Geological and Geoelectrical Evaluation of Groundwater Pollution Status Related to Gold Mine Lechates Within Bariki and Environs, North–Central Nigeria

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Abstract
Groundwater pollution status, related to heavy metal leachates from gold mine tailings, was investigated in Bariki and environs. It involved mapping rock outcrops, groundwater elevation, total dissolved solids (TDS), electrical conductance (EC), acidity – alkalinity level (pH), heavy metal concentration, and electrical resistivity sounding. Heavy metals' composite contribution to pollution status was ascertained with metal pollution index (MPI). The rock outcrops are gneiss, schist, amphibolite, quartzite, and granite. The main TDS plume exists in vicinity of active mine site 6. Subsidiary plumes exist within neighbourhood of abandoned mine sites 1 and 2. The plume diminishes southward in direction of the groundwater flow. Highest EC value exists around main TDS plume. Other high TDS values occur around subsidiary plumes. The pH is lowest in vicinity of main plume. Highest pH value within lowest TDS area indicates regolith adsorption in an alkaline environment. Largest concentrations of Co (0.42 ppm), Cr (3.4 ppm), Cd (0.22 ppm) and Ni (0.7 ppm) associates with main TDS plume, highest EC, and lowest pH within neighbourhood of active mine 6. Very high concentrations of Cd and Ni also exist within neighbourhood of abandoned mine site 2. Regolith resistivity is lowest around mine sites 1, 2 and 6. It is highest within Latitudes N09° 29' 10" to N09° 29' 24" and Longitudes E06° 31' 30.0" to E06° 31' 48.0", where TDS and ionic concentration are lowest. This implies regolith resistivity is inversely related to TDS and ionic concentration. The groundwater overshot globally recommended concentration of Co, Cr, Cd and Ni in potable water. Computed MPI is 2.004, which indicates elevated heavy metal concentration. This reveals that the groundwater is polluted due to heavy metal leachates from mine tailings.

Key words: Heavy metals, mine tailings, leachates, pollution status

INTRODUCTION

Bariki and environs is a rural suburb of Chanchaga in Minna, North-Central Nigeria. It is located within latitudes N09^0 29' 00" to N09^0 30' 00" and longitudes E06^0 31' 00" to E006^0 33' 00" of Paiko sheet 185NW scaled 1:50,000 (Figure 1).

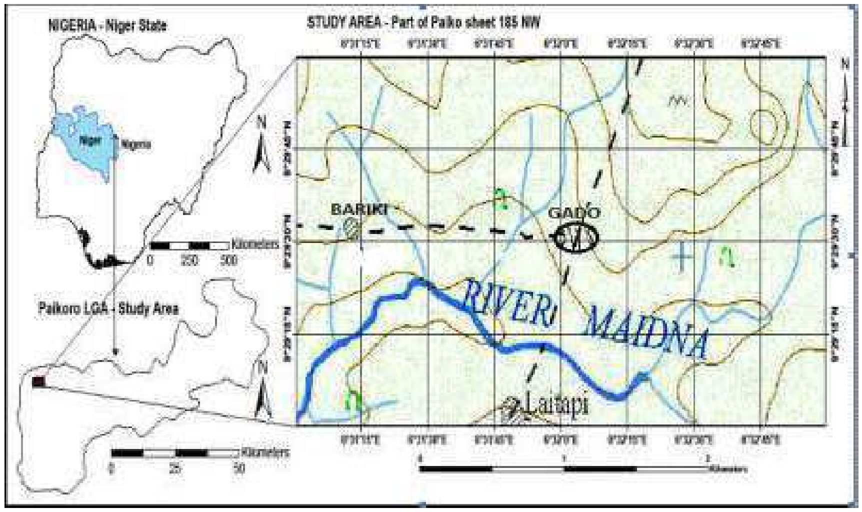

Figure 1: Topographic map showing Bariki and environs, part of Paiko Sheet 185NW, Nigeria

The rocks in Minna and surrounding areas are an integral part of the basement complex in the Northern Nigeria Massif. Some of them bear the lithologic signature of greenstone belts, being in the greenschist metamorphic facies and bearing gold deposits in many areas.

Active and abandoned gold mines abound within Bariki and environs, where gold mining has proceeded for over ten years. The geographical coordinates of the mine locations are shown in Table 1.

