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Environmental impacts of artisanal and small-scale gold mining within Kambele and Pater gold mining sites, East Cameroon

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Abstract The increasing demand for gold, notably in the jewellery industry and other sectors such as finance, electronics, and aerospace, has exerted pressure on gold exploration and exploitation worldwide. Recently, Batouri has witnessed several exploration and exploitation efforts, predominantly by small scale mining companies. These activities have impacted the quality of the environment within Batouri gold district. This research assesses the impact of artisanal and small-scale gold mining on the environment in the Batouri gold district, notably in the Kambele and Pater mining sites, where limited scientific studies on the environmental impacts of gold mining activities have been carried out. Eighteen surface water samples were collected from the Kambele and Pater mining sites during the dry season. Four trace elements (Mercury, Lead, Cyanide, and Arsenic) were analyzed to determine the quality of water in the study area using a Buck Scientific Atomic Absorption Spectrometer 205. The concentration of Mercury (102.64—5550.38 µg/L) and Lead (336.7–2072 µg/L) was found to be far greater than the European directives and the WHO pollution guidelines while the concentration of Cyanide (1.45–10.35 µg/L) and Arsenic (0.12–0.42 µg/L) were below both the European directives and WHO pollution guidelines. The order of abundance was as follows: Hg > Pb > CN > As. Spatial interpolation was used to understand the spatial and concentration distributions of the pollutants over the study area. A timeseries analysis was conducted to determine the changes in the environment as a result of mining activities in Batouri over 20 years (2002–2022). The results of the change fallowing, or farming areas, and bare ground areas, while mature and young savannah forests together with water resources showed a decrease as a result of mining activities. Deforestation, abandoned pits, mine collapse, rockfall, air pollution, soil and subsoil degradation, water pollution, and destruction of the natural environment are the main environmental problems observed in the field. These environmental problems can be averted by encouraging reforestation, filling mine pits with waste rock, and gold recovery using gravity-based methods such as jigs and shaking tables, which are more environmentally friendly and enforce environmental protection policies.

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Introduction

Artisanal and small-scale gold mining (ASGM) operations occur in more than 70 countries, with over 20 million people involved in the activity, particularly in developing countries (Veiga & Gunson, 2020). This activity is generally poverty-driven in rural settings and involves men, women, and children (Adewumi et al., 2020; Allan-Blitz et al., 2022; Orleans-Boham et al., 2020; Zolnikov, 2020). Artisanal mining is purely manual mining performed on a very small scale with little or no mechanization, usually by individuals, groups, families, or cooperatives using panning and locally made sluices while small-scale mining involves some mechanization and is on a larger scale using methods such as sluicing, jigging, tabling, and centrifuging (Veiga & Gunson, 2020). Most often, mercury is used in the gold extraction process as it forms an amalgam with gold, allowing gold to be more easily concentrated and recovered. This is done by passing gravity concentrates or ore through mercury-coated plates in sluices or processing centers that offer amalgamation services to artisanal miners and leach mercury-contaminated tailings with cyanide (Veiga & Gunson, 2020). This process generally results in large losses of Hg to the environment, and it is one of the most anthropogenic sources of Hg pollution in the world, with approximately 2000 tpa of Hg lost to the environment (Castilhos et al., 2015; Cordy et al., 2011; Gerson et al., 2022; Veiga & Gunson, 2020). Environmental problems in mining operations occur mainly because of inappropriate mining practices and rehabilitation measures (Kamga et al., 2018; Malehase et al., 2017). Environmental pollution is mainly controlled by the release of harmful elements from tailings and other mine wastes, resulting in the formation of acid mine drainage from water infiltration through sulfide-rich gold mine tailings (Fashola et al., 2016). Other sources include chemical products, such as mercury, used during the separation of gold (Esdaile and Chalker, 2018; Veiga & Gunson, 2020; Nandiyanto et al., 2023), and chemical pollution from heavy-duty excavating machines (Emmanuel et al., 2018; Mantey et al., 2020; Rakotondrabe et al., 2017, 2018). To quantify, understand, and mitigate the adverse impacts of mineral exploitation requires an understanding of land use and land cover evolution over time (Maus et al., 2022), as mining activities are responsible for major land use and land cover changes, including the conversion of forests to other purposes such as mines and barelands (Gbedzi et al., 2022). The extent of the impacts of ASGM on the environment depends on the type of mining and the area. In the Batouri gold district, there is some mechanization done by small-scale mining companies involved in alluvial gold mining, which uses mercury amalgamation to optimize gold recovery, and artisanal mining, which is mostly manual where individuals rework waste and tailings generated by small-scale companies. Batouri is one of the major gold districts in the eastern region of Cameroon, with more than 2000 miners involved in artisanal and small-scale gold mining (Ralph et al., 2018) and an annual production of 1500 kg of gold (Chupezi et al., 2009). Three important factors are considered in an artisanal and small-scale gold mining environment: external conditions, physical landscape, and the organisms themselves (Drebenstedt, 2008). ASGM operations cause ongoing environmental degradation (deforestation, flooding, and pollution), and nearby communities are subjected to high levels of trace metal contamination, particularly in water resources. Currently, there is insufficient documentation of these effects. The objectives of this study were to measure the concentration of key pollutants in gold mining in the study area, interpolate them to evaluate their spatial distribution vs. concentration, analyze the land use and land cover impacts induced by mining activities over the last 20 years, and identify the environmental impacts of such activities. Attention is drawn to some of these effects, particularly at Kambele and Pater, two principal mining locations within the Batouri gold district. This study provides useful information for the creation of long-term strategies for environmental monitoring and rehabilitation while tracking artisanal and small-scale gold mining sites within Batouri gold district.

Regional geology

Batouri is located within the Adamawa-Yadé Domain (AYD) of the Pan-African fold belt in Cameroon (Fig. 1). The AYD is dominated by 640–610 Ma syn-to-late-collisional high-K calc-alkaline granitoids intruded by high-grade gneisses that represent a Paleoproterozoic basement, most likely dismembered during the Pan-African orogeny (Jean-Claude et al., 2019). Three main groups of rocks are identified along the AYD: metasedimentary rocks (Paleoproterozoic) and orthogenesis (Archean) group, 640–610 Ma syn-to-late-tectonic granitoids of transitional composition and crustal origin group, and 612–600 Ma low- to medium-grade metasedimentary and metavolcaniclastic rocks (Hamdja Ngoniri et al., 2021; Jean-Claude et al., 2019; Tchakounté et al., 2017). The major faults and shear zones within the AYD include the Sanaga fault (SF), Central Cameroon shear zone (CCSZ), and Mayo Nolti shear zone (Ngako et al., 2008).

Methods

Sample collection

Eighteen water samples were collected from the field (Fig. 2). Samples were collected from two main mining areas: Pater and Kambele. At both sites, samples were collected from surface water at active mine sites, principally at point sources and abandoned mine sites and rivers, washing points, and panning sites. At any point where samples were collected, geographical coordinates (longitude, latitude, and

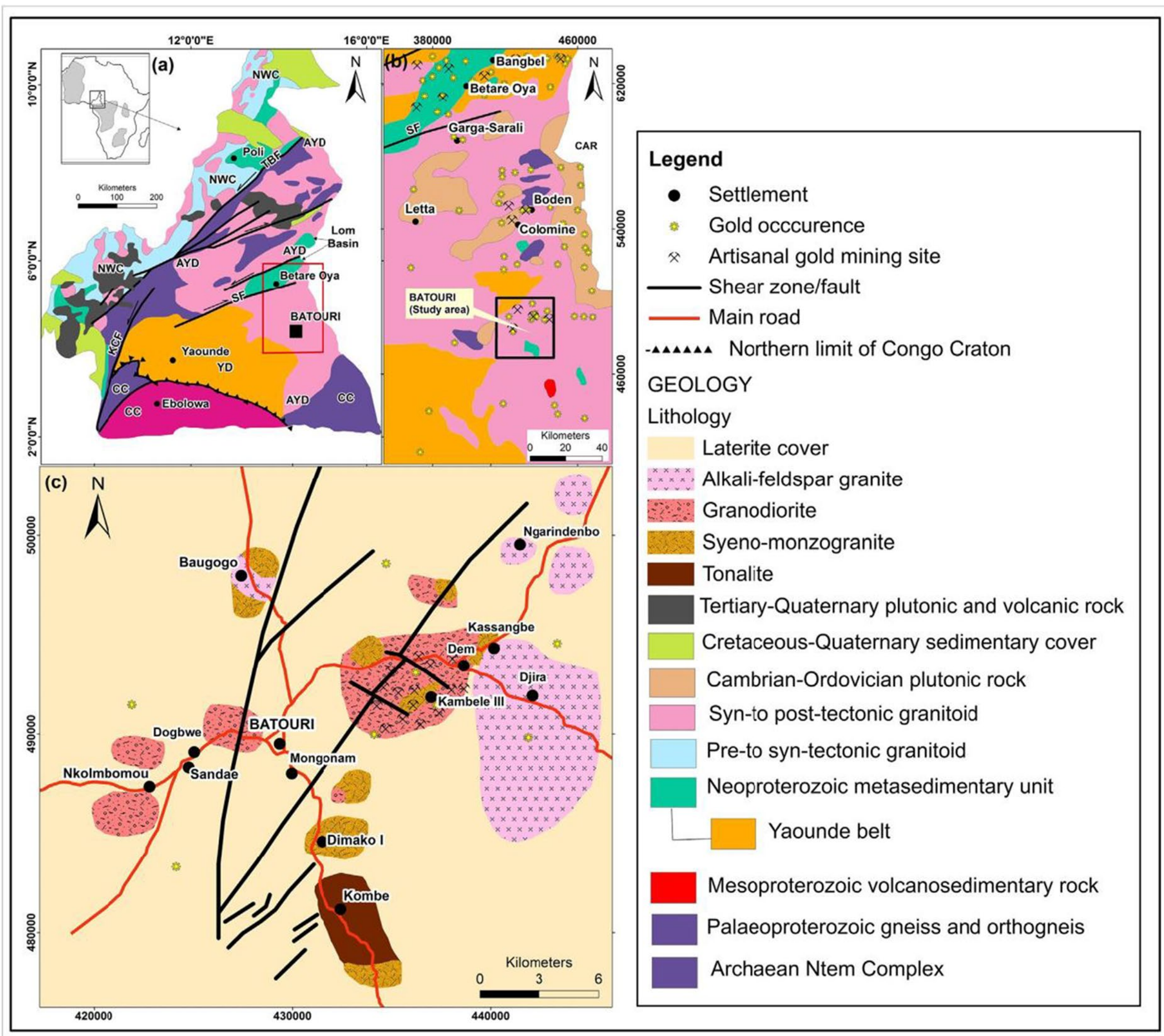

Fig. 1 Geology of Cameroon. (**a**) Main geological subdivisions of Cameroon, (**b**) Regional geology of east Cameroon, and (**c**) Geologic map of Batouri (Vishiti et al., 2015)

