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Assessment of Arsenic Contamination and Human Health Risk in Water Resources with Mining Influence in Fiji

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ABSTRACT

Arsenic mobilisation from anthropogenic sources can have a significant impact on water resources and pose a serious concern to human health. Therefore, the objectives of this investigation were to determine the levels of arsenic contamination in water resources and evaluate the associated human health risks to the local residents from a mining environment in Fiji. Concentrations of arsenic were determined at fifteen sampling stations located at Dakavono Creek, Lololevu Creek and Nasivi River in the Vatukoula Goldmine Region over a period of time. Arsenic levels in the water resources ranged from 0.87-43.03 µg l^{-1}, whereby 20% of the samples exceeded the drinking water guideline set by the World Health Organisation (10 µg l^{-1}). Concentrations of arsenic did not show significant temporal variations (ANOVA, $p > 0.05$) however, significant variation (ANOVA, $p < 0.05$) were observed between the sampling stations. The data were further used to assess the health risks of the water for drinking and recreational use. The use of the water for drinking (ingestion pathway) and recreational purposes (dermal pathway) showed high non-carcinogenic (hazard index > 1) and carcinogenic (cancer risk > 10^{-4}) health risks with respect to arsenic exposure at several sampling stations, particularly in children. Overall, the carcinogenic risk from arsenic exposure through the ingestion pathway was much greater than that of dermal pathway for the inhabitants in the study area. These findings could assist with the formulation of necessary policies in order to ensure the long-term management of water resources and mitigate health risks for inhabitants in mining locations of Fiji.

Key words : *Arsenic, Water contamination, Health risk assessment, Non-carcinogenic risk, Carcinogenic risk*

Introduction

Water quality degradation has become a global issue due to increasing anthropogenic activities (Ahmed *et al*., 2021). Contamination of the aquatic environment, particularly with toxic metals and metalloids, has contributed to increasing exposure and adverse effects on human health around the world (Stachnik *et al*., 2020). Even at low concentrations, metalloids such as arsenic (As) are toxic to humans and cause a variety of health problems upon its exposure in the environment. Arsenic exposure can occur through different routes, which include the oral and dermal exposure to contaminated water (Obiri *et al*., 2016). Therefore, the risk of chronic poisoning induced by As contaminated drinking water has continued to increase public concern (Ko *et al*., 2008; Chen *et al*., 2015; Senila *et al*., 2017). Classified as a Group 1 carcinogen by the International Agency for Research on Cancer, long-term exposure to As from drinking water can cause skin and bladder cancer, cardiovascular diseases and diabetes mellitus (Senila *et al*., 2017; Ahmed *et al*., 2021), as well as increased mortality from multiple internal organ cancers (Obiri *et al*., 2016).

Since Asoccurs widely in the earth's surface, anthropogenic activities have the potential to release significant levels of As into the aquatic environment from inadequate wastes disposal procedures (Senila *et al*., 2017). For example, manufacturing and mining activities has led to the presence of elevated levels of As in aqueous environments (Alonso *et al*., 2020; Tupiti *et al*., 2021). Present as a natural constituent in gold ores, As can be mobilised during the gold mining processes when minerals containing As are dissolved and end up in mine tailings (Ko *et al*., 2008). Surface water systems can be impacted through seepage from tailings or when itseffluents are discharged into the environment (Mohapatra and Kirpalani, 2017). Consequently, As concentrations in surface water may rise (Stachnik *et al*., 2020) and may affect the health of people who may be dependent on the water resources for drinking and recreational use (Koomson and Asiam, 2013).

With increasing economic and infrastructural development in the past few decades, the small developing island states in the South Pacific have been challenged by the toxic metal contamination of its environment (Chand *et al*., 2010; Chand and Prasad, 2013;Diarra and Prasad, 2021). In spite of this, limited investigationson the environmental impact of the mining activities in this region have been carried out to date (Tupiti *et al*., 2021). Furthermore, the presence of several mining operations in the region and previously reported cases of environmental contamination warrant regular assessment of any potential health risk to the inhabitants of mining regions. For example, a study reported elevated level of As in a river water sample from the Vatukoula Goldmine Region (VGR), Fiji, an area where adverse health effects on people (skin lesions) using the water resource for recreational activities were also noted (Singh and Mosley, 2003). Subsequently, the present work reports on As levels and human health risks associated with occupational exposure to As in surface waters of VGR. It is anticipated that the findings of the study will contribute to the increasing research on risk assessment of As exposure from contaminated environments and assist policy makers indetermining the most effective approaches to address these concerns in developing countries.