Table 1: Geographical Coordinates of Mine Locations

S/N	LATITUDE	LONGTITUDE	ELEVATION	MINE
1	09° 29' 21.1"N	006° 31' 19.1"E	200M	Abandoned Mine
2	09° 29' 58.9"N	006° 32' 42.7"E	212M	Abandoned Mine
3	09° 29' 51.3"N	006° 32' 56.3"E	223M	Abandoned Mine
4	09° 29' 23.0"N	006° 32' 48.8"E	223M	Active Mine
5	09° 29' 21.6"N	006° 32' 47.6"E	214M	Active Mine
6	09° 29' 32.6"N	006° 31' 41.0"E	215M	Active Mine
7	09° 29' 25.6"N	006° 31' 00"E	211M	Active Mine

Possible reactions of sulphur in mine tailings with surface runoff from rain water could leach out gold pathfinding elements (As, Bi, Cu, Fe, Mo, Pb, Zn, Mn, Ni, Sb and Cd) into solution that may eventually infiltrate the groundwater. The elements become harmful to human health when ingested at toxic concentrations (Ayolabi*et al.*, 2013; Singh *et al.*, 2015; Amadi *et al.* 2016, and Adeyemi and Ojekunke, 2021). In rural settings of countries like Nigeria, ingestion can be by drinking water obtained from hand-dug wells that contain groundwater at toxic concentrations of the elements. Among the harmful effects are miscarriages in women, skin cancer, and damage to the nervous system as well as cardiovascular and skeletal systems (Deming, 2002).

Despite the potential health risks posed by over ten years of gold mining in Bariki, no study has hitherto focused on evaluating pollution status of the groundwater in the area, with respect to its concentration of potentially toxic elements. The situation prompted this study to evaluate the pollution status of groundwater in Bariki in relation to heavy metal leachates from mine tailings.

STUDY METHODOLOGY

The study was conducted by surface lithologic mapping, groundwater elevation mapping in hand-dug wells, and measurement of physical parameters such as acidity -alkalinity level (pH), total dissolved solids (TDS) and electrical conductance (EC). Water samples from hand-dug wells were also analysed for heavy metal concentrations. The physical parameters and concentration data were compared with World Health Organisation (WHO, 2011) prescribed values for safe drinking water. The combined effect of the heavy metals on the pollution status was evaluated using metal pollution index (MPI). Vertical geoelectrical sounding data was acquired and compared with spatial variation pattern of measured physical parameters and metal concentrations to validate observed patterns.

Field-base map used for the surface lithologic mapping was made from Nigeria's Paiko Topographic Sheet185NW and scaled 1:25000. Lithology of outcropping rock was identified in fresh hand specimen, using Mafic Colour Index (MCI) and texture. The textural parameter used was foliation. Non-foliated rock with 0 – 15% MCI was identified as granite. Black, greenish and heavy (high relative density) rocks were identified as amphibolite. Rocks with 16 – 45 % MCI and alternating light and dark bands were identified as gneiss. Rocks with schistose texture were identified to be schist. Milky white non-foliated rocks that were unreactive to dilute acids were called quartzite. Rock identification in hand specimen was refined by petrographic examination under plane and cross polarized light of a MEIJI manufactured petrographic microscope N_p – 107B model and serial number 000341). Outcrop attitude (foliation strike, dip direction and amount) were obtained using SUNTO MC2 compass clinometer. The geographical coordinates of the outcrop locations were obtained using *etrex* version of hand held geographic positioning system (GPS). The identified lithologic units were plotted on the field base map, using their coordinates. Rock attitude data were also plotted and the geological map for Bariki and environs was completed. Depth to water level in eleven hand-dug wells was obtained using Geotech electronic water level meter. The depth was subtracted from surface elevation (obtained with GPS) at each hand-dug well location to obtain water level elevation with respect to sea level. Geographical coordinates of the hand-dug well locations were also obtained with GPS. Groundwater elevation map was then plotted by plotting groundwater elevation data versus the geographical coordinates. Water samples from the eleven hand-dug wells were collected in clean 75 ml plastic bottles for physical parameters and geochemical analyses. A drop of concentrated nitric acid was added to sample in each bottle to prevent oxidation and precipitation of cations, and adsorption of metals on the container walls.

The measured physical parameters are acidity – alkalinity level (pH), electrical conductance (EC), and total dissolved solids (TDS). A multifunctional TDS / EC / pH water tester was used for the measurements. The geochemical analysis was conducted at the National Geoscience Research Laboratory (NGRLC) in Kaduna. The elemental concentrationsof the heavy metals were determined using HACH 2800 model of Atomic Absorption Spectrometry (AAS) DR machine. The concentrations were compared with WHO (2011) recommendation for safe drinking water, to ascertain harmlessness or otherwise of the water. Metal pollution index (MPI) was determined to ascertain the composite effect of the heavy metals on the pollution status, following Thambavani and Uma (2013):

$$\mathrm{MPI} = \mathrm{Log}\sum_{i=1}^{6}\frac{X_{Ave}}{\mathrm{MAC}} \qquad (1)$$

Where X_{Ave} represents average concentration for each heavy metal in water samples from all the hand-dug wells, MAC is a normalizer (which is the maximum allowable concentration for safe drinking water), and 'n' is the total number of metals analysed for.