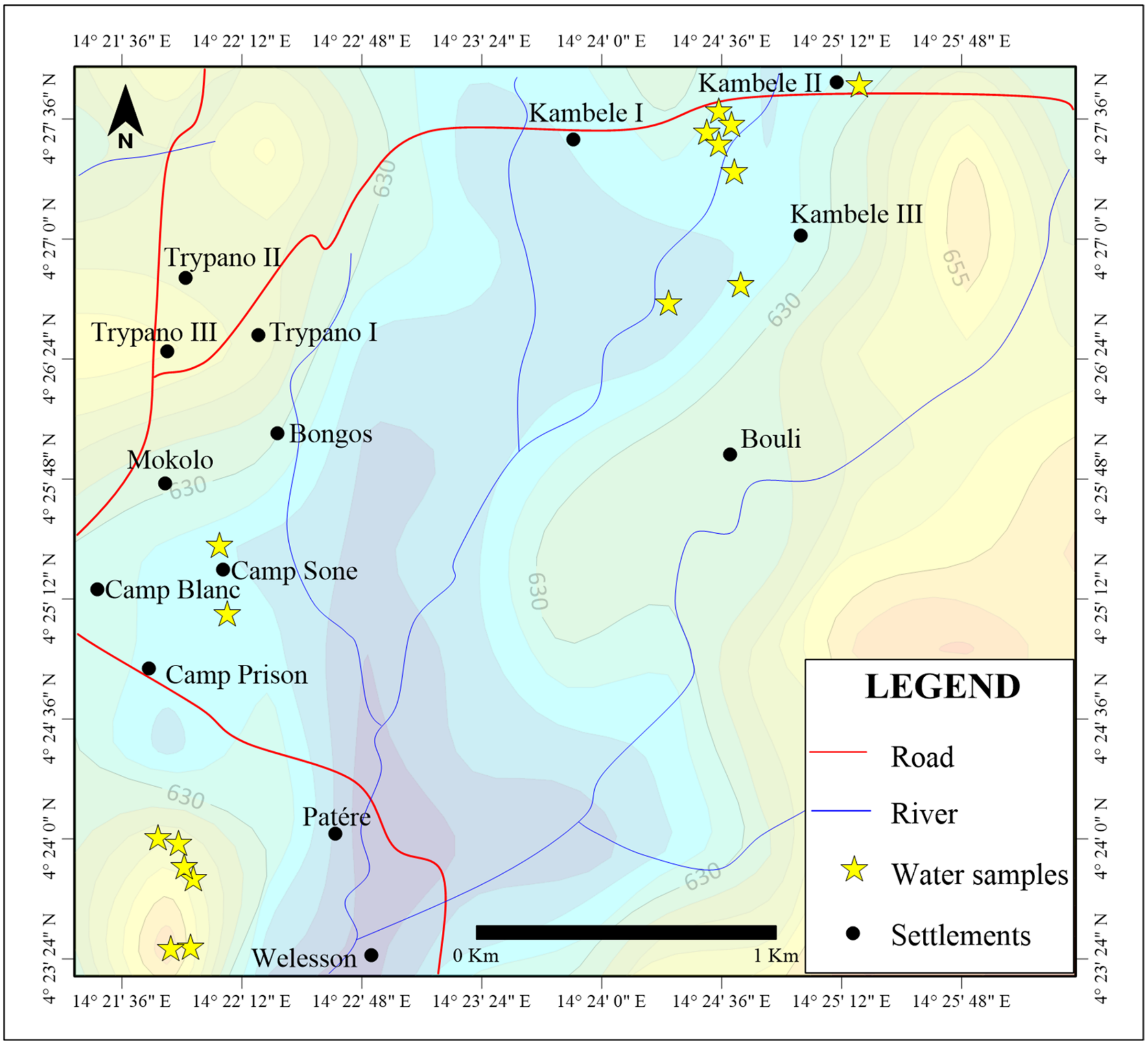

Fig. 2 Sample location points in the study area

elevation) were obtained using GPS. The samples were filtered on-site through filters on acetate cellulose 0.45 µm in 0.33L polyethylene bottle and immediately acidified to pH < 2 with ultrapure nitric acid. They were then labeled using a marker and wooden sill tape. All samples were stored in an ice chest at a temperature of less than 4 °C to prevent the breakdown of contaminants. They were then transported to the laboratory and analyzed within ten days. The environmental changes resulting from artisanal mining activities in the study area, such as deforestation, pitting, rockfalls, flooding, water pollution, and soil degradation, were noted at each sample site.

Laboratory analysis

Trace metal analysis was carried out at the Soil and Water Laboratory, University of Dschang, using atomic absorption spectrometry (AAS). The apparatus used was a Buck Scientific Atomic Absorption Spectrometer 205. The trace metals analyzed were arsenic, lead, mercury, and cyanide. The standards were prepared from the commercial solution at 1000 ppm in the following proportions (0, 2, 4, and 8 ppm) for As, (0, 2.5, 5, 7.5 ppm) for Pb, (0, 0.03, 0.1, 0.20 ppm) for CN, (0, 0.03, 0.06, 0.12 ppm) for Hg, and read directly on the AAS. This was followed by the samples. This enabled measurement of the absorptance of each standard of the calibration curve and the samples. The concentration of each sample was obtained using linear regression of the concentrations compared to the absorptance of the standards. The calibration curve and calculation of the concentrations, expressed in µg/L, were established using Excel software.

Geo-statistical modeling of trace metal pollutants in water

Environmental impacts were modeled using the results of the laboratory analysis of trace metals in water samples to predict trace metals at non-sample location sites. The results were combined with spatial analysis to make the interpolation (geostatistics) more accurate. Geo-statistics is a set of tools and models developed for the statistical analysis of continuous data. These data can be measured at any location in space; however, they are available on a limited number of sample points. Geostatistics is applied in various branches of geography, particularly those involving the spread of pollutants and diseases. Geostatistical algorithms have been incorporated in many places, including geographic information systems (GIS) and the R statistical environment. The values at unmeasured locations were calculated using the kriging method. The Kriging method was used to produce surface maps of the predicted values. Water sample parameters were interpolated using geostatistical methods. A geostatistical interpolation model consists of statistical models based on autocorrelation. The geostatistical method assumes that at least some spatial variations in natural phenomena can be modeled by random processes with spatial autocorrelation. The geostatistics technique was used to (i) predict values at non-sampled locations, (ii) assess the uncertainty associated with the predicted values, and (iii) model the spatial patterns.

Ecological risk assessment and potential ecological risk factor

Ecological Risk Assessment (Er) and Risk Index (RI) were used to assess the ecological risks of trace metals in water. The ecological risk factor quantitatively expresses the potential ecological risk of a given contaminant using the following:

$$\mathrm{Erf} = \mathrm{Tr} * \mathrm{CF}$$

where Tr is the toxic response factor for a given substance (Tr for Pb, As, Hg, and CN are 10, 40, 5, and 10, respectively), CF is the contamination factor, and CF = Concentration of heavy metals in the water/concentration of the background (Ouabo et al., 2019).

Landsat 7 ETM + of 2002 and Landsat 8 images of 2022, were used for mapping land use and land cover, followed by image pre-processing, enhancement, transformation, and classification. The images were collected during the dry season (December and January). The same multispectral bands were used for both images. Finally, several indices were calculated: Normalized Difference Built-up Index (NDBI), Difference Vegetation Index (DVI), Normalized Difference Water Index (NDWI), and Soil Adjusted Vegetation Index (SAVI) to improve the accuracy of the classification algorithms. Indices enhance the spectral information and increase the separability of the classes of interest. All of these factors increased the quality of the land use land cover maps produced.

Results

Trace metals

The concentrations of the analyzed trace elements are listed in Table 1. The concentrations of Hg and Pb were found to be far greater than the European directives (2000) and World Health Organization (WHO, 2011) pollution guidelines (Hg < 1 µg/L and Pb < 10 µg/L), whereas the concentrations of cyanide and arsenic were below both the European directives (2000) and WHO (2011) pollution guidelines (CN < 50 µg/L and As < 10 µg/L). The order of abundance of trace metals was Hg > Pb > CN > As.

Mercury levels exceeded the WHO guidelines for drinking water (Table 1). The highest value is 5550.38 µg/L and the lowest value obtained is 102.64 µg/L which is still very far above the European directives (2000) and WHO (2011) standard (< 1 µg/L) for potable water. The mean (738) and median (427) values were similar, indicating a symmetrical (normal) distribution. The skewness value

Table 1 Laboratory results of the trace metal analysis

Sample	Hg(μg/L)	Pb(μg/L)	CN(μg/L)	As(μg/L)
MWT1	194.05	466.20	5.42	0.22
MWT2	504.83	1554	4.55	0.12
MWT3	322.02	492.10	3.45	0.32
MWT4	5550.38	2072	28.45	0.42
MWT5	925.29	440.30	2.15	0.32
MWT6	462.78	1554.00	3.33	0.12
MWT7	477.40	440.30	8.45	0.2
MWT8	236.09	518.00	1.59	0.28
WT1	395.14	440.30	1.45	0.25
WT2	925.29	466.20	2.22	0.23
WT3	440.84	362.60	7.28	0.20
WT4	651.07	336.70	10.35	0.32
WT5	358.58	440.30	8.35	0.28
WT6	577.95	1813.0	5.23	0.23
WT7	413.42	440.30	2.47	0.22
WT8	358.58	440.30	7.28	0.12
WT9	102.64	440.30	4.38	0.27
WT10	395.14	1554.0	2.75	0.21
European Directives (2000)	< 1	< 10	< 50	< 10
World Health Organization (2011)	< 1	< 10	< 70	< 10

(4.03) also indicates that the data are normally distributed because they are neither skewed to the left nor the right (Table 2).

Voronoi maps of trace metals were produced to show the geometric representation of spatial proximity and partitioning, which divides our study area into regions based on the closest proximity to the set of predefined points known as samples in this case. These points represent the water samples with geographic coordinates. Voronoi maps were created by drawing perpendicular bisectors between each pair of adjacent samples, thus creating a polygon that enclosed the space closest to each sample. The Voronoi map for Hg shows that the area is highly polluted (Fig. 3), with higher values found around the active mine sites.

