Integrated Risk Information System (IRIS) does not provide an oral cancer slope factor (CSF) for Cd, as the available evidence has not established a suitable orally administered dose–response relationship. Published oral slope factors are instead derived from inhalation data and carry substantial uncertainty when applied to drinking-water ingestion [18,19].

Accordingly, Cd-related lifetime cancer risk (LCR) estimates are presented for the published range of slope factors and interpreted solely as screening-level estimates. LCR was calculated as the product of LADD and CSF, which represents the estimated carcinogenic potency of a substance. The commonly applied screening risk range is 1×10^{-6} to 1×10^{-4}; estimates above this range may warrant further investigation but do not establish the occurrence of cancer in the exposed population. The LCR was calculated according to eqn. 4 [15,20].

$$LCR = LADD \times CSF \quad (4)$$

Household questionnaire survey: A questionnaire survey was conducted among 100 households to collect information on daily drinking water intake, body weight and age for estimating chronic daily intake (CDI) through drinking-water ingestion. Each completed questionnaire was linked to the corresponding household water sample, allowing measured element concentrations to be examined in relation to the reported drinking water source.

Statistical analysis: All experiments were conducted in duplicate (n = 2) and the data were reported as mean ± standard deviation (SD). Descriptive statistics summarized element concentrations, health risk assessments and survey responses. Element concentrations were compared between households reporting the use of packaged or purified water and those relying solely on local supplies using Fisher's exact test for detection frequency and the Mann-Whitney U test for concentrations among detected samples. The Holm procedure was applied within each family of five tests to correct for multiple comparisons. Data analysis was carried out using Minitab version 20.3 and Microsoft Excel 16.

RESULTS AND DISCUSSION

Element concentrations in drinking water: The detection frequencies of the 5 elements in the 100 drinking water samples are shown in Fig. 1, while their concentration distributions are summarized in Table-3. Zinc (Zn) and copper (Cu) are essential trace elements involved in various physiological processes [21]. Their mean concentrations were 0.0592 ± 0.0737 mg/L and 0.0138 ± 0.0065 mg/L, respectively, well below the WHO guideline values of 5 mg/L for Zn and 2 mg/L for Cu [2,22]. At these concentrations, neither element exceeded its respective drinking-water guideline value. In contrast, the mean detected concentrations of Pb (0.0349 ± 0.0102 mg/L; semi-quantitative) and Cd (0.0224 ± 0.0047 mg/L) exceeded the WHO guideline values of 0.01 mg/L and 0.003 mg/L, respectively. These means represent only the samples in which each element was detected (10 for Pb and 69 for Cd), rather than all 100 samples. When non-detects were assigned a value of zero, the corresponding means across all samples were 0.0035 mg/L for Pb and 0.0155 mg/L for Cd (Table-4). The elevated Cd concentrations and the detected Pb levels raise concerns about potential exposure through prolonged consumption, although the health implications depend on actual intake and exposure duration.

The present study assessed drinking water quality at a single point in time and did not evaluate participants' health status. The results show that some samples exceeded drinking water guideline values, but no actual health effects were assessed [3,23]. Potassium (K) had the highest measured concentration among the elements analyzed. However, the reported mean is a lower-bound estimate since six samples exceeded the upper calibration limit and were not extrapolated beyond the calibrated range. The WHO has not established a health-based guideline value for potassium in drinking water, as it is an essential macronutrient and is generally not a concern at typical drinking-water concentrations [14,24]. In this study, potassium was measured to provide additional information on dissolved-ion content rather than being treated as a contaminant of concern.

