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Illegal mining impacts on freshwater Potamonautid crab in a subtropical Austral highland biosphere reserve

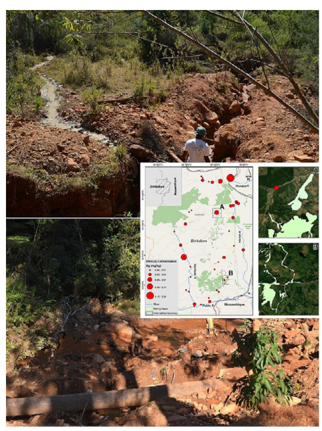
Tatenda Dalu [a,b,*], Timothy Dube [c], Farai Dondofema [d], Ross N. Cuthbert [e]

[a] Aquatic Systems Research Group, School of Biology and Environmental Sciences, University of Mpumalanga, Nelspruit 1200, South Africa
[b] Stellenbosch Institute for Advanced Study, Wallenberg Research Centre at Stellenbosch University, Stellenbosch 7600, South Africa
[c] Institute of Water Studies, Department of Earth Sciences, University of the Western Cape, Bellville 7535, South Africa
[d] Department of Geography and Environmental Sciences, University of Venda, Thohoyandou 0950, South Africa
[e] Institute for Global Food Security, School of Biological Sciences, Queen's University Belfast, Belfast BT9 5DL, United Kingdom

HIGHLIGHTS

- Mercury (Hg) concentrations being detected in 35 sites (71.5 %).
- Two crab species (i.e., *Potamonautes mutareensis*, *P. unispinus*) were found.
- Observed negative and significant effects for K, Fe, Cu and B on Potamonautid crab abundances.
- Working together, it is possible to promote sustainable mining practices to enforce regulations.

GRAPHICAL ABSTRACT



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ABSTRACT

The contamination of surface water by heavy metals, especially mercury, has become a global issue. This problem is particularly exacerbated in rivers and reservoirs situated in developing nations. Therefore, the objective of this study was to evaluate the potential contamination effects of illegal gold mining activities on freshwater Potamonautid crabs and to quantify the mercury levels in 49 river sites under three land use classes: communal areas, national parks and timber plantations. We used a combination of field sampling, multivariate analysis and geospatial tools to quantify mercury concentrations in relation to crab abundances. Illegal mining was prevalent throughout the three land use classes, with mercury (Hg) being detected in 35 sites (71.5 %). The mean range of Hg concentrations detected across the three–land uses was: communal areas 0–0.1 mg kg^{-1}, national parks 0–0.3 mg kg^{-1} and timber plantations 0–0.06 mg kg^{-1}. Mean Hg geo–accumulation index values showed *strong to extreme contamination* in the national park, with *strong contamination* observed for communal areas and timber plantations; furthermore, the enrichment factor for Hg concentrations in the communal and national park areas showed *extremely high enrichment.* Two crab species (i.e., *Potamonautes mutareensis*, *Potamonautes unispinus*) were found in the Chimanimani area, with *P. mutareensis* being the dominant taxon in the region across all the three land use areas. The national parks had higher total crab abundances than communal and timber plantation areas. We observed negative and significant K, Fe, Cu and B effects on total Potamonautid crab abundances, but surprisingly not for other metals such as Hg which might reflect their widespread pollution. Thus, illegal mining was observed to impact the river system, having a serious impact on the crab

* Corresponding author at: Aquatic Systems Research Group, School of Biology and Environmental Sciences, University of Mpumalanga, Nelspruit 1200, South Africa.
E-mail address: dalutatenda@yahoo.co.uk (T. Dalu).

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abundance and habitat quality. Overall, the findings of this study underscores the need to address the issue of illegal mining within the developing world as well as to establish concerted effort from all stakeholders (e.g., government, mining companies, local communities, and civil society groups) to help protect the less charismatic and understudied taxa. In addition, addressing illegal mining and protecting understudied taxa aligns with the SDGs (e.g. SDG 14/15-life below water/life on land) and contributes to global efforts to safeguard biodiversity and promote sustainable development.

1. Introduction

Natural metal pollution frequently occurs due to weathering; however, anthropogenic activities have increasingly resulted in unnatural levels of metals becoming an environmental issue (Nhiwatiwa et al., 2017; Dalu et al., 2018; Kortei et al., 2020). These anthropogenic activities, particularly mining, have caused the discharge or leaching of heavy metals, such as mercury, into the natural environment (Viana et al., 2021). Illegal mining results from unauthorised activities, such as those without a permit (Banchirigah, 2006). Increasing usage of heavy metals in illegal mining activities over recent years has caused severe environmental pollution (e.g., leading to species loss and habitat degradation) and health concerns (e.g., mercury toxicity leading to deaths) (Viana et al., 2021). Notably, illegal artisanal miners use mercury to remove gold from the host ore. Once the gold is extracted, the tailings, which include excess mercury, are often dumped in the natural environment, including rivers. Hence, heavy metal pollution of surface waters, particularly from mercury, is now a global phenomenon, with the problem amplified in rivers and reservoirs located in developing countries (e.g., Zimbabwe, Zambia, Ghana, and South Africa) where illegal mining is rampant (Banchirigah, 2008; Dalu et al., 2017b; Viana et al., 2021).

The recent upsurge of illegal mining activities in sub–Saharan Africa has been highlighted as “opportunism” and people's desire to “get rich quick” (Nyamunda et al., 2012). However, in most instances, this is linked to poverty (Dalu et al., 2017a). Therefore, it is paramount to ensure that there are adequate research, monitoring, and evaluation campaigns on heavy metals focusing on the aquatic environments due to concerns of over accumulation and toxic effects on animal and human health since these heavy metals can exist in sediments for several years (Kortei et al., 2020). Despite short–term economic gains for miners in developing countries, the long–term damages to aquatic biota and human livelihoods can be pervasive in areas where illegal mining is taking place (Kambey et al., 2001; Dalu et al., 2016, 2017a). In essence, illegal mining can have significant impacts on aquatic biota, including fish, plants, and other organisms that live in or depend on aquatic ecosystems, with potential impacts including habitat destruction and alteration, water pollution, water flow alteration and temperature changes, overexploitation, sedimentation and altered food webs (Peralta-Videa et al., 2009; Abeysinghe et al., 2017; Azevedo-Santos et al., 2021; Darko et al., 2021).