Materials and Methods

Study Area

The Vatukoulagoldmine is situated approximately 200 km northwest by road from the capital Suva on the northern coast of Viti Levu, the main island of Fiji. The mine, which has been in operation for eight decades, is located within the Nasivi Catchment (Ackley, 2008). Sudge waste material from the mining process has been deposited in its five tailings dam (Kumar *et al*., 2021). Adjacent to the mine and tailings dams are the farmland and residential areas which share the freshwater resources in the VGR for subsistence use, sustenance and agriculture, as demonstrated by the anecdotal interviews and surveys. For the purpose of this study, Lololevu Creek, Nasivi River and Dakovono Creek were the water resources chosen because these are the locations where VGR residents may come into contact with contaminated surface waters for recreational purposes or drinking on a regular basis (Ackley, 2008). Furthermore, the effluents from the one of the mine's tailings dam (Toko) is decanted into the Dakovono Creek (Kumar *et al*., 2021), which merges with the Nasivi River. Several households inthe VGR receive untreated water supplied from the Nasivi River and the residents also commonly use river water for washing, swimming and fishing (Ackley, 2008).

Sampling Procedure

Water samples were collected from fifteen selected stations (Fig. 1) over three sampling trips. All sampling bottles and glass ware were washed with dilute nitric acid and then with distilled water before use. High-density polyethylene bottles were rinsed with the river/creek water several times before water sample collection. In the laboratory, samples were filtered using Millipore nitrocellulose filters (0.45 μm), acidified withnitric acid (pH < 2) and stored at 4 ^{o}C until the laboratory analysis was performed. Physicochemical parameters such as pH, oxidation-reduction potential, conductivity, turbidity, dissolved oxygen and total dissolved solids at each sampling station were also taken using a calibrated hand held multi-parameter digital meter (Model 85, YSI Inc., USA).

Analytical Method

All solutions were prepared in ultrapure water (Millipore system). Analytical grade reagents were used without further purification. A 1 g l^{-1} As(III) calibration standard (C.P.A. Ltd) was used to prepare working and calibration standards daily before use. All analytical measurements were performed with an atomic absorption spectrometer (AAnalyst 400, Perkin Elmer, USA). An arsine generator system (MHS15, Perkin Elmer, USA) coupled to the spectrometer was manually operated. The recommended operating conditions as per the manufacturer's manual were used for As analysis. Peak height was used for signal measurement and the As calibration curve was linear (R>0.99) in the 0-50 µg l^{-1} range.

Quality Control

A certified reference material, spiked solution, procedural blank and use of replicates were used to maintain quality control in Asanalysis. Spike recoveries were found to be between 96.2 ± 5.3% and relative standard deviation for replicate analyses was within 5% (n = 3). The percent recovery (%) of As in Trace Elements in Natural Water (SRM No. 1640, NIST, USA) using the average of five replicates was 96.2 ± 6.2%. The limit of detection (LOD) for As, calculated as the metal concentration that corresponded to three times the standard deviation of seven independent measurements of the procedural blank, was 0.5 µg l^{-1}.

Statistical Analyses

The ArcGIS Pro application (Esri) was utilised for map plotting of spatial distribution of As concentration in the study area. A one-way analysis of variance (ANOVA) was used to determine any statistically significant ($\alpha = 0.05$) temporal and spatial differences of As concentrations.

Human Health Risk Assessment

Human health risk assessment is the process of evaluating whether an environmental contaminant is likely to cause adverse effects to people as result of exposure (Custodio *et al*., 2020). There are different ways through which As can enter the human body (e.g. via ingestion, dermal and inhalation), however, ingestion and dermal absorption are the main exposure pathways of As in water (Varol, 2021). Therefore, the human health risks of As in water resources of the VGR were evaluated using non-carcinogenic and carcinogenic risks through these two pathways, as well as for adults and children as separate groups. The average daily dose (ADD) was determined to estimate human exposure dose to As through the ingestion and dermal absorption routes using Equations(1) and (2), respec-