Geoelectrical resistivity sounding was conducted to verify spatial distribution pattern of the ionic concentration of heavy metals in groundwater. The Schlumberger field array was employed with electrodes deployed in strike direction. The maximum electrode spacing employed was 100 m. This was distant enough to capture resistivity of the regolith, which is the aquifer tapped in hand-dug wells. The sounding data was interpreted using version 1.0 of Win RESIST 1D resistivity inversion software. The regolith resistivity at each sounding location was plotted against the geographic coordinates to obtain iso – resistivity map for the regolith, and compared with iso – concentration for the ions.

RESULTS AND INTERPRETATION

I. Geologic Setting

The lithologic units establishedduring the surface lithologic mapping are gneiss, amphibolite, schist, quartzite and granite. Plate 1 is a gneiss outcrop with isoclinally folded quartz vein.

Plate1.Gneiss outcrop with isoclinally folded quartz vein in the study area (Location N09° 29' 25.8"; E006° 31' 19.9")

Plate 2 is micrographs of the gneiss under plane polarized (a) and cross polarized light (b) respectively.

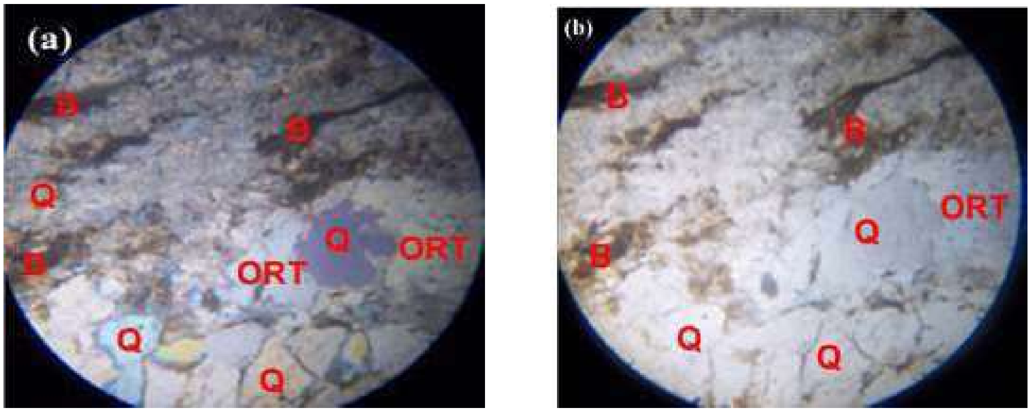

Plate 2. Photomicrograph of gneiss in (a) Plane polarized light and (b) cross polarized light. (B-biotite, Q-quartz, ORT-orthoclase).

An outcrop of amphibole schist found at a location with geographic coordinates**N**09° 29' 17.0" and E006° 32' 48.0" is Plate 3. Plate 4 is its micrographs under plane polarized (a) and cross polarized light (b) respectively

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Plate 3: Amphibole schist outcrop in the study area
(Location**N**09° 29'17.0"; E006° 32' 48.0.")

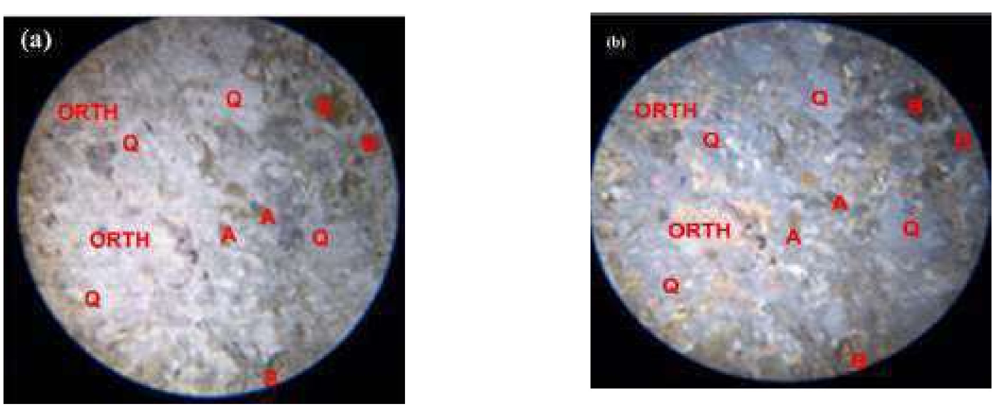

Plate 4. Photomicrograph of amphibole schist in (a) Plane polarized light and (b) cross polarized light (A-amphibole, Q-quartz, ORT-orthoclase, B-biotite)

Outcrops of muscovite schist and quartzite are shown in Plates 5 and 6 respectively.