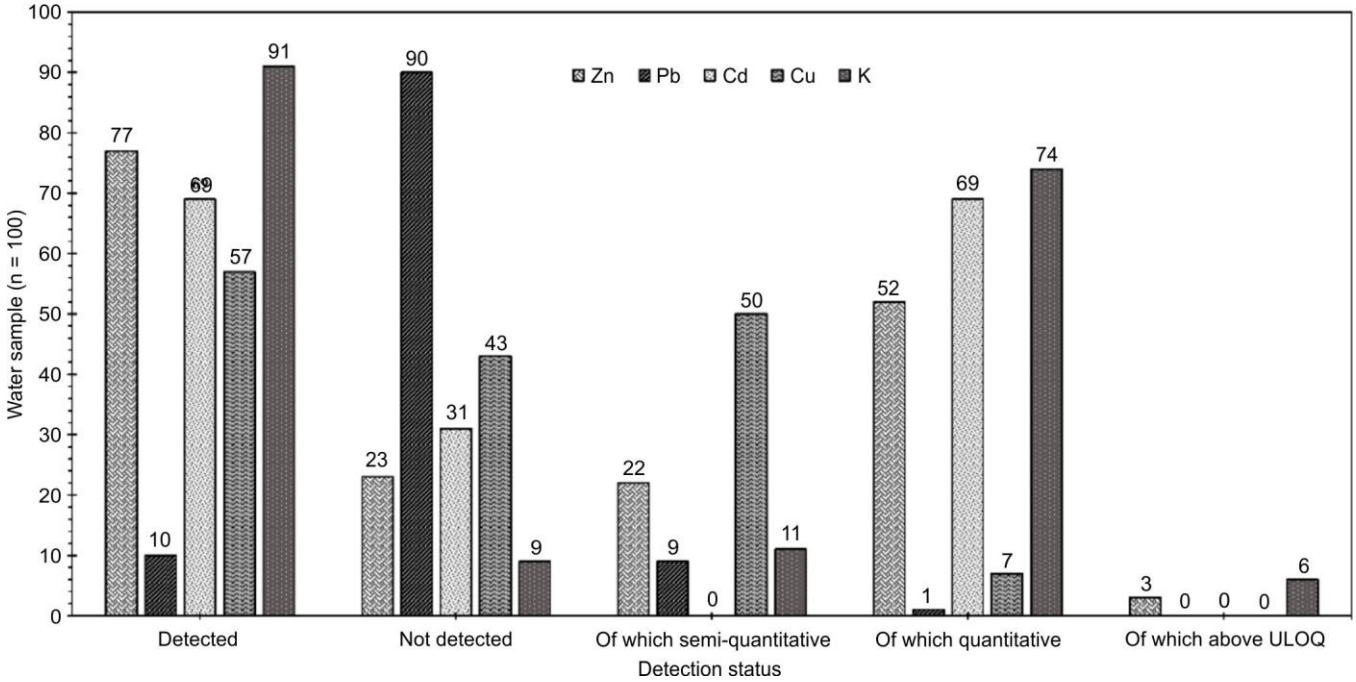


Fig. 1. Detection status of determined elements in water sample (n = 100)

TABLE-3
SUMMARY OF CONCENTRATION RANGES, MEAN LEVELS, DETECTION FREQUENCIES AND WHO LIMITS OF SELECTED ELEMENTS IN DRINKING WATER

Element	Range (mg/L)	Average ± SD (mg/L)	n above working range	WHO limit (mg/L)	Detection frequency (%)
Zn	0.0060-0.3970	0.0592 ± 0.0737	3	5	77.00
Pb	0.0205-0.0570	0.0349 ± 0.0102	0	0.01	10.00
Cd	0.0120-0.0289	0.0224 ± 0.0047	0	0.003	69.00
Cu	0.0065-0.0356	0.0138 ± 0.0065	0	2	57.00
K	0.0930-2.7625	1.3223 ± 0.6970	6	–	91.00

Note: SD = Standard Deviation. Ranges and means are calculated over the samples in which the element was detected and are not means across all 100 households; the detection frequency column gives the relevant denominator. Censoring is applied at both ends of the working range given in Table-1. A result was recorded as non-detected where the absorbance was negative, or the concentration fell below the LOD; a result above the highest calibrated standard was recorded as exceeding it. Neither is quantified and neither enters the mean, so the Zn and K means are lower bounds. Results between the LOD and the LOQ are semi-quantitative.

TABLE-4
COMPARATIVE ASSESSMENT OF CONCENTRATION ESTIMATES AND HAZARD INDICES UNDER DIFFERENT TREATMENTS OF NON-DETECT VALUES

Treatment of non-detects	Zn (mg/L)	Pb (mg/L)	Cd (mg/L)	Cu (mg/L)	K (mg/L)	HI children	HI adults
Detected samples only (reported)	0.0592	0.0349	0.0224	0.0138	1.3223	2.46	2.07
ND = 0	0.0451	0.0035	0.0155	0.0079	1.1957	1.43	1.21
ND = LOD/2	0.0457	0.0105	0.0160	0.0093	1.2002	1.57	1.33
ND = LOD/√2	0.0460	0.0134	0.0163	0.0098	1.2020	1.63	1.37