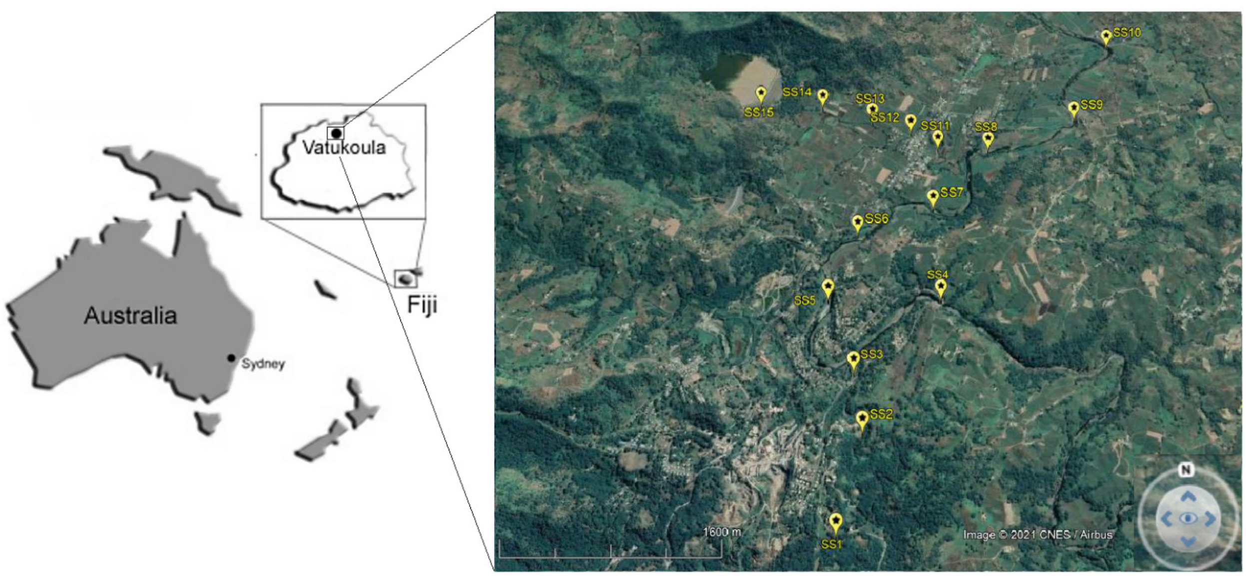

Fig. 1. Depiction of the study area in Fiji. The water sampling stations at Lololevu Creek (SS1-SS3), Nasivi River (SS4-SS10) and Dakavono Creek (SS11-SS15) are indicated with yellow markings in the VGR.

tively, which were adapted from USEPA (2004) and used by several other similar studies (Senila *et al*., 2017; Alidadi *et al*., 2019; Custodio *et al*., 2020):

$$ADD_{ing} = \frac{C \times IR \times EF \times ED}{BW \times AT \times 365\ days/yr} \quad .. (1)$$

$$ADD_{der} = \frac{C \times K_p \times SA \times ET \times EF \times ED \times CF}{BW \times AT \times 365\ days/yr} \quad .. (2)$$

where $ADD_{ing}$and ADD_{der}arethe average daily dose of As through the ingestion and dermal absorptionpathways, respectively (μg kg^{-1} day^{-1}), C is the measured concentration of As in water (μg l^{-1}), IR is the ingestion rate per unit time (2.0 ad 1.8 l day^{-1} for adults and children, respectively), EF is exposure frequency (350 days $year^{-1}$), ED is the exposure duration (30 and 6 years for adults and children, respectively), BW is body weight (70 and 15 kg for adults and children, respectively), AT is the average time of human exposure (70 years), K_p is the dermal permeability coefficient for As (0.001 cm h^{-1}), SA is the exposed skin area (18,000 and 6,600 $cm^2$for adults and children, respectively), ET is the exposure time 0.58 and 1.0 h day^{-1} for adults and children, respectively) and CF is the unit conversion factor (0.001 l cm^{-3}). For non-carcinogenic effects, AT = ED (Senila *et al*., 2017).

Non-carcinogenic health risk refers to other adverse health effects due to exposure to a contaminant, except cancer (Obiri *et al*., 2016). In present study, the non-cancerrisk hazard quotient (HQ) were evaluatedusing Equation(3)(Senila *et al*., 2017; Alidadi *et al*., 2019; Custodio *et al*., 2020).

$$HQ_{ing/der} = \frac{ADD_{ing/der}}{RfD} \quad .. (3)$$

The $RfD_{ing}$and RfD_{der}values of 0.300 and 0.285 μg kg^{-1} day^{-1}, respectively, were used for As (Senila *et al*., 2017). Adverse health effects are unlikely if HQ ≤ 1 (Custodio *et al.*, 2020) and the exposed population is assumed to be safe (Alidadi *et al*., 2019). However, HQ > 1 indicates that it may have potential non-carcinogenic but probable adverse health effects (Custodio *et al*., 2020). The total potential non-carcinogenic riskfrom different exposure routes, expressing as a hazard index (HI), was assessed using Equation (4)(Senila *et al*., 2017; Alidadi *et al*., 2019; Custodio *et al*., 2020).

$$HI = \sum_{i=1}^{n} HQ_s = HQ_{ing} + HQ_{der} \quad .. (4)$$

Non-carcinogenic adverse effect due to a particular route of exposure or chemical is considered insignificant if HI < 1, while aHI > 1 indicates a potential risk for humans (Custodio *et al*., 2020).