Plate 5: Muscovite schist outcrop in the study area (LocationN09° 29' 58.9"; E006° 32' 56.1")

Plate 6: Quartzite outcrop in the study area (LocationN09° 29'39.3"; E006° 34'2.7")

The metamorphic outcrops generally dip 60-70°eastwards and strike northwards. Granite is fine to medium grained in the study area. Plate 7 shows the fine grained granite outcrop.

Plate 6: Fine grained granite in the study area (locationN09° 29' 35.6"; E006° 32' 19.6")

Figure 2 is the geological map produced from the spatial distribution of the outcrop locations

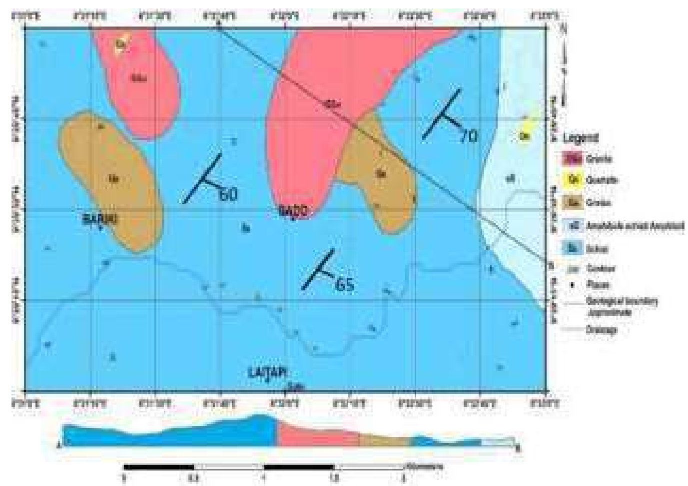

Figure 2: Geological map of Bariki and environs

The map reveals that the granite intruded gneiss and schist in the area. Thus granite is the youngest lithologic unit in the area. The contact between the schist and amphibolite is conformable with regional strike, which indicates they are of the same geological age. Gneiss is the most deformed unit. It hosts isoclinally folded biotite-quartz veins. This intense deformation indicates gneiss is the oldest lithologic unit in Bariki and environs.

II. Groundwater flow direction

Table 2 shows measurement locations of physical parameters, as well as their respective Eastings and Northings, groundwater elevation (with respect to sea level), TDS in ppm, EC in µS/cm and pH.

Table 2. Physical parameters measurement locations, with their respective Eastings and Northings, location elevation, water depth in hand-dug wells, groundwater elevation TDS in ppm, EC in µS/cm andpH

Location	Northing	Easting	Location Elevation	Water depth in hand-dug wells(metres)	Groundwater Elevation (metres)	TDS (ppm)	EC (µS/cm)	pH
L1	09° 29' 54.0"N	06° 32' 56.5"E	242	0.40	241.60	1783	556.62	
L2	09° 29' 28.3"N	06° 32' 04.5"E	217	0.30	216.70	398	798	6.72
L3	09° 29' 28.7"N	06°32' 05.7"E	223	1.20	221.80	545	1090	6.24
L4	09° 29' 31.7"N	06° 32' 05.7"E	223	2.80	220.20	140	280	6.61
L5	09° 29' 46.3"N	06° 31' 07.5"E	223	1.78	221.22	41	83	6.35
L6	09° 29' 43.8"N	06° 31' 17.9"E	227	1.33	225.67	49	98	8.04
L7	09° 29' 55.3"N	06° 31' 16.2"E	226	0.26	225.74	54	109	7.31
L8	09° 30' 00.0"N	06° 31' 26.8"E	215	4.80	210.20	188	377	8.47
L9	09° 29' 32.9"N	06° 31' 50.3"E	226	0.70	225.30	37	75	6.51
L10	09° 28' 59.2"N	06° 31' 45.0"E	249	4.15	244.85	102	203	7.78
L11	09° 28' 06.1"N	06° 32' 16.1"E	211	2.10	208 .90	53.7	108	9.35

The produced groundwater elevation map is shown as Figure 3.