Pb values were found to be greater than the European directives (2000) and WHO (2011) guidelines for drinking water in all samples. The highest concentration was 5550 μg/L, and the lowest concentration was 336.7 μg/L. The values of the mean (793), median (453), and skewness (1.21) indicate a normal distribution (Table 2). The study area is highly polluted with Pb, as shown in Fig. 4.

The studied samples contained cyanide, but were below the European directives (2000) and WHO (2011) guidelines for drinking water. The frequency distribution of the data is normal, with minimum and maximum values ranging from 1.45 to 28.45, and a standard deviation of 3.05 (low). The median (4.46), mean (6.06), and skewness (3.05) indicate a normal distribution, as shown in Table 2. The contamination level increases from top to bottom, as shown in Fig. 5. The spread decreases as one moves away from heavily contaminated areas.

The concentrations of arsenic obtained were all below the European standard of pollution, which is < 10 μg/L, and the WHO (2011) guidelines for drinking water. The slight discrepancy between the maximum value (0.42) and minimum value (0.12) indicated that the distribution of the data was normal. Additionally, the low standard deviation (0.28) indicated that there were no outliers (Table 2). The contamination level increased from top to bottom, as shown by the values at the right corner of the study area (Fig. 6).

Ecological risk assessment and potential ecological risk factor

The results of the ecological risk assessment and risk index of heavy metals show a mean ecological risk for all elements of 3692, 792.8, 0.86, and 0.96 for Hg, Pb, CN, and As, respectively, with a mean potential

Table 2 Statistical summary of trace element distribution in the Batouri gold district

	Min	Max	Mean	Median	Std Dev	Skewness
Hg	103	5550	738	427	1220	4.03
Pb	337	2072	793	453	597	1.21
CN	1.45	28.45	6.06	4.46	6.18	3.05
As	0.12	0.42	0.2406	0.23	0.0783	0.28

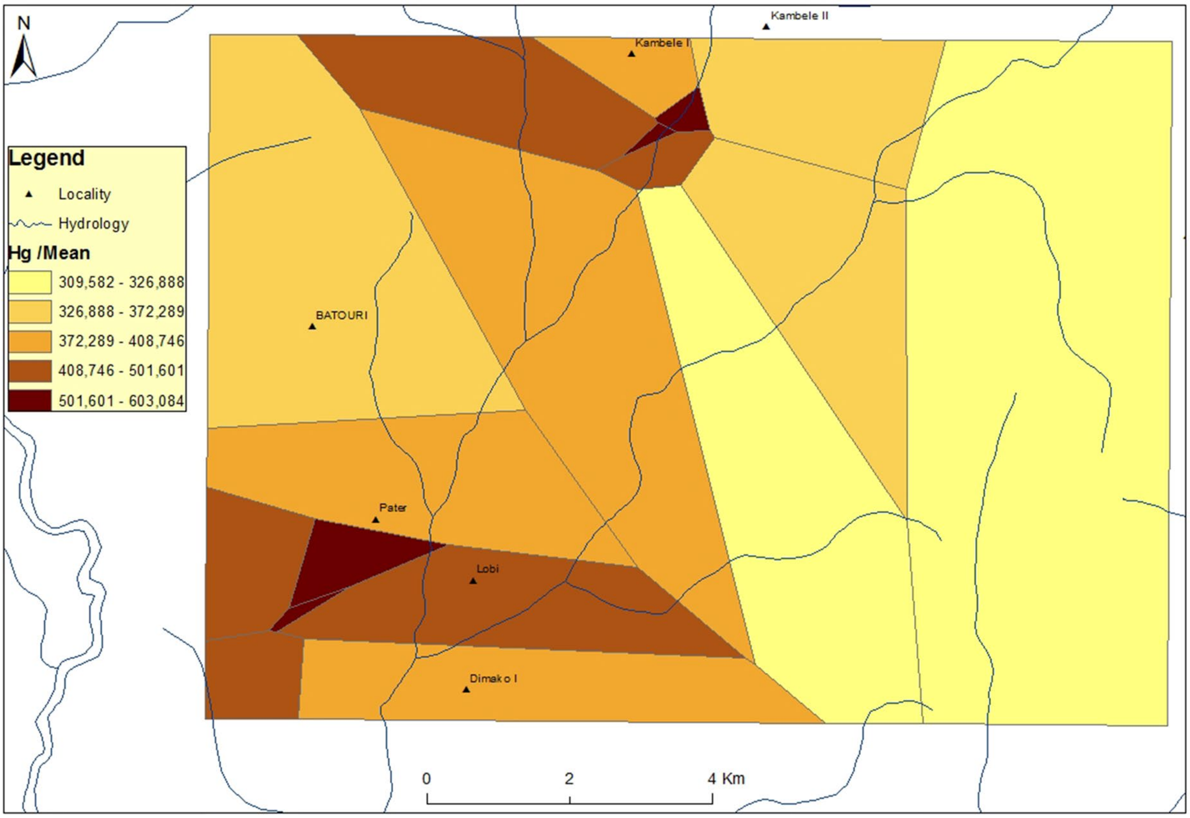

Fig. 3 Voronoi map showing the spatial distribution of Mercury in the study area

ecological risk index (4486.74). This result shows that the area has a low environmental risk factor (Er < 40) with respect to CN and As, and a very high environmental risk factor for Hg and Pb (Er > 320). The mean potential ecological risk index value of 4486.74 (PERI > 600) indicates the study area is at a very high potential ecological risk (Hakanson, 1980). Ordinary kriging applied to pollutant concentrations showed a potential distribution of these pollutants based on the ecological risk factor and their spatial distribution.

Land use and land cover

Six classes were considered: water, built-up areas, fallow farming, mature savannah forests, young savannah forests, and bare ground (Fig. 7). Figure 8 shows the change detection from 2002 to 2022 associated with these classes. Notably, there is an area that has not witnessed any changes from to 2002–2022. An increase in built-up areas from 2002 to 2020, as shown in Figs. 7a and b, is associated with mining activities, as mining entails the development of mine sites and facilities, such as markets, schools, mining accommodation centers, hospitals, playgrounds, and construction of roads. In addition, bare land has increased because most of the forest has been cleared for mining purposes, and these sites are not rehabilitated after mining. A decrease in both young and mature savanna forest land is associated with mining activities, and a decrease in the area occupied by water as mining activities have destroyed forests that harbor most of the water sources in the area.

Indices of land use and land cover over time

Changes using normalize difference built-up index in batouri (NDBI)

This index indicates urban areas that usually have higher shortwave infrared (SWIR) reflectance than near-infrared (NIR) reflectance. The applicability of

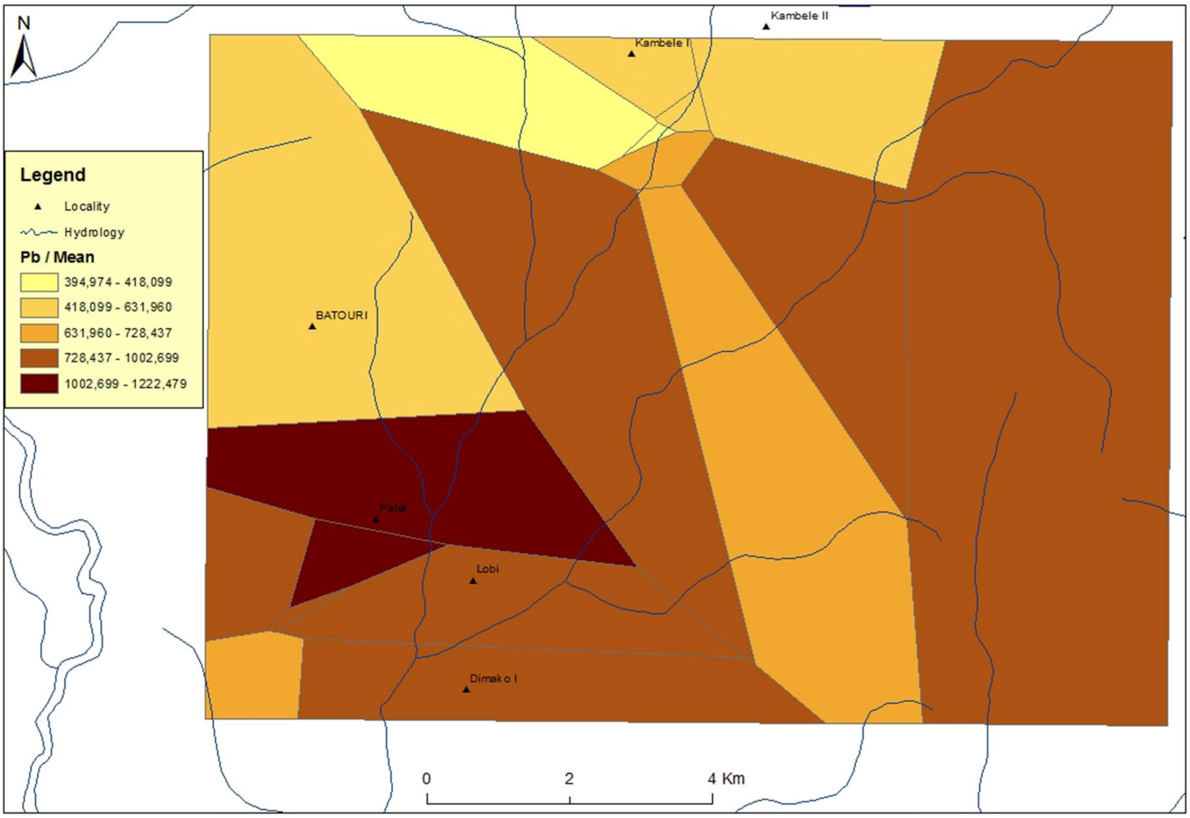

Fig. 4 Voronoi map showing the spatial distribution of Lead in the study area

this study focused mostly on land use planning. The NIR and SWIR bands were used by the Normalized Difference Built-up Index (NDBI) to highlight industrially constructed built-up areas. Built-ups are highlighted between values of 0.024–0.15 and show a clear progression of built-up areas between 2002 and 2022 (Fig. 9). It is also interesting to note that the same index provides critical information about vegetation quality evolution over the same period, with a value of -0.25 in 2022 rather than -0.38 in 2002. Therefore, there is a need to adapt the land planning evolution to mining activities in the study area.