A study in China reported Cu, Pb, and Cd concentrations of 1.92-3.68, 0.021-0.04 and 0.02-0.05 µg/L, respectively, in river water. In tap water, the reported mean concentrations were 1.04 ± 2.08 µg/L for Cu, 1.66 ± 1.52 µg/L for Pb and 0.03 ± 0.01 µg/L for Cd [15]. In Ethiopia, Zn concentrations in drinking water were also investigated, although the reported value of 0.06 ± 2.72 mg/L requires verification against the original source [22]. Compared with these studies, the present samples showed relatively low Cu and Zn concentrations, while Pb and Cd concentrations were higher. These differences suggest potentially higher exposure concerns in the study area, particularly for Cd. However, direct comparisons should be interpreted cautiously since variations in the water sources, treatment practices, sampling designs and analytical methods may influence the reported concentrations.

Health risk assessment

Chronic daily intake: The estimated chronic daily intake (CDI) values for children and adults are given in Table-5. Children had higher CDI values than adults for the same drinking water exposure, which the reflect the differences in body weight and water ingestion relative to body mass. A similar pattern was also reported in a study conducted in Poland [25], where children showed higher CDI values for several metals than adults. The average CDI values for both age groups followed the order K > Zn > Pb > Cd > Cu. This ranking reflects the relative intake of each element based on its measured concentration and the exposure parameters used. Although K and Zn contributed more to the estimated daily intake, both are essential elements with established physiological roles. In contrast, Pb and Cd remain important toxicological concerns even at comparatively lower intake levels due to their adverse health effects and lower reference doses [25]. Therefore, CDI values alone should not be used to compare the health risks of different elements; their toxicity and corresponding reference doses must also be considered.

TABLE-5
LIST OF CHRONIC DAILY INTAKE (CDI) VALUES OF SELECTED ELEMENTS FOR CHILDREN AND ADULTS

Element	CDI (mg/kg/day)	
	Children	Adult
Zn	0.00263	0.00221
Pb	0.00155	0.00130
Cd	0.00100	0.00084
Cu	0.00061	0.00052
K	0.05870	0.04942

Hazard quotient and hazard index: Children had higher hazard quotient (HQ) values than adults for all four elements assessed (Fig. 2), which is consistent with the higher exposure relative to body weight. Cd was the largest contributor to non-carcinogenic risk, with HQ values of 1.99 for children and 1.68 for adults, both above the threshold of 1. The corresponding HQ values for Pb were 0.44 and 0.37, whereas those for Zn and Cu were substantially lower. The hazard index (HI), calculated as the sum of the HQs for the four elements, reached 2.46 for children and 2.07 for adults. These estimates point to potential concern from combined exposure under the assessed conditions. However, the calculations use the mean detected concentration of each element simultaneously and therefore represent a conservative screening scenario rather than typical household exposure. When non-detectable results were treated as zero, the HI decreased to 1.43 for children and 1.21 for adults, although both values remained above 1 (Table-4). Recalculating the HI using the higher Cd dietary reference dose (0.001 mg/kg·day) yielded values of 1.46 for children and 1.23 for adults, again exceeding the threshold of concern.

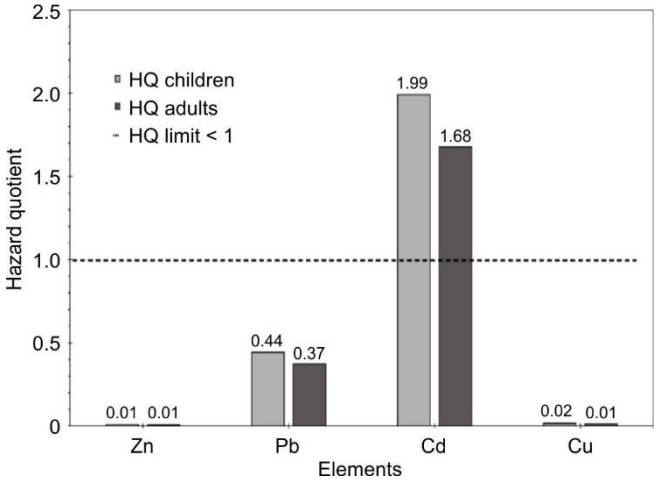


Fig. 2. Comparison of hazard quotient (HQ) values for Zn, Pb, Cd and Cu in children and adults relative to the acceptable limit (HQ < 1)

Liu *et al*. [15] reported HQ and HI values < 1 for heavy metals in tap water from Wuhan, China. By comparison, a study of the Upper Ganga River in India reported HI values of 0.85-1.64 for adults and 0.92-1.77 for children, with some locations exceeding 1 [21]. Differences in water sources, treatment practices, sampling designs, and exposure assumptions may account for the variation between these findings. The households examined in the present study used boiled, packaged, rainwater or groundwater supplies, rather than relying exclusively on a centrally treated distribution system. Cd contributed approximately four-fifths of the HI in both age groups.