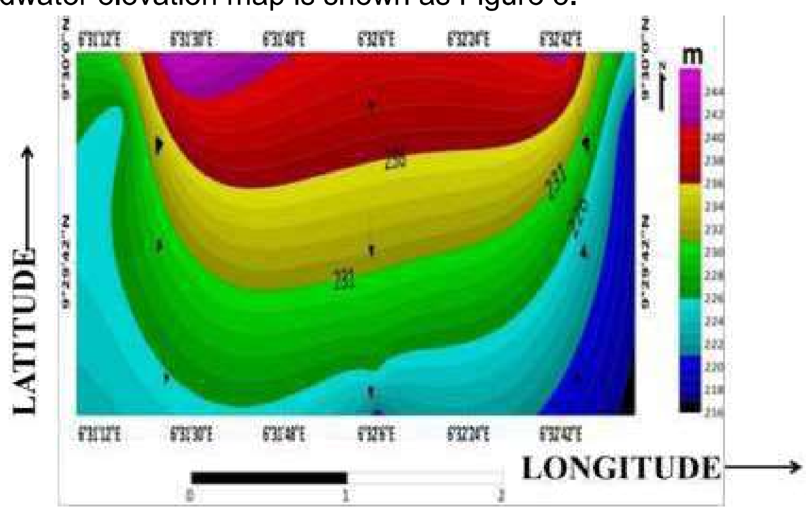

Figure3.Groundwater level elevation map in regolith in Bariki and environs

The map reveals that groundwater generally flows southwards within regolith aquifer in Bariki and environs.

III. Groundwater Chemistry and Metal Pollution Index

The produced maps for TDS and EC values are Figures 4 and 5 respectively.

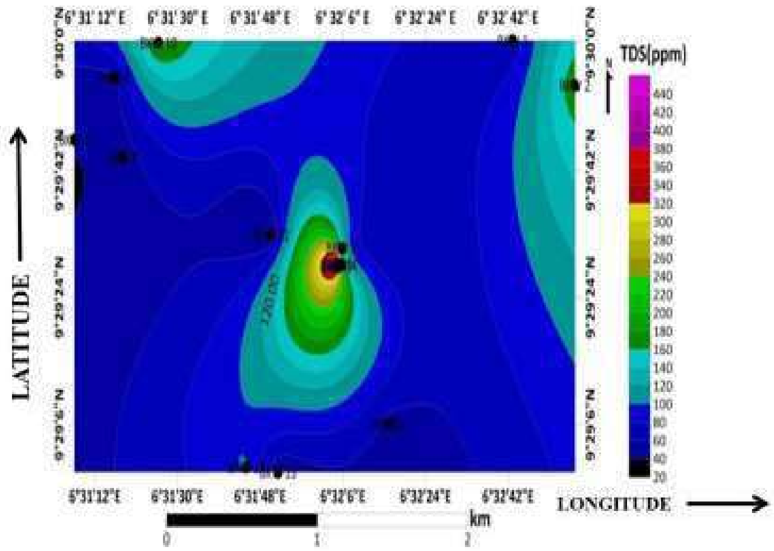

Figure 4: Map of TDS values for sampled hand dug well locations

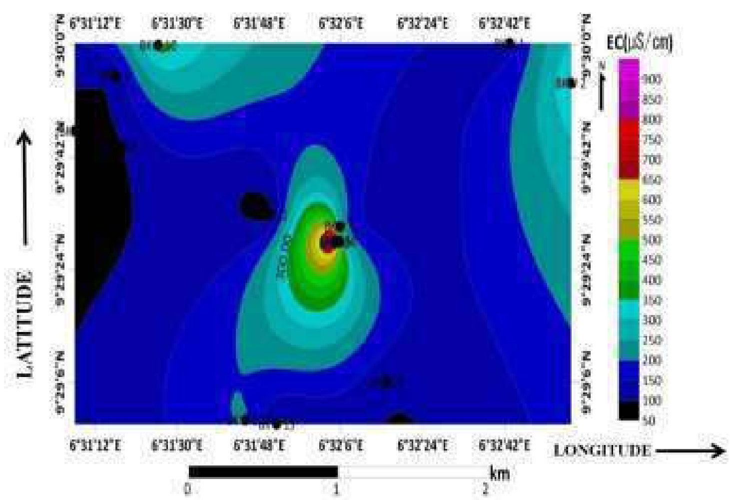

Figure5. Map of EC values for sampled hand dug well locations

TDS and EC maps reveal that location of largest TDS amount coincides with location of largest EC value at the position where geographic coordinates are Latitude N9°29'28" and LongitudeE6°32'00". This is in neighbourhood of active mine 6site at Latitude N 9°30' 00" and Longitude E6°31'41". The TDS plume diminishes southwards from this active mine site, in groundwater flow direction.

Subsidiary plumes on the map are at Latitude N 9°30' 00" and Longitude E6° 31' 30", as well as at LatitudeN 9°30' 00" and LongitudeE6° 32' 50". These are close to abandoned mine sites 1 and 2 respectively. They likewise diminish southwards in groundwater flow direction. Figure 6 is the pH value map for Bariki and environs.