Changes using the difference vegetation index (DVI) in Batouri

The DVI calculated in Batouri is sensitive to the amount of vegetation in the study area. As shown in the image, the study area is less occupied by vegetation in 2022 than in 2002 (Fig. 10). This is explained by the fact that the forest and vegetation have been cleared not only for mining and building purposes but also for farms. All values between -880 and 0 represent built-up water and bare soil. However, it is important to identify the image areas that are bare soil or abandoned, but with values that are lower because of the dry season when the image was collected. The difference between the vegetation and soil is distinctly visible in the index image because the soil presents a high spectral response in the NIR and Red bands. However, the reflectance and radiance caused by the atmosphere or shadows are not taken into consideration by this index because it does not compute that aspect very well during the process.

Changes using normalize difference water index in batouri (NDWI)

The Normalized Difference Water Index (NDWI) measures the change in water content of leaves using the NIR and SWIR bands. Because NDWI is sensitive to the water content of plants as well as

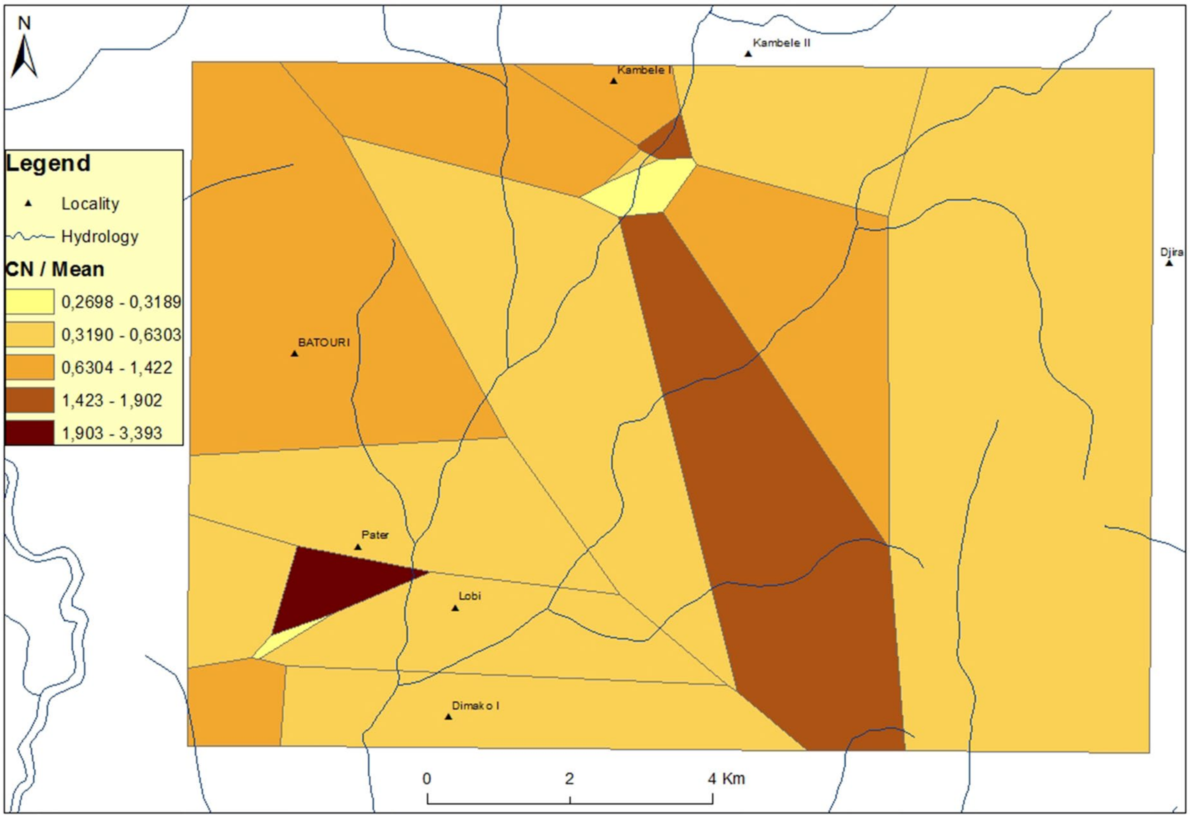

Fig. 5 Voronoi map showing the spatial distribution of Cyanide in the study area

bodies of water, it is often used for drought monitoring, recording yield reductions, reservoir discharge, and lowering groundwater levels. The values for the water bodies were larger than -0.5. Vegetation had much smaller values, making it easier to distinguish between vegetation and water bodies. The built-up features had positive values between zero and 0.24. Therefore, water bodies have been facing stress over the years due to ongoing human activities in the area, coupled with climate change (Fig. 11).

Changes using soil adjusted vegetation index in batouri (SAVI)

The soil-adjusted vegetation index (SAVI) was proposed by Huete (1988). It is aimed at minimizing the soil influence on vegetation quantification by introducing the soil adjustment factor L. For high vegetation cover the value of L is 0.0 (or 0.23), and for low vegetation cover 1.0. For intermediate vegetation cover, L = 0.5, this value is the most widely used. As can be seen in Fig. 12, SAVI minimizes soil brightness, indicating that the soil background has less effect on the extraction of vegetation information. By looking at the value of SAVI of the study area, it can be concluded that it is an intermediate vegetation density, which is characteristic of an area that is facing an expansion of farmland, and human activities such as mining, based on the fact that it is a tropical rainforest zone. It can also be noticed that in all the areas with a value equal to or greater than 0.5 (2002), SAVI has successfully minimized the effect of soil variations on green vegetation compared to DVI. Therefore, it can be concluded that farmland and its associated human activities occupy a large part of the study area.

Environmental Changes

Deforestation

Two types of forest were identified within the study area: mature savannah forest and young savannah

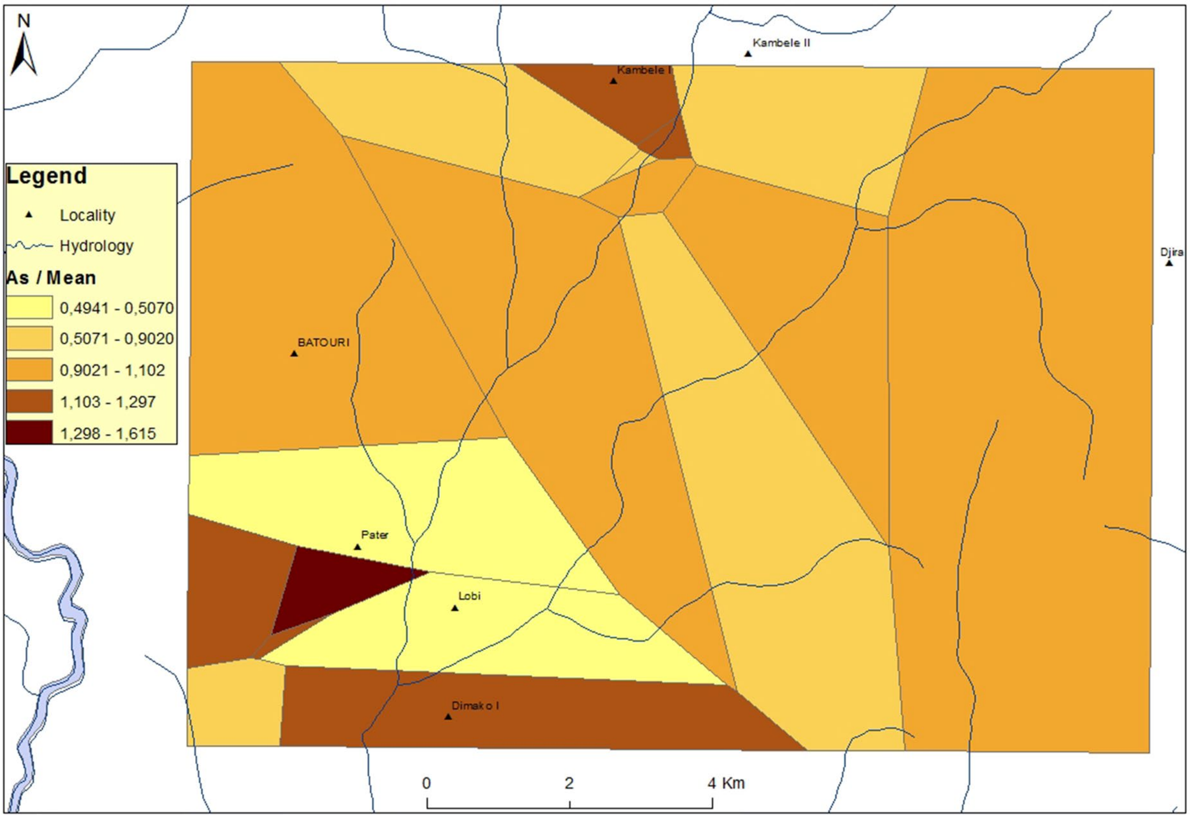

Fig. 6 Voronoi map showing the spatial distribution of Arsenic in the study area

forest. Between 2002 and 2022, 14.737 forest lands were cleared down. The vegetation of the Batouri gold district consists mainly of forest, which is part of the Congo basin rainforest, the second largest tropical rainforest in the world. Due to uncontrolled mining activities in this area, most of the forest has been cut down in search of precious gold metal (Figs. 13a and b), construction of mining `accommodation camps (Fig. 13c) and roads. Similarly, deforestation here is a result of the effects of chemical pollutants on trees from mine tailings and flooded water, resulting in them drying up due to the effect of chemical pollution from the flood on trees, as shown in Fig. 13d.

Soil degradation

Apart from trace metal contamination, uncontrolled mining also has an inverse effect on the soil. Open pit mining involves the use of heavy-duty machines in search of precious gold metal at depth; soils that are excavated above the alluvial gold deposit are deposited without any protective measures to be used during rehabilitation (Figs. 14a and b). Flooding from the water used during the mining process washed away the topsoil (Figs. 14c and d), which is essential for agriculture. This seriously affects plant growth, leading to extreme hunger and poverty in the area as people depend so much on agriculture, as observed in Ghana by Agariga et al. (2021).