Potamonautid crabs are decapod crustaceans inhabiting freshwater lotic and lentic ecosystems (Daniels et al., 1998; Stewart and Cook, 1998). These freshwater crabs play an essential role in the food webs of these ecosystems and are useful indicators of the health of the rivers they inhabit (Phiri and Daniels, 2013). In recent years, freshwater crabs have been increasingly used as bioindicators for monitoring the health of freshwater ecosystems because they are highly sensitive to changes in their environment, are readily affected by changes in water quality and are often the first organisms to show signs of pollution or other disturbances (e.g., Chagas et al., 2009; Arya et al., 2014; Somerset et al., 2015; Gholamhosseini et al., 2023). Due to their sensitivity to water quality changes, they can provide a more accurate and reliable assessment of the overall health of freshwater ecosystems than other methods or groups of invertebrates. Potamonautid crabs (Crustacea: Decapoda) are relatively easy to sample and identify compared to some other aquatic organisms. Their distinct morphological features and behaviour make them readily identifiable, enabling efficient monitoring and data collection (Cumberlidge et al., 2009; Dvoretsky and Dvoretsky, 2023). Furthermore, crabs are benthic organisms which inhabit the sediments of aquatic systems, and as such they are directly influenced by changes in sediment quality and habitat structure. Hence, specific habitat requirements and physiological sensitivities to environmental changes make monitoring crab populations important, as they provide information on the suitability of habitats, including sediment composition, substrate stability, and availability of food resources (Bertrand et al., 2018). However, these species are not well studied compared to other aquatic organisms, causing limitations to our understanding of their biology and behaviour (Cumberlidge et al., 2009; Oliva et al., 2019; Wang et al., 2020). Their responses to anthropogenic stressors such as pollution are also often unknown. At the same time, they may be vulnerable to over–harvesting or other forms of exploitation, which could threaten their populations (Dalu et al., 2017a, 2017b; Tejada et al., 2015).

Despite the apparent impacts illegal mining activities could have on the receiving environment and with social impacts in sub–Saharan Africa generally well documented (e.g., Banchirigah, 2008; Dalu et al., 2017a), no study to date has comprehensively assessed the impacts on the associated biota such as freshwater crabs within biodiverse conservation areas, such as the Eastern Highlands of Zimbabwe. Thus, the present study assessed the impact of illegal gold mining activities on freshwater Potamonautid crabs and further quantified mercury levels within river sites, as river sediments tend to become sinks for heavy metals (i.e., mercury), and sometimes act as sources to other environments (Duncan et al., 2018). We hypothesised that areas within protected areas will have high abundances of crab species as these will be considered pristine compared to other areas such as communal and plantation zones.

2. Materials and methods

2.1. Study area

The study was done in the intensive illegal mining region of the Chimanimini areas in the Eastern Highlands of Zimbabwe. We measured 49 localities in rivers and/or streams towards the end of winter (12–16 July 2017) (Fig. 1). The sampling was done along the three main tributaries (i.e., Musapa, Nyahode, Haroni) and associated streams (i.e., Adanki, Machongwe, Manase, Mouwa, Muchira, Mutekesani, Nyadonga, Pwazi, Taka, Nyapande, Zungundu) of the Rusitu River (Zimbabwe) / Buzi River (Mozambique) system. The Musapa River flows through mostly communal villages in a west–to–east direction into Mozambique; the Nyahode River headwaters are in the Chimanimani Elands Sanctuary and Martin Forest Reserve and flow through timber plantations and communal villages before joining the Rusitu River towards the south. The Haroni River headwaters are located in the Chimanimani National Park, with the river flowing through a resettlement area and next to a diamond mine through timber plantations and the national park before joining the Rusitu River at the border with Mozambique.

The Chimanimani area is a narrow mountain belt region which forms the central part of the ~450 km long Eastern Highlands region of Zimbabwe, located on eastern Zimbabwe–western Mozambique border (see Fig. 1). The Chimanimani region is dominated by communal villages (west, north), coffee (north), timber (west, central, north) and banana (south) plantations, a protected area (i.e., Chimanimani National Park, east) and a diamond mining company (i.e., central, edge of the national park boundary). The Chimanimani area was declared as a UNESCO biosphere reserve in 2022 and features six key biodiversity areas rich in endemic plant species and 88 archaeological sites. It is home to over