The potential human carcinogenic or cancer risks (CR) expresses the probability that a person would develop cancer over a lifetimefrom chemical exposure (Obiri *et al*., 2016). The CR of As on human health and total cancer risk (TCR) from both exposure pathways are given by Equations (5) and (6), respectively (Senila *et al*., 2017; Custodio *et al*., 2020; Varol, 2021):

$$CR_{ing/der} = \frac{ADD_{ing/der}}{CSFing/der} \quad .. (5)$$

$$TCR = CR_{ing} + CR_{der} \quad .. (6)$$

TheCSF value of 1.5 mg^{-1} kg^{-1} day^{-1} was used for As (Custodio *et al*., 2020). A CR value above 1.0×10^{-4} is considered unacceptable and poses health hazards (Alidadi *et al*., 2019). CR values between 1.0×10^{-6} and 1.0×10^{-4} are considered an acceptable range, while CR values below 1.0×10^{-6} is deemed insignificant for health effects (Alidadi *et al*., 2019).

Results and Discussion

Physico-chemical characteristics of sampling stations

The pH at the sampling stations was slightly alkaline (range 7.13-8.44) but within the WHO drinking water guideline range of pH 6.5-8.5 (WHO, 2008). The highest pH values were observed at the Dakavono Creek sampling stations, particularly at SS12-SS14, which were consistent with the study reported previously (Kumar *et al*., 2021). These sites are closest and downstream to the Toko Tailings Dam effluent discharge point into the Dakavono Creek. Similarly, a study of Sabeto River in Fiji, which is influenced by a separate gold mining activity, also showed pH upto 7.9 (Tupiti *et al*., 2018). Discharged tailings dam effluent can have pH around 8.2 resulting from the treatment of the original ore with calcium hydroxide, used in the cyanide-based gold extraction process by the Vatukoula Goldmine (Ko *et al*., 2008). The sampling stations had high turbidity with an average of 11.37 ± 11.39 NTU. The turbidity levels for most locations exceeded WHO guideline of 5 NTU (Obiri *et al*., 2016). Average TDS in the water samples were from 0.84 ± 0.55 g l^{-1}. Except for SS11-SS14, TDS were within WHO guideline value of 1 g l^{-1}(Obiri *et al*., 2016).

Drinking water may pose significant health challenges to consumers with pre-existing medical conditions if the TDS value exceeds 1 g l^{-1}(Obiri *et al.* 2016). The tailings dam discharge could be the contributing factor for the particularly high turbidity of Dakavono Creek water from SS11 to SS14, since mining activities have been shown to contribute to high turbidity and TDS of surrounding water resources (Acheampong *et al.*, 2013; Hadzi *et al.*, 2018). Dissolved oxygen, electrical conductivity and salinity had average values of 8.81 ± 1.12 mg l^1, 1.20 ± 0.85 ms cm^{-1} and 0.6 ± 0.5 ppt, respectively. Dissolved electrolytes, such as Fe^{3+}, SO_4^{2-}, PO_4^{3-} and NO_3^- in the tailings dam wastewater could be contributing to the high EC values of the water samples (Acheampong *et al.*, 2013). The ORP values of the sampling stations were observed to below and highly variable (190 ± 21 mV), which is also an indicator of possible pollution of the water resources.

As concentrations in the VGR water resources

The minimum, maximum and average concentrations of As at the different sampling locations and stations over the sampling period are presented in Table 1. Concentrations of As did not show significant temporal variations (ANOVA, $p> 0.05$) in the study area. This is consistent with the study of Kumar *et al*. (2021), who did not find any temporal variation of other heavy metals concentrations analysed in the water resources of the region. However, as shown in Fig. 2, there were significant variation (ANOVA, $p< 0.05$) of As concentrations between the sampling stations. The As concentration ranged from 0.87 to 43.83 µg l^{-1} and 20% of the samples exceeded the WHO drinking water guideline of 10 µg l^{-1}(WHO, 2008). The maximum level of the As was observed at SS14, which was four times higher than the WHOguideline. This site is immediate downstream of the Toko Tailings Dam wastewater discharge point at Dakavono Creek, which is probably the point source of As into the creek. The next highest levels of As were detected further downstream of Dakavono Creek and it was observed that the concentration of As decreased going further downstream, possibly due to dilution effects. However, sampling stations SS12 and SS13 stillhad. As levels above the drinking water guideline.