Lifetime cancer risk: Lifetime cancer risk (LCR) is used to estimate the potential risk of cancer associated with long-term exposure to contaminants in drinking water [26]. The US EPA commonly applies a screening risk range of 1×10^{-6} to 1×10^{-4}. Risks below 1×10^{-6} are generally considered negligible, whereas values above 1×10^{-4} may require further investigation and risk management [3].

Cancer risk was calculated separately for childhood and adult exposure and then combined to obtain an age-adjusted lifetime estimate (Table-6). For Pb, the estimated risks were 1.77×10^{-6} for childhood and 7.75×10^{-6} for adulthood, giving a combined lifetime estimate of 9.52×10^{-6}. All three values fall within the commonly applied screening range. These estimates suggest that Pb exposure through drinking water was below the upper risk threshold under the modelled conditions. A study conducted in Bandar Abbas, Iran [27], similarly reported Pb-related cancer risk below the upper threshold across the age groups examined.

TABLE-6
COMPARATIVE LIFETIME CANCER RISK (LCR) ESTIMATES FOR Pb AND Cd IN CHILDREN AND ADULTS

Elements/slope factor	Child stage	Adult stage	Age-adjusted lifetime
Pb (CSF 0.0085)	1.77×10^{-6}	7.75×10^{-6}	9.52×10^{-6}
Cd, screening (CSF 0.38)	5.09×10^{-5}	2.23×10^{-4}	2.73×10^{-4}
Cd, screening (CSF 6.1)	8.18×10^{-4}	3.57×10^{-3}	4.39×10^{-3}
Cd, screening (CSF 15)	2.01×10^{-3}	8.78×10^{-3}	1.08×10^{-2}

Note: Risk was calculated as the LADD multiplied by the cancer slope factor (CSF), with each group's survey-derived exposure duration averaged over a 70-year lifetime. The child and adult stages are successive life stages of one resident; the age-adjusted column is their sum. No validated oral CSF exists for Cd, so the Cd rows are screening estimates spanning the published range of inhalation-derived values and are not quantitative risk estimates. US EPA acceptable range: 1×10^{-6} to 1×10^{-4}.

For Cd, no validated oral cancer slope factor is available, and reported values ranging from 0.38 to 15 $(mg/kg\cdot day)^{-1}$ are derived from inhalation data [16,19]. Consequently, the estimated lifetime cancer risk was calculated across this range and should be interpreted cautiously. The resulting values ranged from 2.73×10^{-4} to 1.08×10^{-2}, which exceed the value of 1×10^{-4} throughout. Although the magnitude of this risk remains uncertain since the slope factors are not validated for oral exposure, the screening estimates consistently exceeded the upper risk threshold. Similar concerns regarding Cd have been reported in drinking-water studies from Anambra State, Nigeria and Pakistan [3].

The adult exposure stage contributed more to the combined lifetime cancer risk for both elements, largely as the assumed exposure duration was substantially longer than that for childhood. However, this does not imply higher biological susceptibility among adults. In contrast, the non-carcinogenic assessment identified higher exposure relative to body weight among children. Thus, the two assessments describe different aspects of potential risk under the modelled exposure conditions; neither represents directly observed health effects [28].

Household characteristics and drinking water source: A total of 147 participants were included in the study, comprising 100 adults and 47 children. Gender information was available for 99 adults, of whom 66 were female (66.7%) and 33 were male; one participant did not provide this information. The mean ages of adults and children were 48.9 and 9.4 years, respectively. Mean body weight and height were 58.6 kg (n = 88) and 157.5 cm (n = 90) for adults, compared with 24.8 kg and 126.4 cm for children (n = 47 for both measurements). The average daily drinking-water consumption was 2.19 L for adults and 1.10 L for children. Body weight was unavailable for 12 adults and height for 10; these participants were retained in the sample and the relevant means were calculated using the available observations. Four participants aged 15-17 years were classified as adults, which represents a limitation of the age-group definition. The demographic and physiological data used in the health risk assessment are given in Table-7.