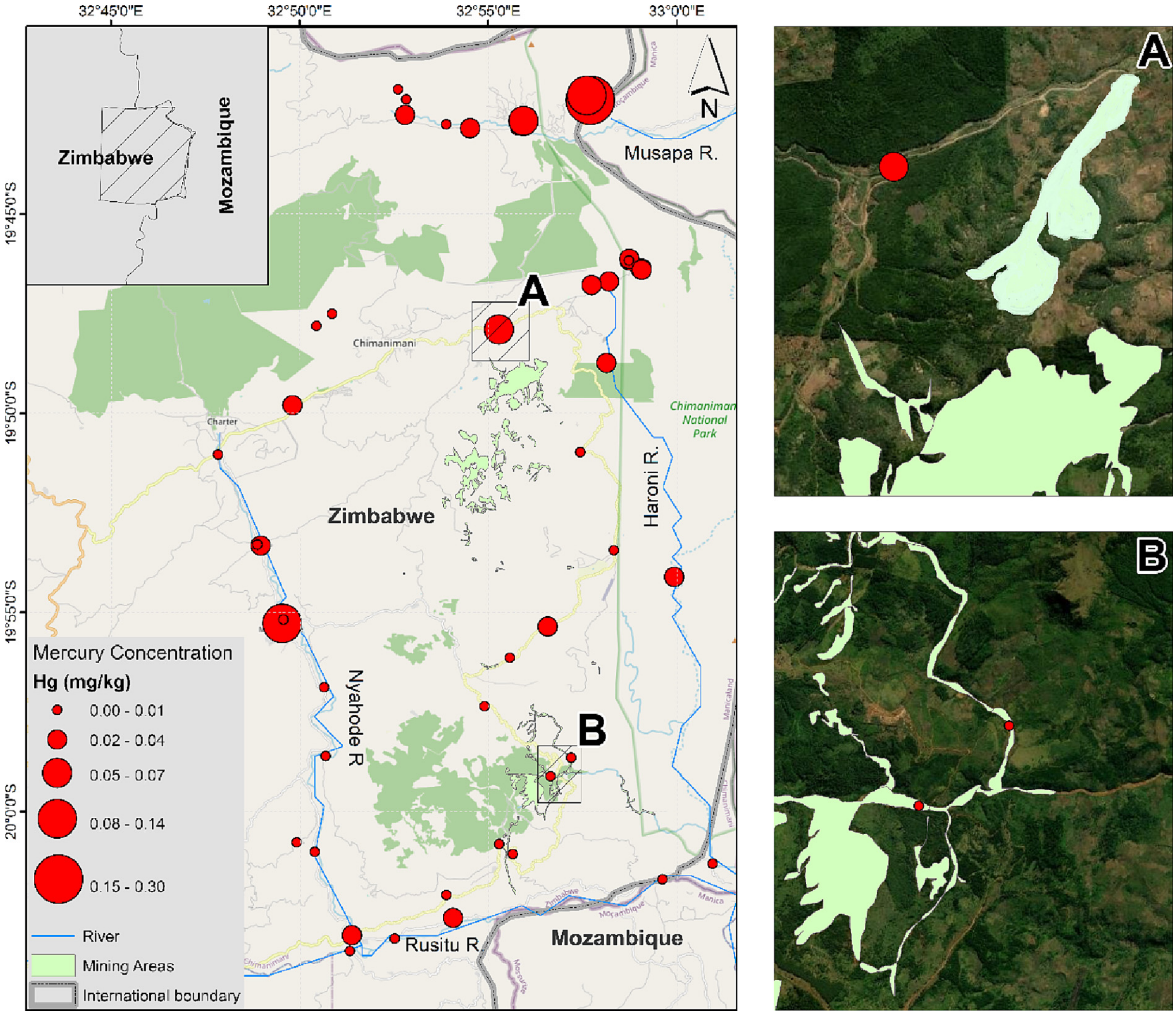

Fig. 1. Mercury concentration variation with the Chimanimani area, Zimbabwe. The three major river systems (i.e., Musapa (north), Nyahode (west), Haroni (east)), all tributaries of the Rusitu (Zimbabwe) / Buzi (Mozambique) River system (i.e., south), are shown. Panels A and B were randomly chosen to highlight mercury concentration in relation to illegal mining within the timber plantations.

154,000 inhabitants from the Ndau culture, most of whom speak an endangered language. The area's population was 134,939 according to the 2012 census, with most of the people living in communal villages (i.e., 94 %) and from the Ndau culture (i.e., most of whom speak an endangered language). The poverty levels are relatively high (i.e., ~ 60–96 %). Hence most families have been pushed into illegal mining to support their livelihoods (Dalu et al., 2017a). The regional altitude rises from ~700 m to a peak of 2400 m, with rainfall rapidly increasing with altitude from about 741 mm per annum along the southeast facing foothills to well over 2000 mm per annum at high altitudes. Temperatures are generally mild to very cold, with heavy frosts during winter. The month with the average high temperature is October (i.e., 29.8 °C), whereas July (21.6 °C) has the average low temperature. December (19.3 °C) has the highest average low temperature, with June (10.7 °C) having the lowest average low temperature (McGinley, 2008). Chimanimani District Biodiversity Hotspot comprises 2182 plant taxa (i.e., >30 % of estimated total plant diversity in Zimbabwe). The Chimanimani Mountains alone is comprised of 977 taxa with 74 endemics, and the entire area has 127 species of conservation importance (i.e., 12 amphibians, 34 birds, 59 butterflies, 2 fish, 9 mammals, 3 Odonata, 8 reptiles) (https://en.unesco.org/biosphere/africa/chimanimani).

Illegal mining in the Chimanimani area occurs on a significant scale, with numerous small-scale miners operating without proper licenses, proper protective gear and/or compliance with the mining regulations. These miners often encroach on protected areas, riverbeds, and agricultural lands, leading to extensive environmental degradation. There are no official data on the number of illegal miners, but they are estimated to be around 400,000 in Zimbabwe (Dalu et al., 2017b). Several rivers and streams are indicated as being polluted by illegal gold mining activities in Chimanimani, with pollution coming from mostly mercury and siltation (Nhamo and Chikodzi, 2021).

2.2. Sediment chemistry variables

The results for the sediment chemistry variables are presented in Dalu et al. (2022). Water samples were not taken, as preliminary investigations found that suspended concentrations of heavy metals were negligible. Integrated 1.5 kg sediment samples from three random areas within each site were collected using acid–washed wooden splints and placed into new labelled polyethylene ziplock bags for further analysis at the South African National Accreditation System accredited laboratory, BEMLAB (Cape Town, South Africa). The samples were initially oven–dried at 60 °C for 72 h before analysis of cation elements (i.e., boron (B), calcium (Ca), magnesium (Mg), potassium (K), and sodium (Na)) and heavy metals (i.e., manganese (Mn), copper (Cu), iron (Fe), mercury (Hg), and zinc (Zn)) were determined using an inductively coupled plasma–atomic emission spectroscopy (ICP–OES) optical emission spectrometer (Varian, Mulgrave). The nitrate phosphorus concentrations were determined calorimetrically based on the SEAL Auto–Analyser 3 (Varian, Mulgrave) (see Agriculture Laboratory Association of Southern Africa (AgriLASA), 2004) and Bray–2 extract method (Bray and Kurtz, 1945), respectively.

2.3. Potamonautid crab sampling

Freshwater Potamonautid crab abundances were estimated based on mixed sampling methods, which involved intensive searching, baited cattle heart lines and nylon hand–held nets (mesh size 500 μm, dimension 30 × 30 cm), employed according to Phiri and Daniels (2013) and Dalu et al. (2016). In brief, intensive hand searching was done for smaller areas with shallow water where rocks and borrows were searched. Care was taken to minimise damage to the crabs and their habitat. The baited cattle heart lines done to lure the crabs and counting was done over a known period of time (~30–40 min) (Phiri and Daniels, 2013). The hand nets were used to collect crabs from all available habitats (i.e., marginal vegetation, riffles, pools). Two crab species found in the area were identified using Phiri and Daniels (2013) identification guides, and the total Potamonautid abundances were recorded for each site visited.

2.4. Data analysis

Geographical positions of study locations within the Chimanimani region were used to produce total abundance distribution and mercury (Hg) maps, with areas showing high illegal mining superimposed on them. The spatial distribution of the Potamonautid crab species sampled and Hg concentrations within the study area were modelled using spatial analyst tools in a GIS environment based on the species and Hg concentration dataset collected during the field survey. The dataset was imported into ArcGIS 10.2 software (ESRI (Environmental Systems Research Institute), 2011) and then processed to show the spatial distribution patterns across the entire study area using the graduated symbolisation interface in ArcGIS (ESRI (Environmental Systems Research Institute), 2011). This interface uses the quantitative values or species population data gathered during field surveys to subdivide the dataset into distinct classes. Within each class, the features were highlighted with the symbol and symbol size.