Previous studies have shown that mine tailings originating from gold mining activity in Fiji can be a significant source of Asdue to the presence of arsenopyritein the source rocks of the region (Ko *et al*., 2008). In a study of contaminated tailings from VGR Fiji, As concentration as high as 683 mg kg^1 was found, with 0.1 mg water-soluble As present per kg of the mine tailings (Ko *et al*., 2008). In another a study, upto 250 mg kg^1. As were found to be present in historical mine tailings of the Wainivesi Gold Mine environment in Fiji, with significant potential of solubilisation and transportation of As through mine runoffs into the aquatic environment (Taga, 2009). This was further confirmed when dispersed contaminated and upstream sediments analysed from VGR water resources showed presence of 10-690 mg kg ^{1}As (Matanitobua *et al*., 2007).

Table 1. As concentration in the VGR water resources of Fiji.

Sampling Location	Sampling Station	As concentration (µg l^{-1})	
		Min-Max	Average (SD)
Lololevu Creek	SS1	5.02 - 9.56	7.37 (2.27)
	SS2	1.85 - 4.02	3.02 (1.09)
	SS3	0.86 - 3.36	2.39 (1.34)
Nasivi River	SS4	0.82 – 0.91	0.87 (0.05)
	SS5	0.98 – 2.02	1.61 (0.56)
	SS6	1.09 - 1.82	1.36 (0.40)
	SS7	0.86 - 1.04	0.95 (0.09)
	SS8	0.85 – 1.23	1.05 (0.19)
	SS9	0.80 – 1.17	1.01 (0.19)
	SS10	0.92 - 1.94	1.56 (0.56)
Dakavono Creek	SS11	2.38 - 6.51	4.47 (2.07)
	SS12	8.50 – 18.6	12.50 (5.37)
	SS13	15.2 – 32.1	24.70 (8.64)
	SS14	36.1 -52.09	43.03 (8.21)
	SS15	3.65 – 5.23	4.36 (0.80)

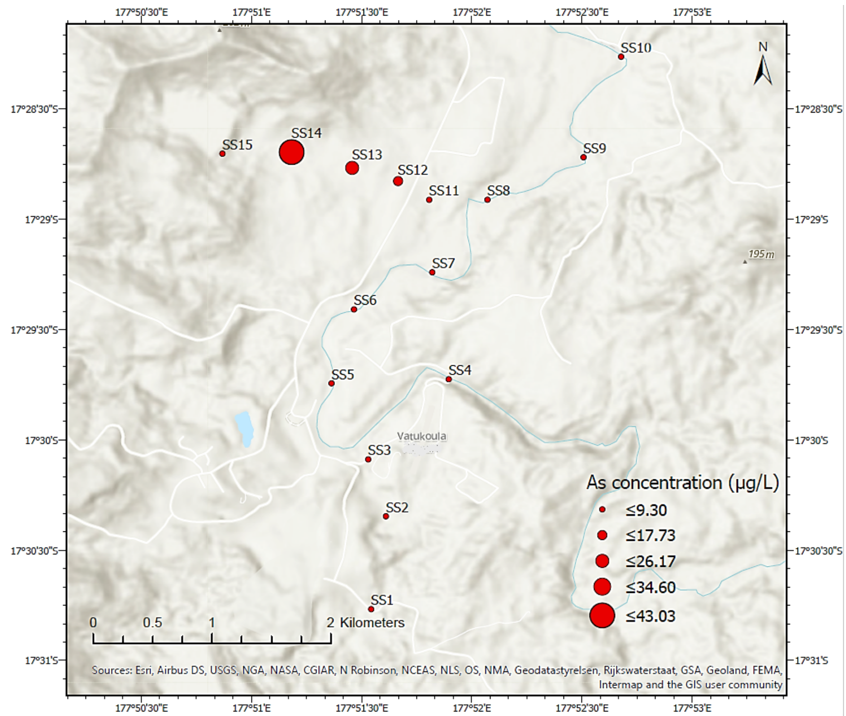

Fig. 2. Distribution of As concentrations in the VGR water resources.

Therefore, it is highly possible that the As present in the Tokodam mine tailings solubilisesin to the wastewater before it get discharged into Dakavono Creek. The concentrations of As obtained in the present study was generally comparable to the surface water systems impacted by other gold mining activities in Fiji and differentcountriesaround the world (Table 2). However, when compared to awater resources from non-polluted environments in Fiji (Gangaiya *et al*., 1988; Singh and Mosley, 2003), the As levels at most of the sampling stations are higher and in some cases, several magnitudes higher than the background levels (<1 µg l^{-1}). This confirms that the aquatic environment in VGR are impacted by mining activities and contributing to elevated As levels in the immediate water resources.