Flood and water pollution

Water pollution is a major environmental problem in the study area, because it's poorly managed in the study area it causes a lot of environmental and health problems. Water is mostly used during the separation of gold from the ore and the winning process. Most small-scale mining companies carry out gold washing (separation from tailings) in the main river channels, which results in mercury pollution. These companies also dredged sediments along the river channels,

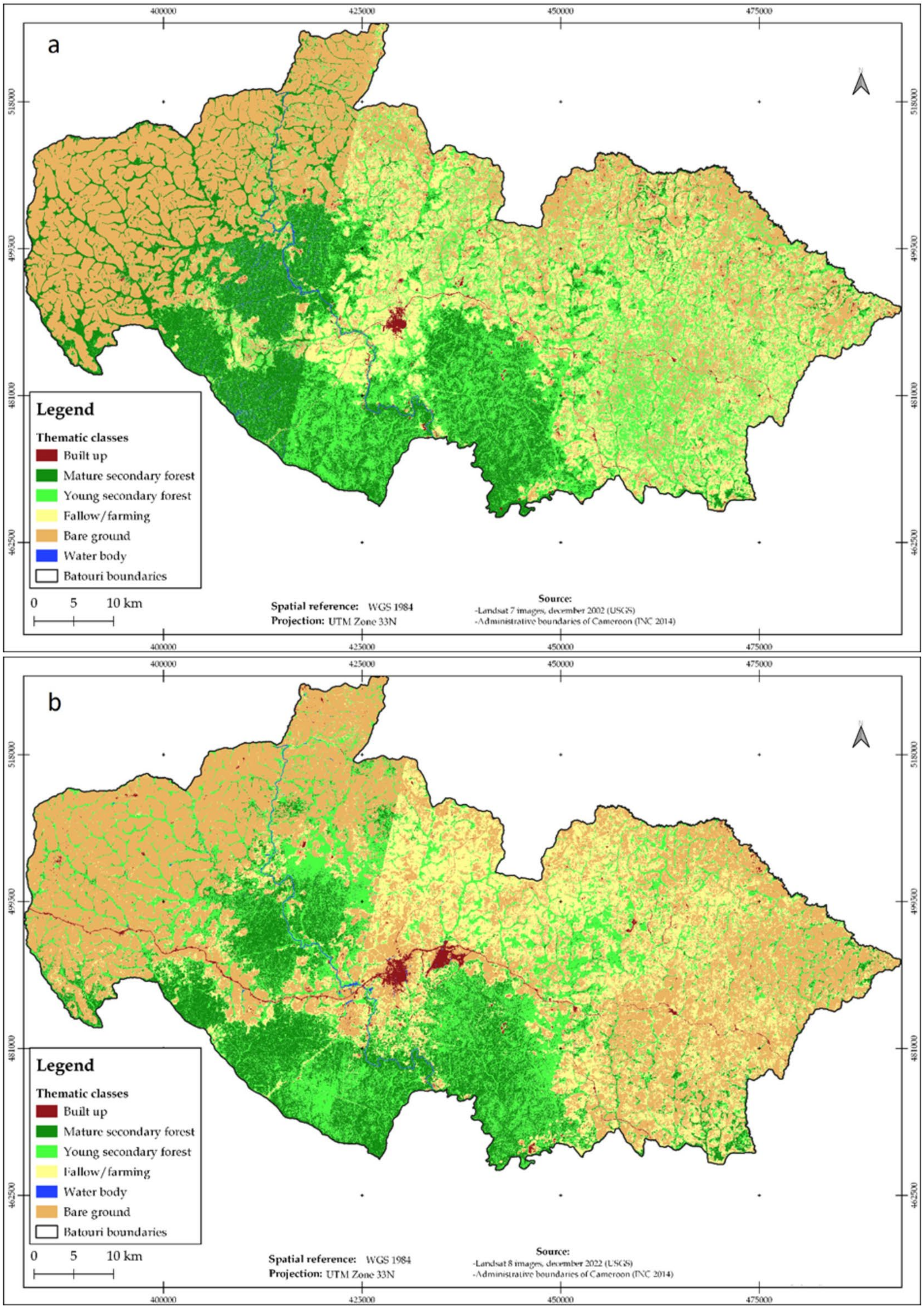

Fig. 7 Changes in the thematic classes from 2002 (**a**)—2022 (**b**) within Batouri

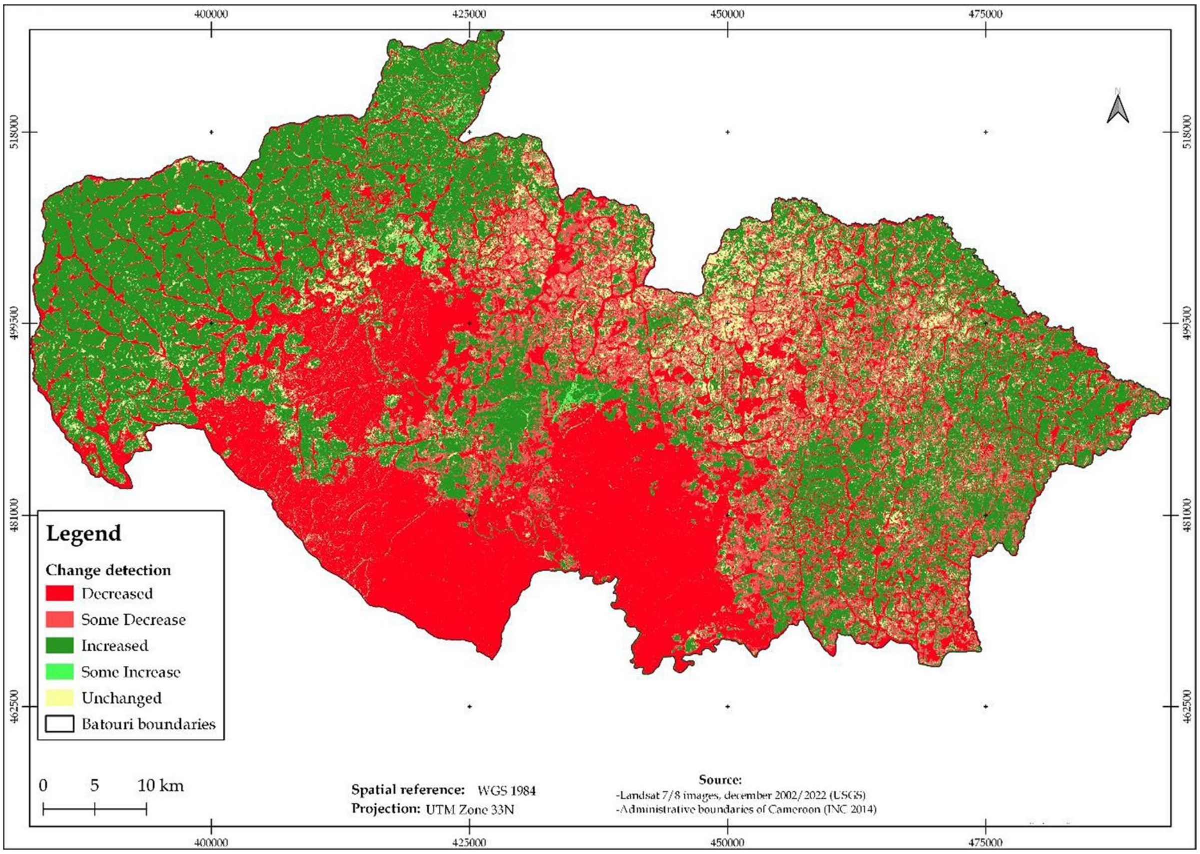

Fig. 8 Areas under change in the Batouri district from 2002–2022

causing flooding of the surrounding environment. Water pollution and flooding have adverse effects on the soil and forest, which explains why most trees in the flooded area are almost dead wood (Fig. 15a). As a result of mining activities along the river channels, most rivers in the study area permanently changed their color to red, as shown in Fig. 15b. Based on the results of the sample analysis, the water in all mining working sites was heavily polluted. A flooded environment is a breathing ground for mosquitoes, which accounts for the high rate of malaria in the study area, as reported by Ralph et al., (2018).

Mine pits

Pits are holes formed as a result of the removal of the overburden load above gold ore deposits. Most of these holes are filled with rainwater, forming artificial lakes that increase in size with time. 67 rehabilitated pits were observed, with an average debt of 3.2 m filled with water. The reddish color of the water, as seen in Fig. 16a, is due to the dissolution of laterite, whereas pits filled with green water, as seen in Fig. 16b, indicate the presence of algae. Between 2014 and 2016, FODER (Forest and Rural Development) reported more than 250 rehabilitated mining pits left by 65 companies that mined gold in the East and Adamawa regions of Cameroon. It was equally observed that most inhabitants bathed in these pits which explain the prevalence of skin diseases among miners and stakeholders in the study area reported by Ralph et al., 2018. These pits are found in the vicinity of the community, which could result in death through drowning when someone falls into the abandoned pits.

Rockfalls

Rockfall is common in both active and abandoned mines. Seven people were reported killed in an