To effectively ascertain the extent of metal pollution due to illegal mining within the Chimanimani region, selected metal concentrations (i.e., Cu, Hg, Zn, Mn, Pb) were compared with international standards of sediment quality guidelines (SQGs) by Persaud et al. (1993), which consider values as threshold metal concentrations that cause adverse biological effects in an aquatic environment, i.e., low effect level (LEL), probable effect level (PEL) and severe effect level (SEL). Geo–accumulation Index (Igeo) and Enrichment Factor (EF) were quantified for the Chimanimani region sediments across the different land use patterns i.e., national park, communal area and timber plantations, according to Dalu et al. (2022). The Igeo, which assesses individual metal pollution levels in sediment, uses the following classes: *< 0* (*class 0*) no contamination, 0–1 (*class 1*) no–to–moderate contamination, *1–2* (*class 2*) moderate contamination, *2–3* (*class 3*) moderate–to–strong contamination, *3–4* (*class 4*) substantial contamination, *4–5* (*class 5*), strong–to–extreme contamination and >*5* (*class 6*) extreme contamination (Muller, 1969). The EF, which is a measure of the concentration of a particular metal in the sediment relative to its natural background concentration, is quantified as follows: *EF < 1* background concentration, *1–2* low enrichment, *2–5* moderate enrichment, *5–20* significant enrichment, *20–40* very high enrichment and *>40* extremely high enrichment (Buat–Menard and Buat-Menard and Chesselet, 1979).

Principal component analysis (PCA) with varimax rotation method was used to determine the natural and anthropogenic sources of sediment metals across 49 river and stream sites using PC–ORD version 5.10 (McCune and Mefford, 2006). A two–way cluster analysis, using Ward's average group linkage method and correlation as a distance measure, was used for metal source identification. Furthermore, we tested for interrelationships among metal concentrations in SPSS version 25 using Pearson correlations.

Generalised linear models with negative binomial error distribution were used in series to examine the effects of environmental parameters on Potamonautidae abundances. There were no significant differences in abundances among the three river systems ($F_{2,46} = 0.486$, $p = 0.618$), and so they were pooled in analyses. Generalised linear models were fit in R v4.1.1 software.

3. Results

3.1. Mercury concentrations

Illegal mining was prevalent throughout the three land use classes, with mercury (Hg) concentrations being detected in 35 sites (71.5 %). In the communal areas, national parks, and timber plantations, 68.2 % ($n = 15$ / 22 sites), 83.3 % ($n = 15$ / 18 sites) and 55.6 % ($n = 5$ / 9 sites) Hg concentrations were detected, respectively. The mean range of Hg concentrations detected across the three–land uses was as follows: communal areas 0–0.1 mg kg^{-1} (mean 0.01 ± 0.02 mg kg^{-1}), national parks 0–0.3 mg kg^{-1} (mean 0.04 ± 0.07 mg kg^{-1}) and timber plantations 0–0.06 mg kg^{-1} (mean 0.01 ± 0.01 mg kg^{-1}) (Fig. 1).

Most of the communal area, national park and timber plantation sites showed *no to moderate contamination* for Fe and Zn metal geo–

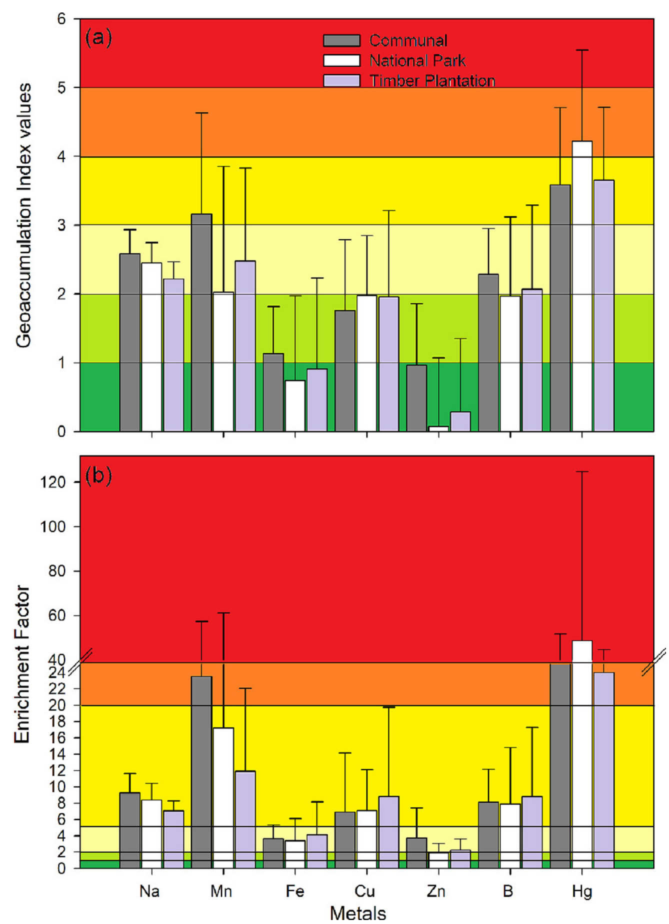

Fig. 2. (a) Geo–accumulation index (Igeo) and (b) enrichment factor (ER) values (+ standard deviation) of metals in sediment samples of each land use category within the Chimanimani area, Eastern Highlands of Zimbabwe. For Igeo, 0–1 (green) no to moderate contamination, 1–2 (light green) moderate contamination, 2–3 (light yellow) moderate to strong contamination, 3–4 (yellow) strong contamination, 4–5 (orange) strong to extreme contamination and > 5 (red) extreme contamination; for ER values, green (<1 background concentration), light green (1–2 low enrichment), light yellow (2–5 moderate enrichment), yellow (5–20 significant enrichment), orange (20–40 very high enrichment) and red (>40 extremely high enrichment).

Table 1
Mean concentrations and sediment quality guidelines for copper, mercury and zinc in the Chimanimani area, Zimbabwe.

	Unit	Copper	Mercury	Zinc
Communal area	mg kg^{-1}	13.30 ± 13.84	0.01 ± 0.02	27.96 ± 27.58
National park	mg kg^{-1}	13.6 ± 9.64	0.04 ± 0.07	14.43 ± 8.52
Timber plantation	mg kg^{-1}	16.88 ± 21.01	0.01 ± 0.01	16.88 ± 10.26
Probable effect level (PEL)		197	0.486	315
Lowest effect level (LEL)		16	0.2	120
Severe effect level (SEL)		110	2	820

accumulation index values, with only Fe falling in the *moderate contamination* in communal areas. Mean Hg geo–accumulation index values showed *strong to extreme contamination* in the national park, with *strong contamination* observed for communal areas and timber plantations (Fig. 2a). For the enrichment factors, most metals (i.e., Na, Cu, B, Mn) were in the *significant enrichment* category for all land use areas except Mn in the communal areas, which showed *very high enrichment*. Metals Fe and Zn showed *moderate enrichment*, whereas Hg concentrations in the communal and national park areas showed *extremely high enrichment* (Fig. 2b). Based on the sediment quality guidelines (SQG), 4 sites (i.e., Muchira River 2 and 3, Rusitu River 1, Adanki River 1), 2 sites (Mutekesani River, Nyahode River 2) and 2 sites (i.e., Tarka River 3, Zungundu River 1) showed LEL for Cu concentrations with the communal areas, national park, and timber plantation, respectively. For Hg, only 1 site Mouwa River 4 showed LEL with the national park area (Table 1).