Boiled water was the most frequently reported drinking water source (n = 52) followed by commercially packaged water in small containers (n = 47). Other sources included tap water (n = 16), rainwater (n = 11), purified water (n = 5), packaged water in large containers (n = 4) and groundwater (n = 4). Herbal tea was reported by one participant (Fig. 3). These responses describe the reported use of different water sources but do not establish their relative safety or the reasons for household preferences.

The link between each questionnaire and its corresponding household water sample allowed reported water sources to be compared with measured element concentrations. House-

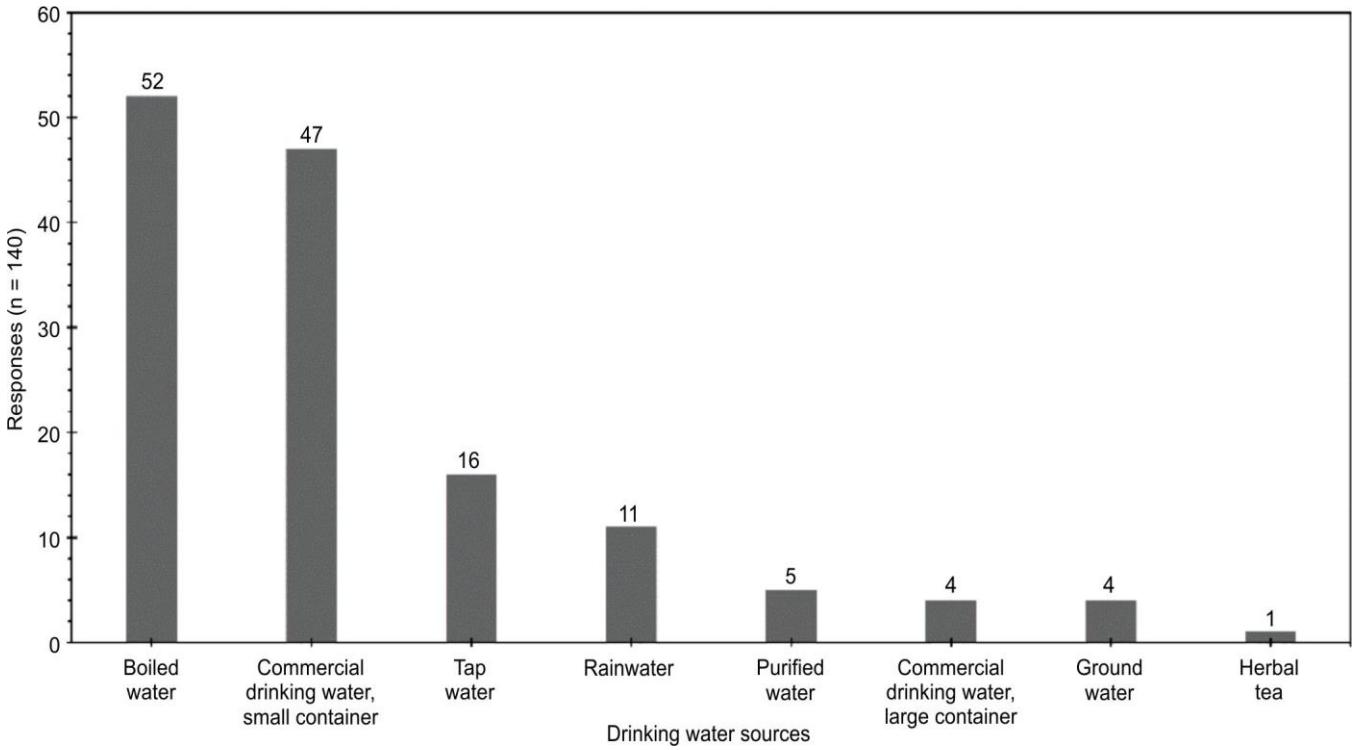


Fig. 3. Types of drinking water sources used by the study participants (n = 140)