Health risk assessment of As in water resources

The intake of As through drinking water ingestion contributed most to overall daily dose between both target groups (Table 3). The ADD values through the ingestion pathway were ~211 and 273 orders of magnitude higher than that of the dermal absorption pathway for adults and children, respectively. Therefore, human exposure to As through water consumption would be considered as the important pathway for As exposure in the study area. This result is in agreement with recent studies that reported the most important exposure pathway for As and other heavy metals in water occurs through the ingestion route (Alidadi *et al*., 2019; Kumar *et al*., 2021). Furthermore, the mean value of ADD_{total} indicated that children were ~4 times more exposed to drinking water than adults, which is also consistent with other studies showing toxic metal intake doses of children being significantly higher than adults (Alidadi *et al*., 2019; Varol, 2021).

As summarised in Table 4, the ingestion HQ and HI values exceeded the threshold of HQ and HI for adults as well as children for several stations. Overall, HQ_{ing} and HI values exceeded the acceptable limit (>1) at stations SS12-SS14 for both age populations, implying that the surface water from the study area presented a potential health risk. Furthermore, at four other sites (SS1-2, SS11 and SS15), the HQ_{ing} and HI values for children were greater than the safe range. The results indicate that HQ_{der} from water for As did not exceed the HQ guide value of 1 for all the sampling stations therefore, the non-carcinogenic risk from As via dermal pathway was in the safe range for children and adult population. Overall, the HI values for children were 2.5 times greater

Table 2. Comparison of As concentrations in surface water systems influenced by gold mines in Fiji and other parts of the world.

Country	Gold mine location	Surface water system	As (μg l^{-1})	Reference
Fiji	Vatukoula	Nasivi River; Dakavono and Lololevu Creeks	0.87 - 43.03	This study
	Tuvatu	Qalibua and Sabeto Rivers	26.9 - 67.0	Tupiti *et al*. (2018)
Solomon Is.	Guadalcanal Island	Metapona River	21.7 - 72.7	Tupiti *et al*. (2018)
		Charivunga/Chovohio, Tinahulu, Kwara and Metapona Rivers	1 - 117	Albert *et al*. (2017)
Papua New Guinea	Porgera, Enga Province	Kakai, Anjolek, Anjolek-Kaiya and Pongema Rivers; Wanbel and Yakatabari Creeks	<1.0 - 19.1	Hoagland *et al*. (2021)
New Zealand	Otago	Streams, surface seeps and springs	1-10	Craw and Pacheco (2002)
Ghana	Ashanti, Western and Eastern	Nyam, Subri, Bonsa and Birim Rivers	2 - 3	Hadzi *et al*. (2018)
Poland	Zloty Stok	Truj¹ca River	5.24 - 200	Stachnik *et al*. (2020)
Colombia	SanturbanParamo	Suratá River	0.6 - 52.3	Alonso *et al*. (2020)
Ecuador	Nambija, Portovelo-Zaruma	Q. Calixto, Calera, and Siete	1.7–470	Carling *et al*. (2013)
Mongolia	Zaamar, Ulaanbaatar	Tuul and Selenga Rivers; Lake Baikal	7.40 – 12.93	Thorslund *et al*. (2012)
Brazil State	Paracatu, Minas Gerais	RibeirãoEntre-Ribeiros, Córrego Rico and Rio Escuro watersheds	<0.5 - 40.10	Bidone *et al*. (2016)

Table 3. Estimated average daily dose (μg kg^{-1} day^{-1}) of As from the VGR water resources through ingestion and dermal contact by adults and children, respectively.

Sampling Station	ADD_{ing}		ADD_{der}	
	Adult	Child	Adult	Child
SS1	2.22×10^{-1}	8.48×10^{-1}	1.05×10^{-3}	3.11×10^{-3}
SS2	9.10×10^{-2}	3.48×10^{-1}	4.32×10^{-4}	1.27×10^{-3}
SS3	7.20×10^{-2}	2.75×10^{-1}	3.42×10^{-4}	1.01×10^{-3}
SS4	2.62×10^{-2}	1.00×10^{-1}	1.24×10^{-4}	3.67×10^{-4}
SS5	4.85×10^{-2}	1.85×10^{-1}	2.30×10^{-4}	6.79×10^{-4}
SS6	4.10×10^{-2}	1.56×10^{-1}	1.94×10^{-4}	5.74×10^{-4}
SS7	2.86×10^{-2}	1.09×10^{-1}	1.36×10^{-4}	4.01×10^{-4}
SS8	3.16×10^{-2}	1.21×10^{-1}	1.50×10^{-4}	4.43×10^{-4}
SS9	3.04×10^{-2}	1.16×10^{-1}	1.44×10^{-4}	4.26×10^{-4}
SS10	4.70×10^{-2}	1.80×10^{-1}	2.23×10^{-4}	6.58×10^{-4}
SS11	1.35×10^{-1}	5.14×10^{-1}	6.39×10^{-4}	1.89×10^{-3}
SS12	3.77×10^{-1}	1.44	1.79×10^{-3}	5.27×10^{-3}
SS13	7.44×10^{-1}	2.84	3.53×10^{-3}	1.04×10^{-2}
SS14	1.30	4.95	6.15×10^{-3}	1.82×10^{-2}
SS15	1.31×10^{-1}	5.02×10^{-1}	6.24×10^{-4}	1.84×10^{-3}

than that of adults, suggesting that children were more prone to non-carcinogenic risk from As. Alidadi *et al*. (2019) and Varol (2021) also noted that the HI values for children were several magnitudes higher than adults in similar types of studies.