3.2. Relationships between metals

The Pearson correlation analysis showed significant positive correlations among selected metals (i.e., K, Fe, Zn, B, Cu), suggesting that these trace elements in marsh soils might originate from common sources. The metals Ca, Mg, and Na also showed strong positive correlations, indicating that they originated from a similar source (Table 2). The two principal components (i.e., PC1, PC2) explained 70.0 % of the total variance, with the eigenvalues of the 2 extracted PCs both being >1.0 (Table 2). PC1 explained 50.8 % of the total variance, whereas PC2 accounted for 19.2 %. The principal component analysis showed that the metals were classified into 3 groups, like the Pearson correlation (Table 3) and cluster analysis (Fig. 3), *group 1* (i.e., K, Mn, Fe, Cu, Zn, B), *group 2* (i.e., Ca, Mg, Na) and *group 3* (i.e., Hg). Cluster analysis, often coupled with principal component analysis to confirm interpretation and outputs, indicated a similar pattern as already highlighted above, with *group 3* containing only Hg being clearly distinguishable from *groups 1* and *2*, suggesting Hg was from a completely different source.

3.3. Potamonautid abundances and relationship with metals

Two crab species (i.e., *Potamonautes mutareensis*, *Potamonautes unispinus*) were found in the Chimanimani area, with *P. mutareensis* being the dominant taxon in the region across all the three land use areas. *Potamonautes unispinus* was found in the south part of Chimanimani along the Rusitu River and lower reaches of the Nyahode River systems and associated tributaries. Areas with where we observed intensive illegal mining did not have or had very small total Potamonautid crab abundances (Fig. 4). The national parks had total abundances of 6.1 ± 5.4 (mean ± standard deviation (SD)), with communal and timber plantation areas

Table 3
Matrix of principal component analysis and total variance explained for the metals in river sediments from Chimanimani area. Significant loadings (>0.5) are marked in bold.

	PC1	PC2
Rotation sums of squared loadings		
Eigenvalue	5.075	1.924
%Variance	50.754	19.24
Cumulative % of Variance	50.754	69.994
Rotated matrix component		
K	**−0.81**	0.18
Ca	**−0.70**	**−0.66**
Mg	**−0.55**	**−0.53**
Na	**−0.61**	**−0.67**
Mn	**−0.82**	−0.13
Fe	**−0.85**	0.35
Cu	**−0.66**	**0.69**
Zn	**−0.84**	0.10
B	**−0.86**	0.32
Hg	0.10	−0.08

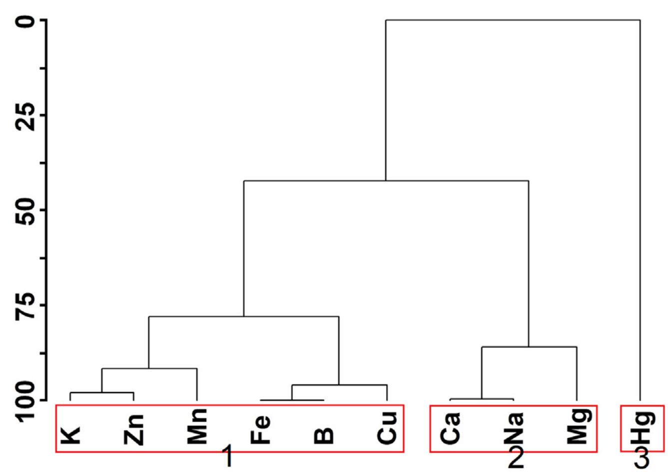

Fig. 3. Cluster analysis showing the clustering of the metals according to the Ward's method within the Chimanimani area, Zimbabwe.

Table 2
Correlation matrix among metals and selected sediment chemistry variables within the Chimanimani area, Zimbabwe. Values in the grey and white areas are the *p* and *r* values, respectively. Bold values indicate significant levels at $p < 0.05$.

	K	Ca	Mg	Na	Mn	Fe	Cu	Zn	B	Hg
K	1	**0.43**	**0.37**	**0.43**	**0.68**	**0.68**	**0.69**	**0.82**	**0.69**	0.16
Ca	**0.002**	1	**0.62**	**0.86**	**0.73**	**0.45**	0.04	**0.61**	**0.46**	–0.04
Mg	**0.010**	**<0.001**	1	**0.58**	**0.43**	**0.43**	0.10	**0.60**	**0.41**	–0.12
Na	**0.002**	**<0.001**	**<0.001**	1	**0.65**	**0.48**	0.10	**0.58**	**0.47**	0.05
Mn	**<0.001**	**<0.001**	**0.002**	**<0.001**	1	**0.79**	**0.54**	**0.85**	**0.79**	–0.05
Fe	**<0.001**	**0.001**	**0.002**	**<0.001**	**<0.001**	1	**0.74**	**0.83**	**0.99**	–0.13
Cu	**<0.001**	0.786	0.503	0.502	**<0.001**	**<0.001**	1	**0.66**	**0.76**	–0.03
Zn	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	1	**0.83**	–0.15
B	**<0.001**	**0.001**	**0.003**	**0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	1	–0.16
Hg	0.283	0.792	0.418	0.722	0.723	0.358	0.821	0.299	0.285	1