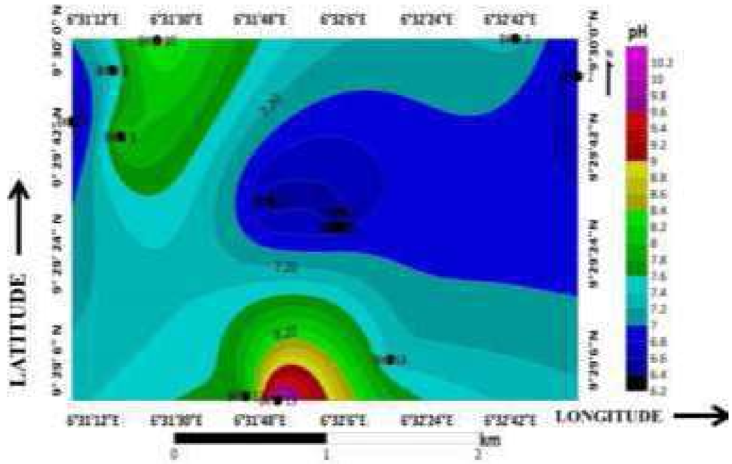

Figure 6. pH value map for Bariki and environs

The pH is between 6.4 and 6.8 in the neighbourhood of active mine 6 siteat Latitude N9°29' 32.6" and Longitude E6°31'41", where TDS and EC have highest value. This implies slightly acidic conditions that favoured formation of aqueous ions of heavy metals. Southwards of this active mine, pH increases and geochemical environment becomes alkaline.

Pyrite dominates accessory metallic sulphides associated with gold mineralization. Pyrite reacts with oxygen and surface water to become converted to sulphuric acid and hydrated ferric oxide as follows:

$$5FeS_{2(s)}+5H_2O_{(l)}+{}^{15}/{}_{2}O_2 = 4H_2SO_{4(aq)}+Fe_2SO_3.H_2O_{(s)}$$

Pyrite sulphuric acid hydrated ferric oxide

The resulting acidic surface water leaches some heavy metals (mostly siderophiles) in the ore body into aqueous solution. As the acidic surface water flows overland, part of it percolates the subsurface and eventually infiltrates the groundwater. Values of groundwater TDS in the mine environs thereby become elevated.

Alkalization also occurs, and both groundwater acidulation and alkalization are not mutually exclusive. Rain water contains appreciable carbon dioxide which forms carbonic acid with it as follows:

$$H_2O_{(l)} + CO_2 = H_2CO_{3(aq)} \qquad (2)$$

carbonic acid

The water with carbonic acid reacts with various silicate minerals in the host rock to produce various alkalis as follows:

$$2KALSi_3O_{8(s)} + H_2CO_{3(aq)} + nH_2O_{3(l)} = K_2CO_{3(aq)} + Al_2(OH)Si_4O_{10}.nH_2O_{(s)} + 2SiO_{2(aq)} \qquad (3)$$

orthoclase carbonic acid water potassium carbonate clay mineral

$$2KMg_2Fe(OH)_2AlSi_3O_{10} + O_2 + H_2CO_{3(aq)} + nH_2O_{(l)} = 2KHCO_{3(aq)} + 4Mg(HCO_3)_{(aq)} + Fe_2O_3.H_2O_{(s)} \qquad (4)$$

biotite potassium bicarbonate magnesium bicarbonate limonite

The leaching of heavy metals increases the groundwater TDS around the mine. Southwards from the mine, the gold mineralization and its accessory metal sulphides decrease in amount, while alkalization increases. The pH thereby increases southwards. The increased pH favoured adsorption of many dissolved solids onto the precipitated clay minerals. This resulted in decreased TDS and concomitant decrease in EC. The groundwater is below 1000 ppm in TDS and 1000 μS/cm in EC, and thus meets the WHO (2011) requirements of less than 1000 ppm TDS and 1000 μS/cm EC. However, it falls short of WHO (2011) pH requirements of 7 – 8.5 for potable water at locations L1, L2, L3, L4, L5 and L9, where pH value is lower than 7.0.

The heavy metal concentration (in ppm) is given in Table 3.

Table 3. Concentration of heavy metals

Heavy metals	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11
Co	0.07	0.11	0.50	0.17	0.05	0.17	0.24	0.16	0.02	ND	0.11
Zn	ND	0.03	ND	ND	ND	ND	0.01	0.13	0.01	0.14	ND
Cd	0.15	ND	0.17	0.21	0.08	ND	ND	ND	0.05	0.09	0.07
Cu	ND	ND	ND	ND	ND	ND	ND	ND	ND	0.002	ND
Ni	0.67	ND	0.85	0.06	0.30	0.09	0.08	0.67	0.02	ND	ND
Cr	0.63	ND	3.75	1.18	2.14	1.03	0.49	0.79	0.75	0.82	0.64

Figure 7 is concentration map for cobalt in Bariki and environs.