TABLE-7
SOCIODEMOGRAPHIC PROFILE AND ANTHROPOMETRIC CHARACTERISTICS OF ADULT AND CHILD PARTICIPANTS

Characteristic	Adults	Children
Participants	100	47
Sex		
Male	33	28
Female	66	19
Sex not stated	1	0
Age (Year)		
Under 25	6	47
25-35	17	–
36-55	38	–
56 and over	39	–
Mean age (years)	48.9 (n = 100)	9.4 (n = 47)
Mean weight (kg)	58.6 (n = 88)	24.8 (n = 47)
Mean height (cm)	157.5 (n = 90)	126.4 (n = 47)
Water drinking (L/Day)	2.19	1.10

Note: Counts are of enrolled participants. Where a characteristic was not recorded for every participant, the denominator is given; one adult did not state sex, body weight was not recorded for 12 adults and height was not recorded for 10. Percentages for sex are calculated on the 99 adults who reported it.

holds reporting packaged or purified water, either alone or alongside other sources, were grouped together (n = 47), while those reporting only local supplies like boiled, tap, rain or groundwater, formed the comparison group (n = 53). K concentrations were lower in the packaged/purified-water group than in the local-supply group (1.09 *vs*. 1.52 mg/L; Holm-adjusted $p = 0.027$). Cu was also detected less frequently in the former group (42.6% *vs*. 69.8%; Holm-adjusted $p = 0.042$). These differences are consistent with variation in water treatment and composition. Neither the detection frequency nor the measured concentration of Pb or Cd was significantly associated with the reported water-source category (Table-8). The observed contamination therefore could not be attributed to a particular source category. The contamination from storage containers or plumbing fittings cannot be ruled out as these sources were not directly investigated.

Limitations: This study has several limitations. The cross-sectional design involved a single sampling round and therefore did not capture temporal or seasonal variations in water quality. The health risk assessment was based on the estimated exposure parameters and published toxicity values without biological monitoring or clinical evaluation. Only total

TABLE-8
ELEMENTAL CONCENTRATIONS AND DETECTION FREQUENCIES BY DRINKING WATER SOURCE

Element	Detected, packaged (n = 47)	Detected, local (n = 53)	*p*	Mean ± SD, packaged (mg/L)	Mean ± SD, local (mg/L)	*p*
Zn	34 (72.3%)	43 (81.1%)	0.346	0.0619 ± 0.0759	0.0571 ± 0.0729	0.416
Pb	3 (6.4%)	7 (13.2%)	0.328	0.0370 ± 0.0045	0.0340 ± 0.0121	0.645
Cd	32 (68.1%)	37 (69.8%)	1.000	0.0229 ± 0.0048	0.0220 ± 0.0045	0.318
Cu	20 (42.6%)	37 (69.8%)	0.008	0.0139 ± 0.0066	0.0138 ± 0.0065	1.000
K	42 (89.4%)	49 (92.5%)	0.731	1.0875 ± 0.7627	1.5213 ± 0.5720	0.005

element concentrations were measured and chemical speciation and bioavailability were not assessed. The assessment considered drinking water as the sole exposure pathway and did not account for other potential sources of exposure. Exposure duration was estimated using the mean age of each group and assumed lifelong residence in the study area while water consumption rates and body weights were self-reported. Furthermore, the study included only 100 households from one province, which limits the generalizability of the findings.

Conclusions

This study evaluated five elements in household drinking water in Kratie Province of Cambodia and assessed the associated health risks for children and adults. Zn and Cu concentrations remained below WHO guideline values whereas Cd exceeded the guideline by up to 7.5-fold in 69% of samples. Lead concentrations also exceeded the recommended limit in some samples. Potassium showed the highest concentration and was significantly lower in households using packaged or purified water. The hazard index exceeded unity for both children and adults with Cd as the predominant contributor. The estimated Cd-related cancer risk exceeded the screening threshold although this finding requires cautious interpretation because a validated oral cancer slope factor for Cd is unavailable. Children were identified as the priority group due to their higher estimated exposure on a body-weight basis. The sources of Pb and Cd remain unidentified and contamination during storage or distribution cannot be excluded. This study provides baseline data on drinking water quality and associated health risks in Kratie Province using population-specific exposure parameters.

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CONFLICT OF INTEREST

The authors declare that there is no conflicts of interest regarding the publication of this article.

DECLARATION OF AI-ASSISTED TECHNOLOGIES

During the preparation of this manuscript, the authors used an AI-assisted tool(s) to improve the language and no data, results or scientific conclusions were generated by AI. All analyses, interpretations and conclusions are the authors' own. The authors reviewed and edited the content and take full responsibility for the published work.

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