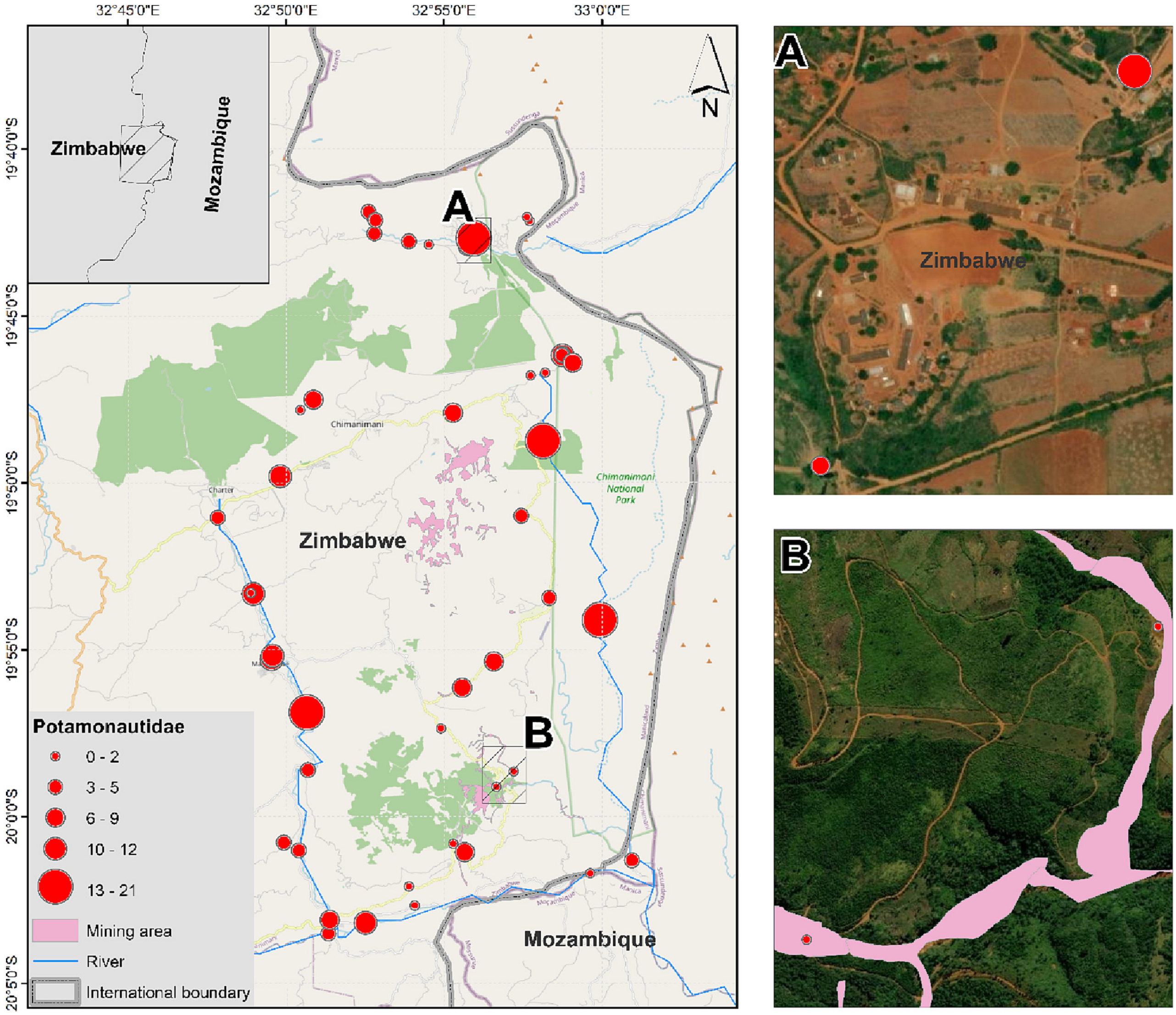

Fig. 4. Freshwater Potamonautidae (i.e., *Potamonautes mutareensis*, *Potamonautes unispinus*) abundance along the major river tributaries with different land uses in the Chimanimani area, Zimbabwe. Panels A (communal area, no illegal mining) and B (timber plantation, illegal mining) were randomly selected to indicate Potamonautid crab abundances within different land use patterns.

having 5.8 ± 4.7 and 3.8 ± 3.2 total abundances, respectively. Based on the GLM analysis, we observed negative and significant effects for K, Fe, Cu and B on total Potamonautid crab abundances (Table 4).

Table 4
Negative binomial generalised linear model coefficients with effects of sediment chemistry parameters on Potamonautid abundances. Significant terms at $p < 0.05$ are in bold.

Term	Estimate	Standard error	*z*–value	*p*-Value
N	−1.068	1.406	−0.76	0.447
P	6.501	10.376	0.626	0.531
K	**−14.5**	**6.779**	**−2.139**	**0.032**
Ca	−0.616	1.603	−0.384	0.701
Mg	4.873	2.937	1.660	0.097
Na	−0.002	0.004	−0.386	0.699
Mn	< −0.001	<0.001	−1.576	0.115
Fe	**< −0.001**	**<0.001**	**−2.146**	**0.032**
Cu	**−0.019**	**0.010**	**−1.993**	**0.046**
Zn	−0.005	0.006	−0.827	0.409
B	**−0.005**	**0.002**	**−2.428**	**0.015**
Hg	−0.957	2.634	−0.363	0.716

4. Discussion

Illegal mining exerts a significant impact on aquatic invertebrates, as revealed by the present study. This impact is particularly severe for Potamonautid crabs, which play a crucial role in freshwater ecosystems. The study found that areas affected by illegal mining generally exhibited low abundances of these crabs. One of the primary consequences of illegal mining is the alteration of water quality (Fig. 5), primarily caused by dredging, excavation, and the use of chemicals. These activities release heavy metals and other pollutants into nearby streams and rivers, contaminating water (Dalu et al., 2017b), with crab abundances significantly negative related to K, Fe, Cu and B in the present study. The presence of these and other pollutants can have detrimental effects on aquatic invertebrates, including reduced growth rates, developmental abnormalities, and increased mortality rates (Monge-Salazar, 2021; Rico-Sánchez et al., 2022).

Furthermore, illegal mining significantly impacts the habitat of Potamonautid crabs through destruction (see Fig. 5). Riparian vegetation is removed, stream/riverbanks become destabilized, and there are alterations in the physical structure of the stream channel and substrate embeddedness (Box 1; Jaiye, 2013; Dalu et al., 2017b; Rentier and Cammeraat, 2022). These changes result in habitat loss and reduced food sources for aquatic invertebrates, ultimately affecting their populations