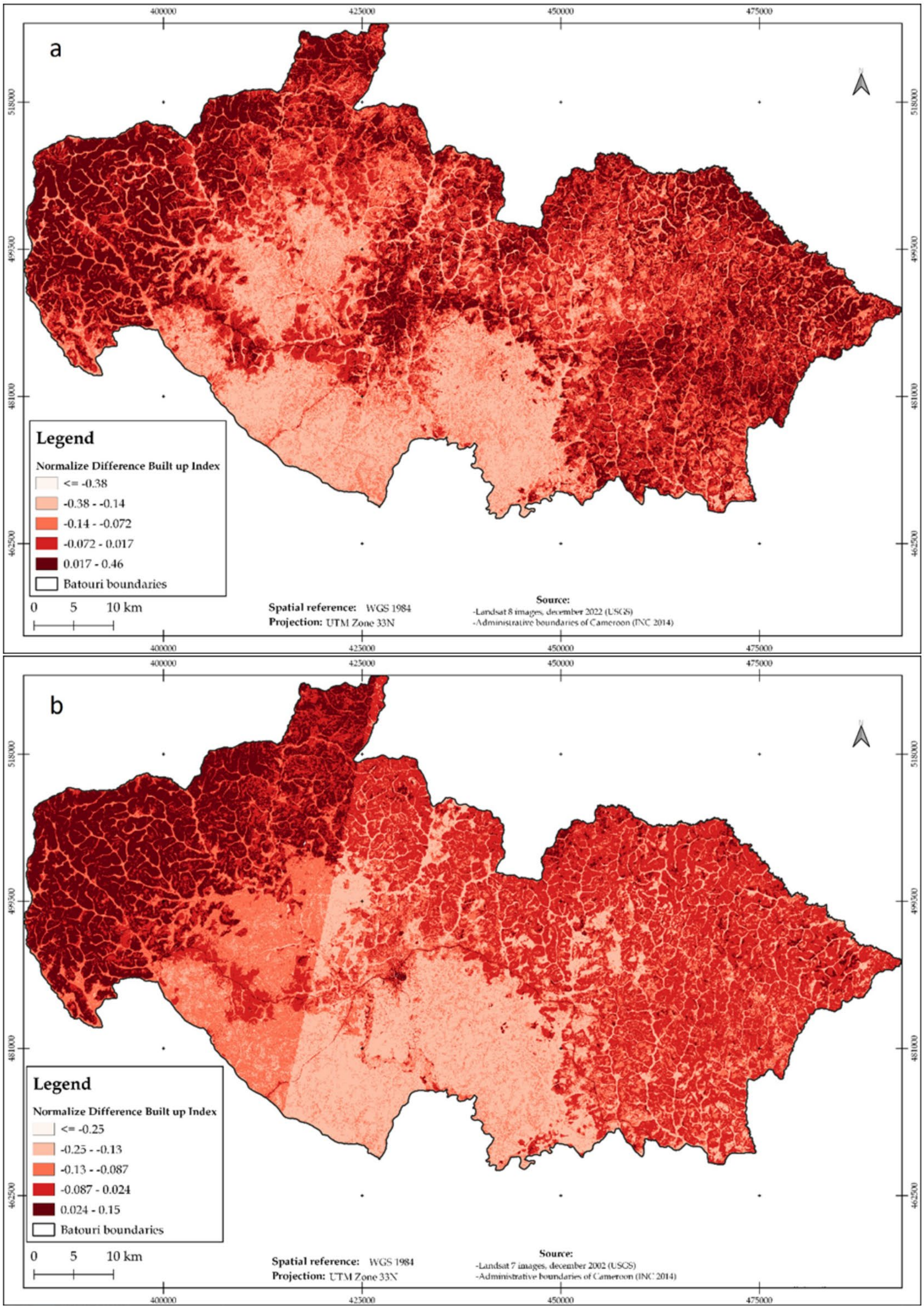

Fig. 9 Changes in normalize difference built up index from 2002 (**a**)-2022(**b**) within Batouri

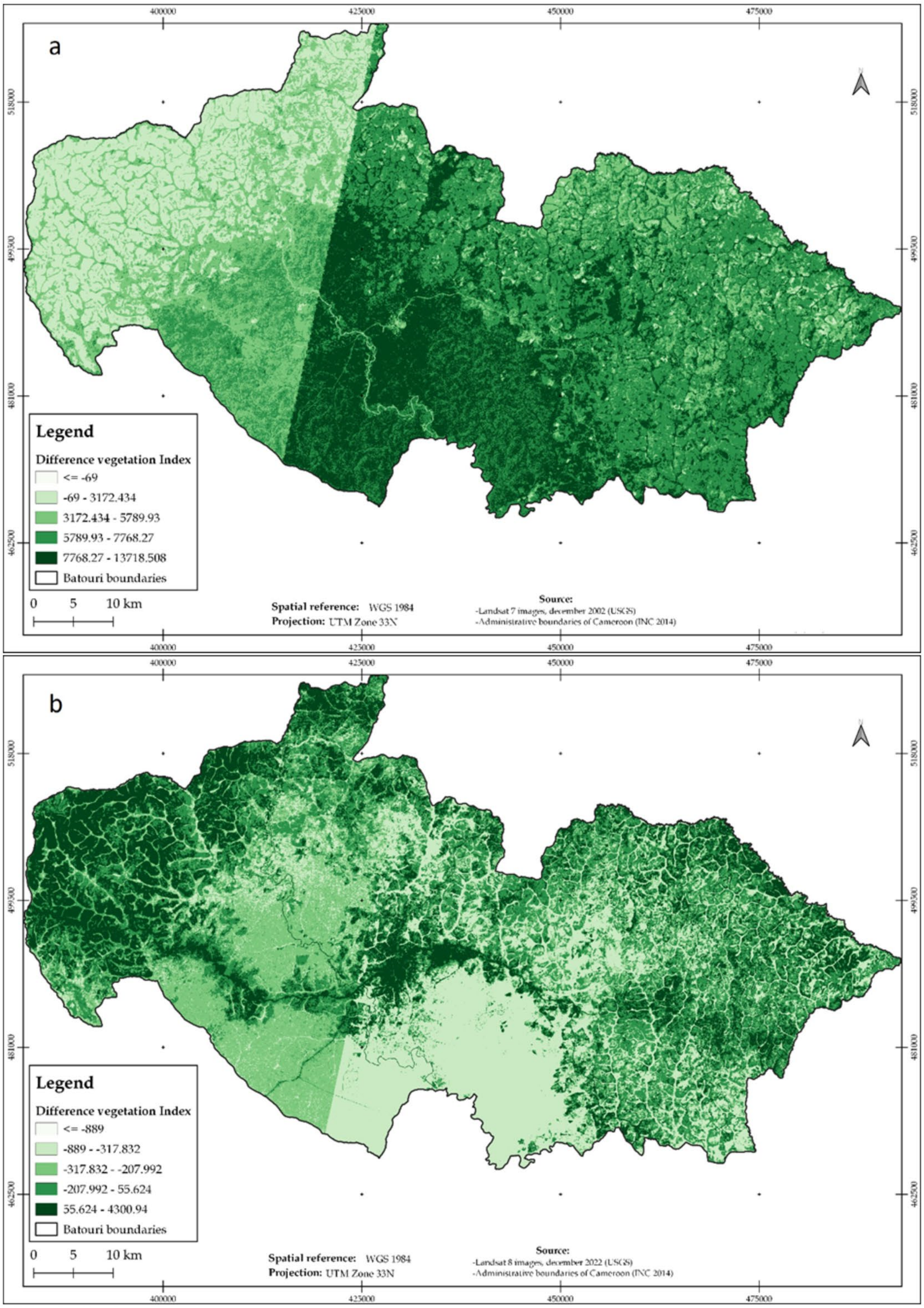

Fig. 10 Difference Vegetation index from 2002(**a**)-2022(**b**) within Batouri

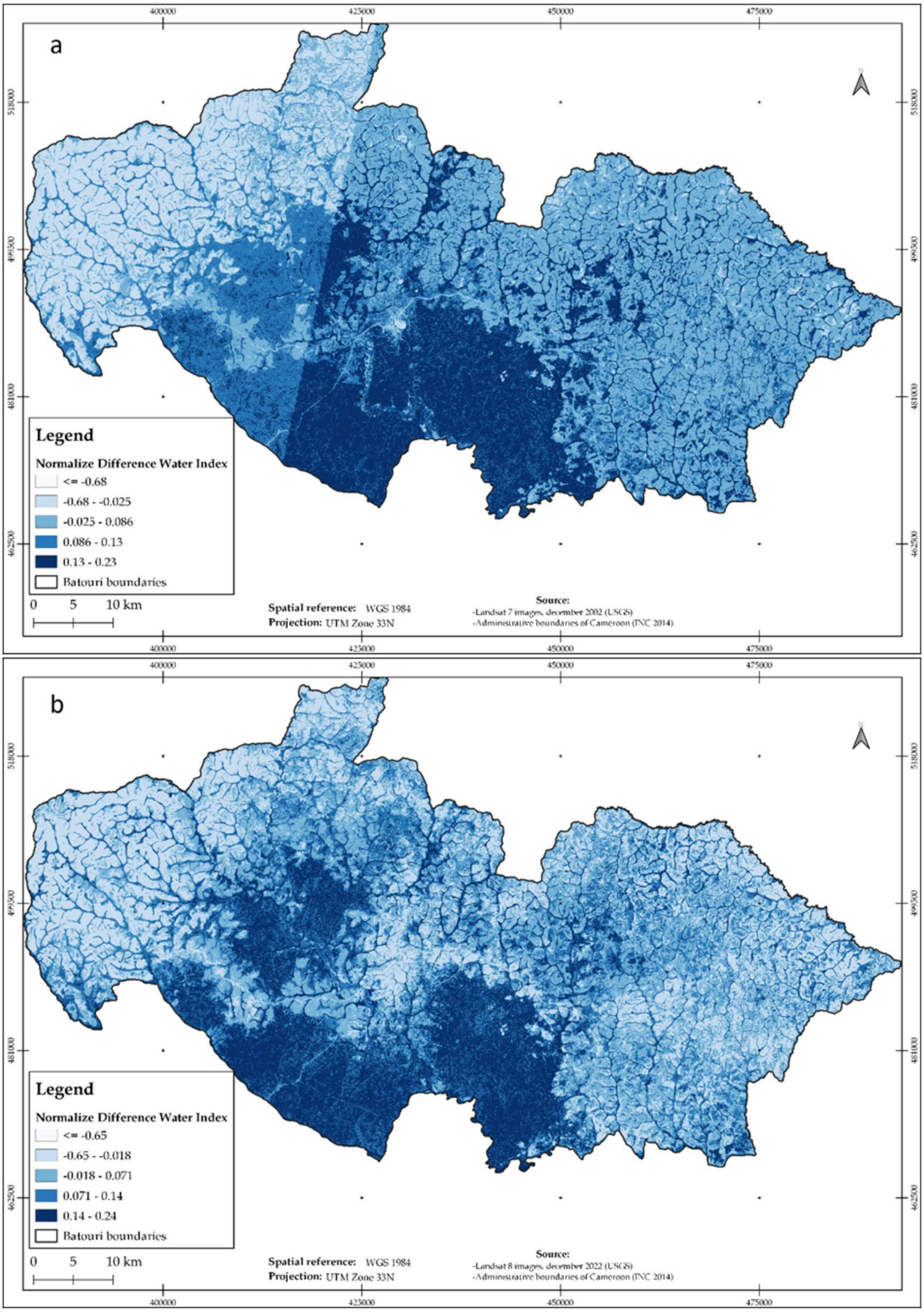

Fig. 11 Changes in the Normalized difference water index from 2002(**a**) -2022(**b**) within Batouri