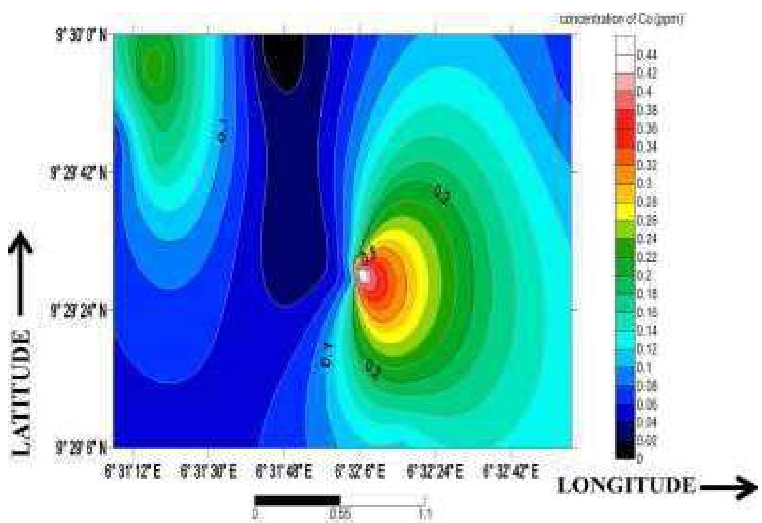

Figure 7. Concentration map for cobalt in Bariki and environs

Cobalt concentration is highest (about 0.4 -0.42 ppm) within Latitude N9°29'20" to N9°29'30" and Longitude E6°32'00" to E6°32'20", in the neighbourhood of active mine site 6. This concentration is eighty-four times the WHO (2011) cobalt concentration limit(0.005ppm) in harmless drinking-water. The concentration naturally attenuates southwards to 0.06 ppm, which is still higher than the WHO (2011) prescribed cobalt limit. The concentration map for chromium in the area is Figure 8.

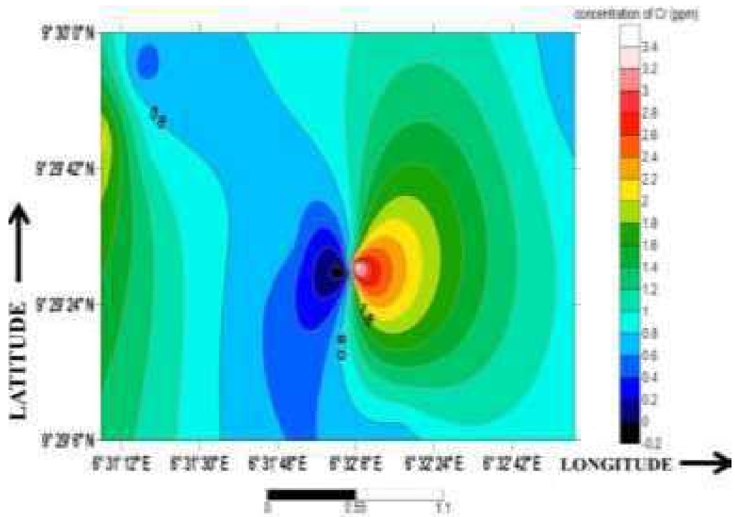

Figure 8. Concentration map for chromium in Bariki and environs

The concentration is highest (about 3.2 -3.4 ppm) within Latitudes N9°29'20" to N9°30'0" and Longitudes E6°31'50" to E6°32'20", in the neighbourhood of active mine site 6. This concentration is sixty-eight times the WHO (2011) chromium concentration limit(0.05ppm) in harmless drinking-water. The concentration naturally attenuates southwards to 0.2 ppm, which is still higher than the WHO (2011) prescribed chromium limit. Figure 9 is the concentration map for cadmium.