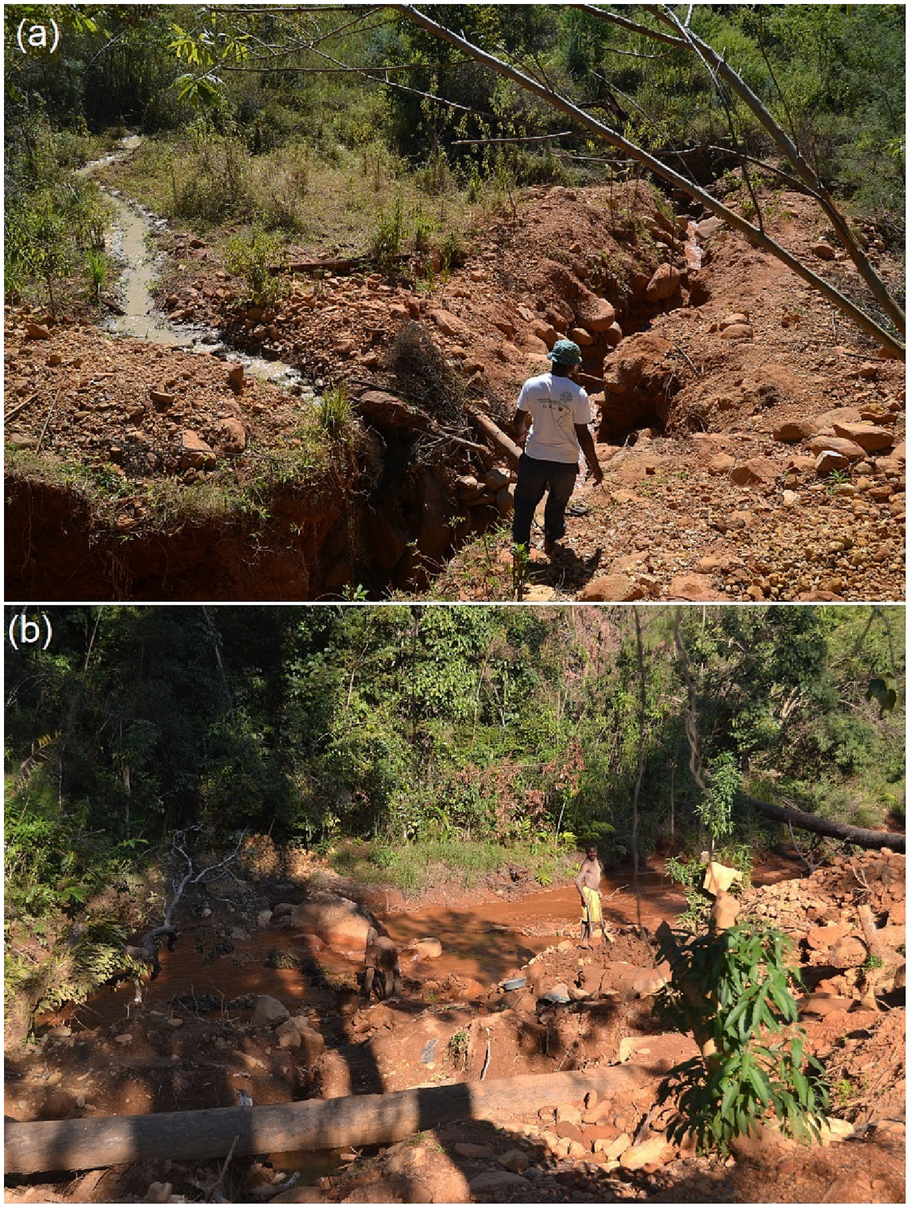

Fig. 5. (a) An entire stream was diverted to enable illegal gold mining in the Tarka Forest Plantations, Chimanimani. Note the main stream channel (right) and diverted new channel with water contaminated with mercury for the wash plant (left). (b) Illegal miners digging for gold along Muchiri River near Kurwaisimba, Chimanimani. Note that illegal miners do not have protective clothing. However, they work with toxic and carcinogenic mercury, and the riparian vegetation is destroyed on the south bank where mining occurs.

and the overall ecosystem's health. The consequences extend to aquatic food webs and sustainable livelihoods for communities reliant on these Potamonautid species (Dalu et al., 2016, 2017a). The findings underscore the urgent need to address the issue of illegal mining and its detrimental effects on aquatic invertebrates, with a particular focus on Potamonautid crabs. By implementing measures to prevent illegal mining and mitigate its environmental impacts, we can protect these critical species, preserve biodiversity, and support the sustainable livelihoods of communities that depend on them.

Several studies (e.g., Cordy et al., 2011; Alcala-Orozco et al., 2019; Moreno-Brush et al., 2020) have indicated that Hg concentrations are elevated in areas downstream of mines or within their vicinity. Similarly, we also observed generally high Hg concentrations in areas where illegal mining was taking place and downstream of these sites. The Hg values in river sediments of mean range 0.01–0.04 mg kg^{-1} (i.e., 10–40 ng g^{-1}) are higher than those reported in the Acre River basin, Brazil (0.02–0.28 ng g^{-1}; Brabo et al., 2003), Negro River, Brazil (0.08–0.32 ng g^{-1}; Fadini and Jardim, 2001), Cuyuni River basin, Venezuela (0.02–0.04 ng g^{-1}; Santos-Francés et al., 2011), Migori–Transmara, Kenya (0.02–1.1 ng g^{-1}; Odumo et al., 2014) and Rwamagasa, Tanzania (<0.05–9.2 ng g^{-1}; Taylor et al., 2005). Rajaee et al. (2015) observed Hg concentrations based on a review of published literature throughout Ghana, with mean concentrations of 0.02–186 ng g^{-1}, falling within the range of our study concentrations. One communal and national park areas had Hg concentrations of 0.1 mg kg^{-1} (1000 ng g^{-1}) and 0.3 mg kg^{-1} (3000 ng g^{-1}), respectively. These sites were where intensive illegal gold mining was observed during field surveys.

High correlation coefficients among metals have been highlighted to indicate common sources and mutual dependence (Skordas et al., 2015). In the current study, we observed three different groupings, with Hg used in illegal gold extraction forming its own grouping as miners bring it into the natural environment. Other metals (i.e., K, Mn, Fe, Cu, Zn, B) that are readily found within the natural environment formed a separate group, and the last group was metals (i.e., Ca, Mg, Na) from fertiliser applications. Variability in Mn, Fe, Cu, Zn and B concentrations can be mediated by the

Box 1
Gold rush fever among poor Zimbabweans leaves trail of destruction. Source: Andrew Mambondiyani (https://www.reuters.com/article/us–zimbabwe–mining–landrights–idUSKBN17J1CJ) and Cyril Zenda (https://www.fairplanet.org/story/mercury–a–silent–killer–in–zimbabwe/).

"Thousands of unemployed Zimbabweans have turned to illegal gold panning in a bid to survive the country's deteriorating economy, leaving a trail of destruction that has alarmed farmers, timber plantation owners and the country's environmental authorities. Economically deprived miners have set up makeshift mines on farmland and timber plantations in the country's eastern provinces, which border Mozambique where gold reaches a higher price. In some parts of Manicaland province, waterways have been diverted and roads destroyed. With more illegal miners likely to exploit the area as the economy continues to slump, and the state is placing responsibility to act on landowners, farmers are fearful of irreversible damage to their land, and the risk of losing their livelihoods."