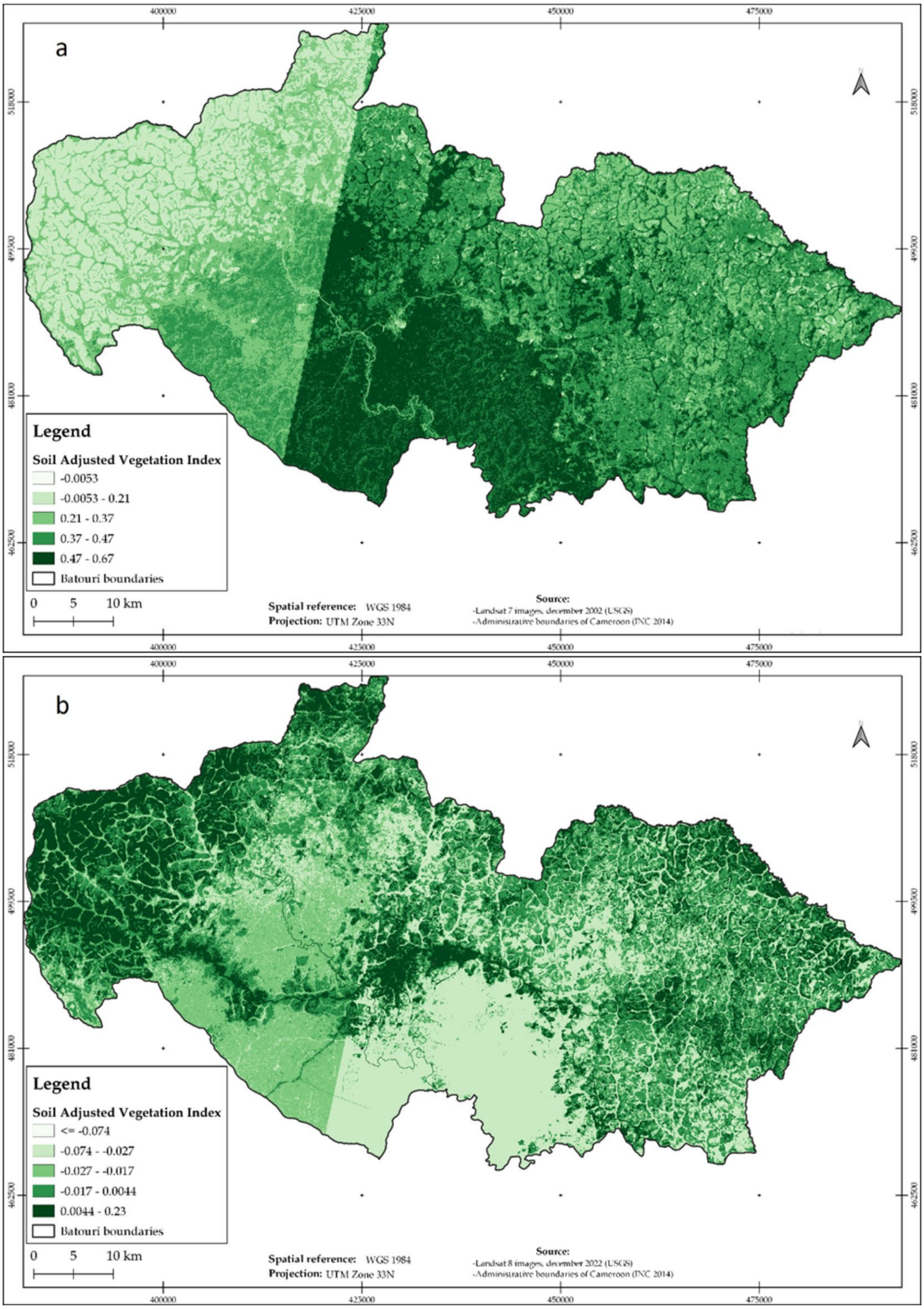

Fig. 12 Changes in soil-adjusted vegetation index from 2002(**a**)-2022(**b**) within Batouri

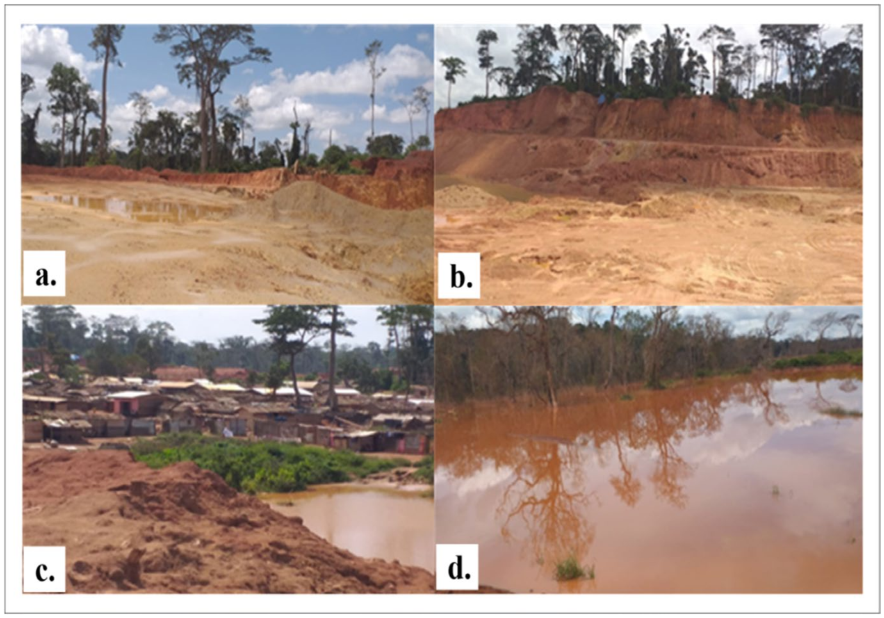

Fig. 13 **a** & **b**) Deforested area during mining activities **c**) Developed mining camp and market, and **d**) Forest area gradually drying up due to pollution from flooded water in Kambele

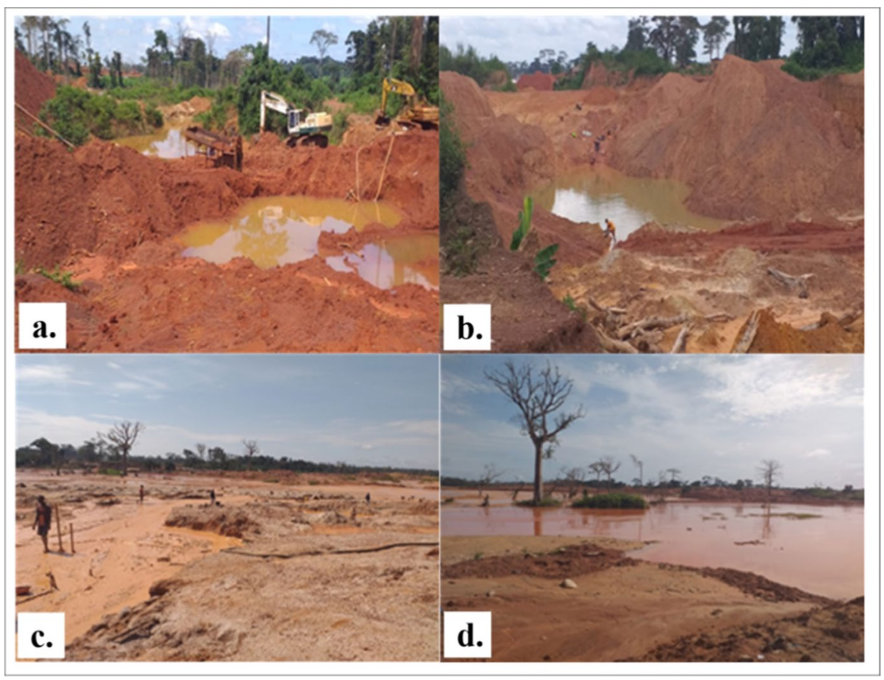

Fig. 14 **a**, **b**) Excavated farmlands, and **c**, **d**) flooded topsoil exposed to pollution in Kambele

abandoned gold mining hole on April 20, 2021, in Malewa and Betaré Oya in the Lom and Djerem division of East Cameroon (InfoCONGO, 2021). Figure 17 shows a collapsed wall in an abandoned mine in a neighborhood surrounded by many houses, exposing the occupants to risk.

Discussion

Trace metal content

The abundance of trace elements was in the order Hg > Pb > CN > As. The measured values of trace elements indicate that the waters in the study area are

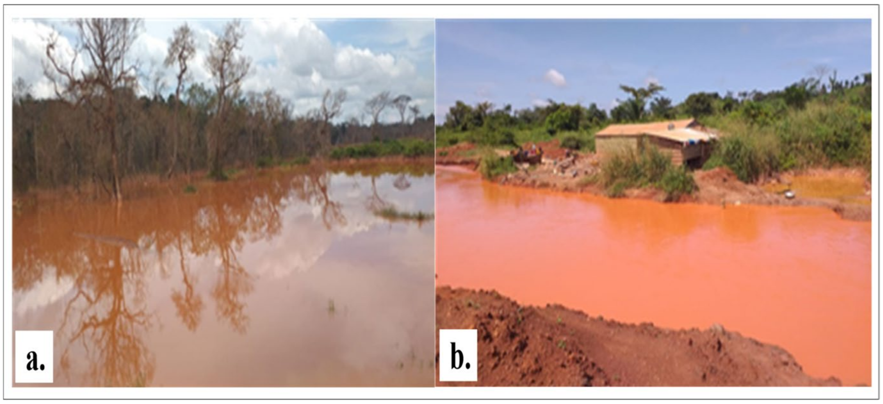

Fig. 15 **a**) Disappearing vegetation due to flood from mining activities, and **b**) River color change as a result of pollution in Kambele

highly polluted and unsuitable for human use. Similar results to those observed in this study were obtained by Rakotondrabe et al. (2017), who determined the concentrations of eight trace metals (Pb, Cd, As, Zn, Cu, Cr, Mn, and Fe) and CN^{-} in the Betare-Oya gold mining area of eastern Cameroon. These findings were similar to those of Porgo and Gokyay (2017), who studied the environmental impacts of gold mining in Essakane, Burkina Faso. According to their findings, the order of abundance of the trace elements was Fe > Mn > Pb > Cr > Cu > Zn > Cd > As > CN, with As, Cu, Zn, and CN not exceeding the WHO (2011) guidelines for water intended for human consumption. Apart from mercury, which they did not consider in their analysis, Pb exceeded the WHO (2011) guidelines for water intended for human consumption.