Considering the ingestion exposure pathway, the estimated carcinogenic risk for Asfor the adult group were between 1×10^{-5} and 1×10^{-4} for most stations, indicating tolerable cancer risks (Table 5). However, there is potential carcinogenic risk from sites SS1 and SS12-14 due to CR values greater than 1×10^{-4}. On the contrary, the children were at much higher risk, both with respect to chance (1.04×10^{-4} to 3.30×10^{-3}) and number of sites as compared to adults. As shown in Table 5, the CRvalues of As exceeded the acceptable USEPA value of 1×10^{-4}at several sampling stations (SS1-SS3, SS5-SS6, SS10-SS14) for children, indicating unacceptable carcinogenic risks. These results indicate that the carcinogenic risk of As from ingestion of water is higher in children compared to adults, which has been noted by other similar studies as well(Alidadi *et al*., 2019; Custodio *et al*., 2020). The CR_{der} values were below the USEPA recommended safety level, suggesting acceptable carcinogenic risk for adults and children in VGR through dermal contact. Greater carcinogenic risk of Asfrom water through ingestion than the dermal pathway has been noted by other authors as well (Senila *et al*., 2017; Alidadi *et al*., 2019).

In terms of the total cancer risk from both expo-

Table 4. Non-carcinogenic risk from As in the VGR water resources through ingestion and dermal contact by adults and children, respectively.

Sampling Station	Non-carcinogenic Risks					
	HQ_{ing}		HQ_{der}		$HI = \Sigma HQs$	
	Adult	Child	Adult	Child	Adult	Child
SS1	7.40×10^{-1}	2.83	3.70×10^{-3}	1.09×10^{-3}	7.44×10^{-1}	2.83
SS2	3.03×10^{-1}	1.16	1.52×10^{-3}	4.47×10^{-3}	3.05×10^{-1}	1.16
SS3	2.40×10^{-1}	9.17×10^{-1}	1.2×10^{-3}	3.54×10^{-3}	2.41×10^{-1}	9.17×10^{-1}
SS4	8.74×10^{-2}	3.34×10^{-1}	4.37×10^{-4}	1.29×10^{-3}	8.78×10^{-2}	3.34×10^{-1}
SS5	1.62×10^{-1}	6.18×10^{-1}	8.08×10^{-4}	2.38×10^{-3}	1.63×10^{-1}	6.18×10^{-1}
SS6	1.37×10^{-1}	5.22×10^{-1}	6.82×10^{-4}	2.01×10^{-3}	1.37×10^{-1}	5.22×10^{-1}
SS7	9.54×10^{-2}	3.64×10^{-1}	4.77×10^{-4}	1.41×10^{-3}	9.59×10^{-2}	3.64×10^{-1}
SS8	1.05×10^{-1}	4.03×10^{-1}	5.27×10^{-4}	1.55×10^{-3}	1.06×10^{-1}	4.03×10^{-1}
SS9	1.01×10^{-1}	3.87×10^{-1}	5.07×10^{-4}	1.50×10^{-3}	1.02×10^{-1}	3.87×10^{-1}
SS10	1.57×10^{-1}	5.98×10^{-1}	7.83×10^{-4}	2.31×10^{-3}	1.57×10^{-1}	5.98×10^{-1}
SS11	4.49×10^{-1}	1.71	2.24×10^{-3}	6.62×10^{-3}	4.51×10^{-1}	1.71
SS12	1.26	4.79	6.27×10^{-3}	1.85×10^{-2}	1.26	4.79
SS13	2.48	9.47	1.24×10^{-2}	3.66×10^{-2}	2.49	9.47
SS14	4.32	16.5	2.16×10^{-2}	6.37×10^{-2}	4.34	1.65
SS15	4.38×10^{-1}	1.67	2.19×10^{-2}	6.45×10^{-3}	4.40×10^{-1}	1.67

Table 5. Carcinogenic risk from As in the VGR water resources through ingestion and dermal contact by adults and children, respectively.