"The wanton use of mercury, a highly hazardous substance that virtually all artisanal miners in Zimbabwe use in harvesting gold particles from the ore, is a silent killer that is causing untold devastation among local mining communities and far beyond. At the river, the skilful washing process reduces the several sacks into just a few handfuls of fine sand. It is at this stage that mercury is used. When mercury – the only chemical cheaply available and affordable to the miners – is added to this slurry, it extracts all the gold particles available in the sand and sinks to the bottom of the pan. This amalgam is separated, excess mercury and water thrown away, and the matter is taken for smelting in order for the mercury to evaporate, leaving any minuscule amount of gold. Findings of studies by the University of Zimbabwe showed widespread unsafe use of mercury acquired through legal and illegal means by artisanal miners."

"Simon Simango, an illegal gold miner in Chimanimani, Manicaland province, acknowledged that the excavations were having a negative impact on the environment. But many workers had run out of options, he said. '*This (illegal mining) is our only source of livelihood. Look, there are no jobs in the country*,' and '*We sell most of our gold to illegal buyers from Mozambique who are offering us very good prices*.' Unemployment runs at 80 %, and even those with jobs face unpaid wages and an acute shortage of cash. There are no official data on the number of illegal miners in Zimbabwe which are estimated to number at >500,000 illegal, artisanal gold miners, with numbers expected to grow as the economy continues to falter. In Tarka Forest, a timber estate owned by Allied Timbers in Chimanimani district, >600 ha of prime timber have been damaged to make way for the illegal digs. The illegal gold mining in Tarka Forest has reached '*alarming levels*', and resulted in the pollution of streams and rivers, and destruction of standing timber. The government says it is the responsibility of landowners or affected businesses to evict the illegal miners. '*If an area belongs to the timber plantations, the government cannot legalise gold mining in the area. The companies must put measures in to stop illegal mining in their plantations*.' Darlington Duwa, CEO of the Timber Producers Federation, warned of lasting damage as a result of the disappearing forests and water pollution caused by illegal mining. '*It (illegal mining) reduces the timber resource, thus affecting direct and indirect employment, economic development, foreign currency earnings and leads to environmental degradation and reduced resilience to climate change effects*,' Duwa told the Thomson Reuters Foundation."

Thus, the fight to eliminate mercury use in Zimbabwe cannot be debated without mentioning the complexity of the mining sector that uniquely has artisanal miners as top gold producers.

local parent rock materials, which mainly comprise highly weathered soils found on the mountain, foothills, and alluvial valleys, with low cation exchange capacities and base status, as well as red sandy clays to clays (Timberlake, 1994). Similarly, Bellos et al. (2004) highlighted increased Ca, Mg and Na concentrations due to river water contamination from industrial wastewater, agricultural fertiliser leaching and sewage discharges (Bellos et al., 2004). Based on the SQGs, all metals were within the recommended limits, except for a few sites where illegal mining activities were high. Metal enrichment factors and geo–accumulation index values were generally high for Mn and Hg. Although illegal mining can be identified as a source, one needs also to consider erosion from ferralitic forest soils (i.e., deeply, old weathered and leached soils typically common in humid tropics such as the Chimanimani area) (Moreno-Brush et al., 2020). Similar to soils of the Chimanimani area, these ferralitic soils have been found to lack soil minerals and nutrients but are enriched in metals such as aluminium and Fe hydroxides, which effectively retain and accumulate Hg through adsorption (Guedron et al., 2009). Hence, this can also be supported by the high Fe concentrations observed in the current study.

We found several abiotic variables to be significantly negatively associated with abundance of Potamonautid crabs. Iron can affect sediment quality by changing its texture and nutrient composition, leading to food and habitat availability changes for Potamonautid crabs (Kristensen, 2008). For example, increased Fe concentrations could lead to the formation of iron sulphide minerals, which can be toxic to crabs (Kristensen, 2008). In crustaceans, Cu is a functional part of the respiratory protein hemocyanin used to synthesise metallothioneins and metalloproteins (Bakker et al., 2016; Saher and Siddiqui, 2019). However, high Cu concentrations exposure can have negative impacts on Potamonautid abundances as it can interfere with cellular processes, causing oxidative stress and damage to DNA, proteins, and lipids leading to stunted growth, reproduction, and survival rates (Saher and Siddiqui, 2019). Copper and Fe can also affect the behaviour of Potamonautid crabs, making them more susceptible to predators or less likely to forage and reproduce, and it can accumulate in the crab tissues over time, leading to bioaccumulation and biomagnification in the food chain. Similar to Cu and Fe, B has been shown to have toxic effects on crabs at high concentrations, and it was observed B concentrations above a certain threshold were lethal to the mud crab *Scylla serrata* larvae. However, the study also found that lower B concentrations had no significant effect on the crab larvae's survival. It is important to note that the effects of K, Fe, Cu and B on crab abundances can be modulated by other environmental factors such as pH, temperature, and dissolved oxygen, making the relationship complex and context–dependent, thereby requiring further investigation.

5. Conclusions

The Hg mercury values in river sediments were found to be higher than those of other studies and crab abundances tended to be lower in heavily impacted areas by illegal mining across different land use. Overall, addressing the issue of illegal mining within the developing world will require a concerted effort from all stakeholders (e.g., government, mining companies, local communities, civil society groups) to help protect the less charismatic and understudied taxa. By working together, it may be possible to promote sustainable and responsible mining practices while also protecting the environment and ensuring worker safety. Illegal mining can have severe and long–lasting impacts on aquatic invertebrates, particularly

Potamonautid crabs, leading to water contamination, habitat destruction, and changes to the food web structure. Thus, to protect these important freshwater organisms and maintain healthy freshwater ecosystems, enforcing regulations and promoting responsible mining practices is essential.

CRediT authorship contribution statement

TDa: Conceptualization, Investigation, Methodology, Data curation, Formal analysis, Funding acquisition, Writing – original draft, review and editing. TDu: Formal analysis, Methodology, Visualisation, Data curation, Writing – original draft, review and editing. FD: Formal analysis, Methodology, Visualisation, Data curation, Writing – original draft, review and editing. RNC: Visualisation, Methodology, Formal analysis, Data curation, Writing – original draft, review and editing.

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Ethics and permits approval

No ethical approval was required since research involved invertebrates. Sample collection permits were granted by Zimbabwe Parks and Wildlife Management Authority (ZPWMA) (permit number: 23(1)I(II)36/2017).

Consent for publication

Not applicable, all data were collected by the authors.

Data availability

Data will be made available on request.

Declaration of competing interest

All authors declare no conflict or financial interests exist for the manuscript.

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