The mercury concentration was similar to that reported by Appleton et al. (2001), who worked on fluvial contamination associated with artisanal gold mining sites in Ecuador, and Umbangtalad et al. (2007), who assessed Hg contamination and exposure to miners and schoolchildren at a small-scale gold mining and recovery operation in Thailand. Ralph et al., (2018) analyzed mercury from blood samples of miners in the study area and the mean blood mercury concentration among miners was 2.27 ± 8.58 µg/L ($n = 44$) which is slightly higher than 2 µg/L for unexposed individuals, and less than the occupational toxic threshold of 10 µg/L according to center for disease control and prevention. The high values of mercury in the study area are due to the use of mercury for gold amalgamation during the separation of gold from tailings by small-scale mining companies. Sample MWT4 with the highest value was obtained from a river channel where separation of gold from the tailings (gold washing pool) was carried out by small-scale mining companies (semi-mechanized mining companies). The second-highest values, WT2 and MWT5, were recorded at gold washing points involving artisanal miners. Since the artisanal mining of gold in Batouri is poverty-driven,

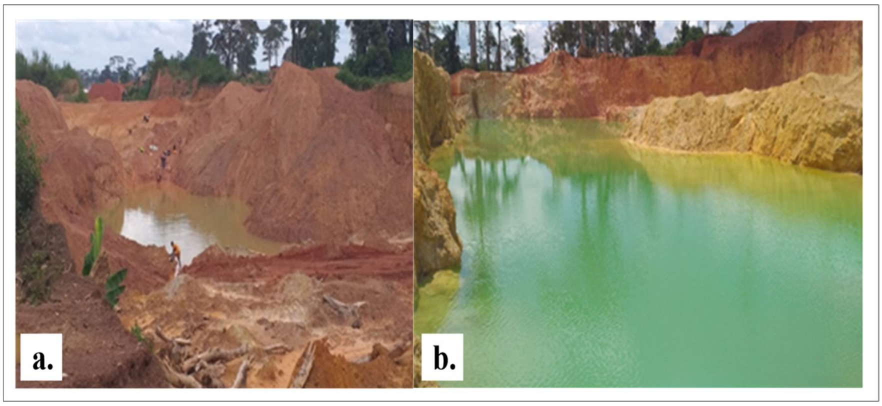

Fig. 16 **a**) Potentially polluted weathered reddish color soil **b**) abandoned mine pit

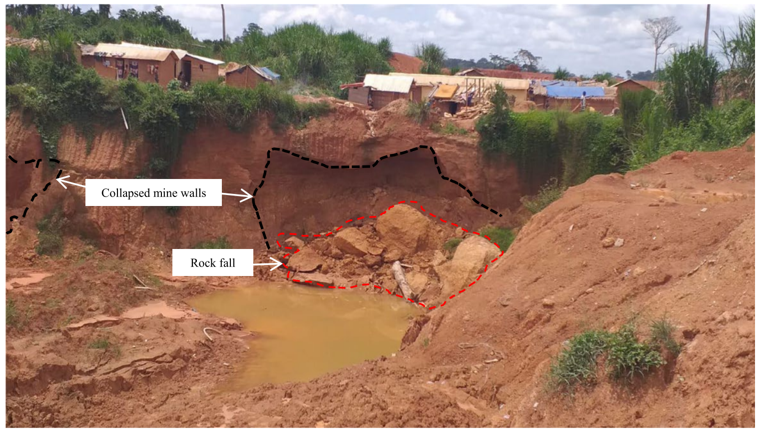

Fig. 17 Collapsed mine wall exposing neighboring houses to risk

artisanal miners depend heavily on small-scale miners for mercury.

In the study area, sample MWT4, which had the highest Pb value, was obtained from the gold washing pool of a small-scale company. Other samples (MWT2, MWT6, WT6, and WT10) with high Pb values were obtained from the panning sites. This high concentration of Pb possibly resulted from leaching associated with galena from the tailings during the washing process. Similar findings were obtained from Betare-Oya (Rakotondrabe et al., 2017). Ralph et al., (2018) reported on the results of lead analysis from blood samples of miners in the study area with a mean Lead concentration of 12.73 ± 32.73 µg/L which is far less than the toxic threshold of 100 µg/L according to the Center for Disease Control and Prevention.

The samples with the highest CN values included MWT4 and WT4, which were obtained from the gold washing point sites of small-scale companies. Contamination here is believed to have been sourced from heavy-duty machines. Even if the samples are below the pollution level, it could become a problem with time if not mitigated because the contamination source is anthropogenic. Similar results have been reported for the Batare-Oya gold district in the eastern region of Cameroon (Rakotondrabe et al., 2017). Waste soil and rocks, tailings, atmospheric emissions from ore roasting, and leaching due to bacterial amplification are the sources of arsenic pollution in the environment from artisanal gold mining settings, such as the Batouri gold district. Similar results have been reported for gold mine tailings in Obuasi, Ghana, even at higher concentrations (average concentration of 8305 mg/kg). This has been connected to the high concentration of naturally occurring arsenic at Obuasi as well as arsenic liberations from gold ores during gold extraction (Ahmad & Carboo, 2000).

Ecological risk assessment and potential ecological risk factor

Mercury and Lead are harmful to the central and peripheral nervous systems, which may lead to neurological and behavioral disorders, and digestive and immune systems problems, lung, and kidney failure, and are corrosive to the skin and gastrointestinal tract (Bose-O'Reilly et al., 2016; WHO, 2003). According to Anka et al. (2020), children are more vulnerable to cyanide and lead than adults, which causes neurological damage, leading to loss of memory, slow learning (intelligence), and problems of coordination. Arsenic retards plant growth and has adverse effects on aquatic life. Long-term exposure to low concentrations of inorganic arsenic, as in the study area, through contaminated water, air, and food will lead to cancer, thickening and decoration of the skin, high blood pressure, and problems with blood vessels, heart, and nerve diseases, and exposure to high concentrations of arsenic will lead to stomach pain, nausea, vomiting, headache, diarrhea, and death (EGLE, 2019; Wongsasuluk et al., 2021).

Evolution of land use and land cover

Land use and land cover changes at artisanal gold mining sites vary depending on factors such as location, scale of mining operations, and local regulations (Awotwi et al., 2018). Artisanal gold mining is often associated with the clearing of large areas of forest for mining operations and construction of camps and infrastructure. The removal of vegetation, topsoil, pitting, tunneling, and exposure of subsoil in artisanal mine sites generally leads to soil erosion, compaction, reduced fertility, increased vulnerability to erosion, loss of biodiversity, and disruption of ecosystems (Funoh, 2014; Meaza et al., 2017; Mimba et al., 2023). Between 2000 and 2017, mining activity increased significantly in Betare-Oya, Ngoura, and Batouri gold districts, leading to more occupied areas and less vegetation. This shift in land use, which causes problems such as deforestation, is linked to the increasing popularity of gold mines, increase in built-up areas, and agricultural activities among the local population (Kamga et al., 2019). These findings are similar to the changes in land use and land cover indices between 2002 and 2022 in this study, notably the progression of built-up areas, reduction of vegetation/forest, and increased stress on watercourses due to human activity.

Environmental impacts of ASGM

As observed in the field, collapsed mine walls, rockfalls, mine pits, soil degradation, floods, and water pollution are some of the significant environmental risks associated with artisanal gold mining sites. These hazards can have severe consequences for both the environment and the health and safety of miners and local communities (Funoh, 2014; Gisore & Matina, 2015; Mensah et al., 2022; Mimba et al., 2023). Artisanal mining operations often involve excavation of pits that are often unsupported, making them prone to collapse. The collapse of mine walls can lead to injuries or fatalities among miners working in the area, and equally expose buildings within the vicinity of the pits to collapse. Instability in the surrounding rock formations can result in the detachment of rocks and boulders from the mining area. Rock falls pose significant safety concerns to miners and can cause injuries and fatalities (Kolapo et al., 2022). Artisanal gold mining often involves the creation of open pits to extract gold-bearing material. These pits, which are usually unprotected and abandoned, can be deep and unstable, filled with rainwater to produce artificial ponds, posing risks of accidental falls for both miners and local communities (Mundi, 2022). Artificial ponds are excellent breeding grounds for mosquitoes, accounting for the high prevalence of diseases within mining sites (Ralph et al., 2018). The gold extraction process, including digging, sifting, and washing, can lead to soil degradation. Topsoil removal, soil compaction, and erosion caused by mining activities can result in loss of soil fertility and productivity (Fodoué et al., 2022; Mimba et al., 2023; Tehna et al., 2015). The degradation of soil quality can have long-term effects on agriculture, affecting local food production and livelihoods (Ofosu et al., 2020). ASGM activities can alter natural drainage patterns, leading to an increased risk of flooding in the surrounding areas. The excavation of land and creation of mine pits can disrupt the natural flow of water, potentially causing waterlogging and increased flood hazards, especially during heavy rainfall events. Floods can damage infrastructure and livelihoods, and exacerbate erosion and sedimentation within the mining vicinity (Abbiw, 2020; Funoh et al., 2017; Tiamgne et al., 2022).

Conclusions

The following conclusions were drawn from this study.

i) The exposure of artisanal miners to high levels of Hg (reaching 5550 µg/L) and Pb ($>$ 337 µg/L) could be detrimental to their health, notably to the central and peripheral nervous systems, leading to neurological and behavioral disorders. They can also affect the digestive and immune systems, as well as the lungs and kidneys. Long-term exposure to low concentrations of arsenic, such as through contaminated water, can lead to health problems, such as cancer, skin thickening, high blood pressure, problems with blood vessels, heart diseases, and nerve diseases. Children working at these artisanal mining sites are particularly vulnerable. These findings underscore the importance of minimizing exposure to these substances and implementing strict measures to prevent contamination and safeguard human health and the environment.
ii) The overall effects of ASGM on land use and land cover in the study area are significant and have wide-ranging ecological implications, notably an increase in built-up areas, a reduction in vegetation and forest cover, and increased stress

on watercourses. It is crucial to consider sustainable mining practices, effective regulations, and environmental management strategies to minimize negative impacts and preserve the integrity of ecosystems in mining areas.

iii) Significant environmental risks associated with artisanal gold mining sites within the study area include collapsed mine walls, rockfalls, mine pits, soil degradation, floods, and water pollution. These hazards not only pose a threat to the environment, but also jeopardize the health and safety of miners and local communities. These findings emphasize the urgent need for effective environmental management and safety regulations, and intensify the sensitization of the local population in ASGM operations. Implementing measures to prevent collapses, rock falls, and accidents, as well as mitigating soil degradation and managing water drainage, are essential to safeguard the environment and protect the well-being of miners and local communities.

Author contribution Mark Monyuy Fonshiynwa: Data curation, formal analysis Writing-Original draft preparation, Christopher Fuanya: Conceptualization, Visualization, Methodology, Supervision, Nils Hoth: Supervision Romaric Emmanuel Ouabo: Software, Tangko Emmanuel Tangko: Reviewing and Editing, Juliane Günther: Reviewing and Editing, Mengu Emmanuel Eseya: Reviewing and Editing, Carsten Drebenstedt: Supervision.

Declarations

Competing interests The Authors disclose that there are no financial or non-financial interests that are directly or indirectly related to the work submitted for publication.

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