Sampling Station	Carcinogenic Risks			
	CR_{ing}		CR_{der}	
	Adult	Child	Adult	Child
SS1	1.48×10^{-4}	5.65×10^{-4}	7.03×10^{-7}	2.07×10^{-7}
SS2	6.07×10^{-5}	2.32×10^{-4}	2.88×10^{-7}	8.49×10^{-7}
SS3	4.80×10^{-5}	1.83×10^{-4}	2.28×10^{-7}	6.72×10^{-7}
SS4	1.75×10^{-5}	6.67×10^{-5}	8.29×10^{-8}	2.45×10^{-7}
SS5	3.23×10^{-5}	1.24×10^{-4}	1.54×10^{-7}	4.53×10^{-7}
SS6	2.73×10^{-5}	1.04×10^{-4}	1.30×10^{-7}	3.83×10^{-7}
SS7	1.91×10^{-5}	7.29×10^{-5}	9.06×10^{-8}	2.67×10^{-7}
SS8	2.11×10^{-5}	8.05×10^{-5}	1.00×10^{-7}	2.95×10^{-7}
SS9	2.03×10^{-5}	7.75×10^{-5}	9.63×10^{-8}	2.84×10^{-7}
SS10	3.13×10^{-5}	1.20×10^{-4}	1.49×10^{-7}	4.39×10^{-7}
SS11	8.98×10^{-5}	3.43×10^{-4}	4.26×10^{-7}	1.26×10^{-6}
SS12	2.51×10^{-4}	9.59×10^{-4}	1.19×10^{-6}	3.52×10^{-6}
SS13	4.96×10^{-4}	1.89×10^{-3}	2.35×10^{-6}	6.95×10^{-6}
SS14	8.65×10^{-4}	3.30×10^{-3}	4.10×10^{-6}	1.21×10^{-5}
SS15	8.76×10^{-5}	3.34×10^{-4}	4.16×10^{-7}	1.23×10^{-6}

sure pathways, the average TCR value for adults and children were 1.48×10^{-4} and 5.66×10^{-4}, respectively, confirming a potential cancer risk for the inhabitants of VGR via ingestion and dermal pathways. The estimated TCR was higher for children compared to adults (Fig. 3), suggesting that children were more susceptible to carcinogenic risk from As. Overall, the results show that children are more vulnerable population to health risks due to the fact that they consume more water per unit of body weight (Custodio *et al*., 2020) and their higher skin adherence compared to adults (Alidadi *et al*., 2019). These findings indicate that exposure to As from drinking and dermal contact of the VGR water resources could endanger the health of the exposed population. Therefore, it is suggested that proper corrective activities must be adopted to protect the health of the residents in the study area.

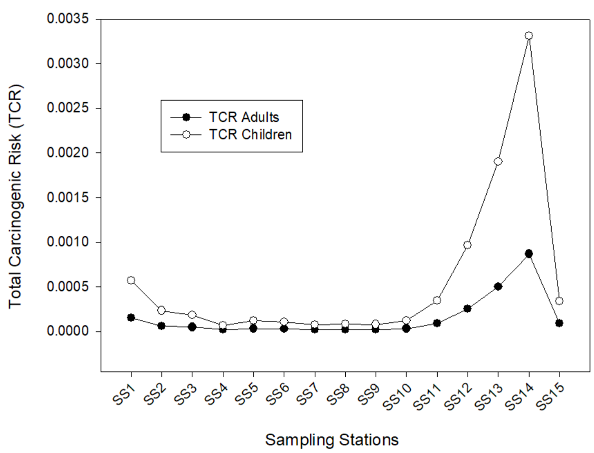

Fig. 3. Estimated total carcinogenic risk from As in the VGR water resources through ingestion and dermal contact by adults and children, respectively.

Conclusion

In this study, the spatial distribution of As in the water resources as well as health risk assessment based on daily intake and exposure through ingestion and dermal absorption pathways was evaluated in the Vatukoula gold mining region in Fiji. Concentration of As were found to exceed the drinking water guidelines at several sampling stations, indicating possible health risk for the local residents. Carcinogenic risk of As through ingestion exceeded the USEPA tolerable risk for several sites, revealing that the inhabitants in the study area are at risk of developing cancer and other non-cancer diseases over their lifetime due to exposure to As from the water resources. Children had a much greater value of non-carcinogenic and carcinogenic risk than adults from both ingestion and dermal pathways of As exposure from the contaminated water resources. Since most of the probability variables applied in this study were derived from the USEPA guideline, the approach used to evaluate the risks to human health has some possibility of uncertainties in the risk estimation. These assumptions could lead to over or underestimates of the potential health risk faced by the VGM inhabitants in the study area, therefore, further investigations are required to corroborate the evaluated risks with epidemiological data. Notwithstanding these limitations, this type of risk estimates provide ways to screen those contaminants that are of public health concern in order to prioritise research and policy interventions.

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Conflict of Interest

There is no potential conflict of interest.

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