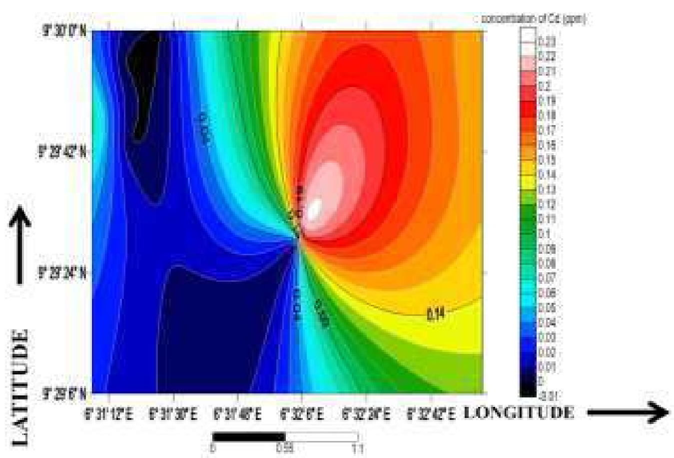

Figure 9. Concentration map for cadmium in Bariki and environs

Cadmium concentration in the groundwater is highest (0.21 to 0.22) within Latitudes N9°29'30" to N9°29'42" and Longitudes E6°32'00" to E6°32'20", in the neighbourhood of active mine site 6. This is one hundred and ten times higher than the WHO (2011) cadmium concentration limit (0.002ppm) in harmless drinking-water. The cadmium concentration is also very high within Latitude N9°29'42" to N9°30'0" and Longitude E6°32'45" to E6°32'50", in the neighbourhood of abandoned mine site 2. The concentration naturally attenuates southwards from both mine sites to about 0.05ppm, which is still much larger than the 0.002 ppm prescribed by WHO (2011). Figure 10 is nickel concentration map.

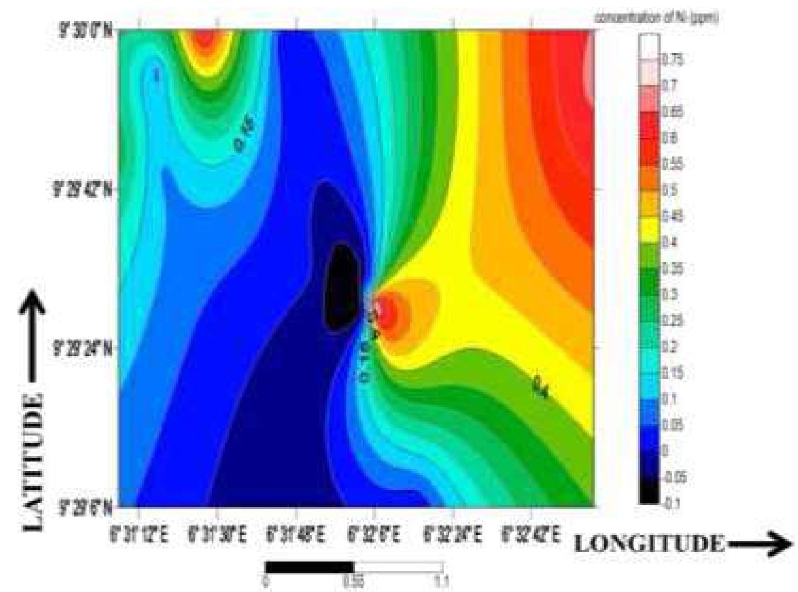

Figure10. Concentration map for nickel in Bariki and environs

Nickel concentration in the groundwater is highest (0.7) within Latitudes N9°29'42" to N9°30'0" and Longitudes E6°31'50" to E6°32'20", in the neighbourhood of mine site 6. This is thirty-five times higher than the WHO (2011) nickel concentration limit (0.02ppm) in harmless drinking-water. The nickel concentration is also very high within Latitudes N9°29'42" to N9°30'0" and Longitudes E6°32'45" to E6°32'50" (in the neighbourhood of abandoned mine site 2) as well as within Latitudes N9°29'50" to N9°30'00" and Longitudes E6°31'20" to E6°31'40", in the neighbourhood of mine site 1. The concentration naturally attenuates southwards from the mine sites to about 0.05ppm, which is still much larger than the 0.05 ppm prescribed by WHO (2011). Figures 11 and 12 are concentration maps for copper and zinc respectively.

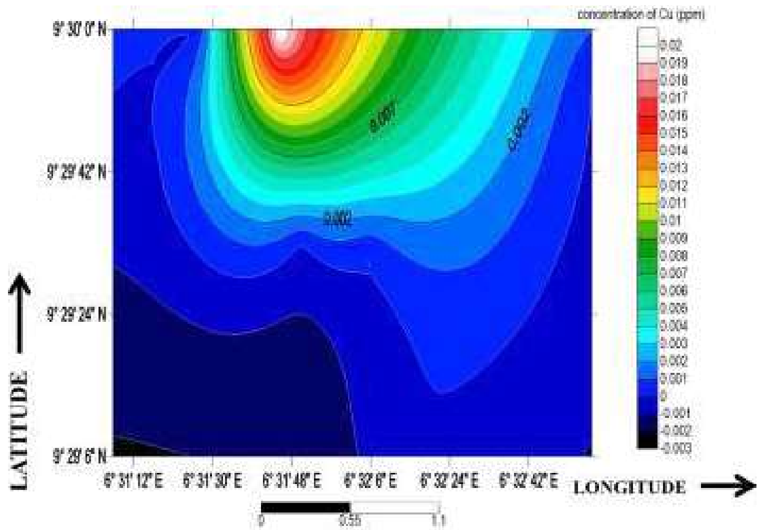

Figure11. Concentration map for copper in Bariki and environs

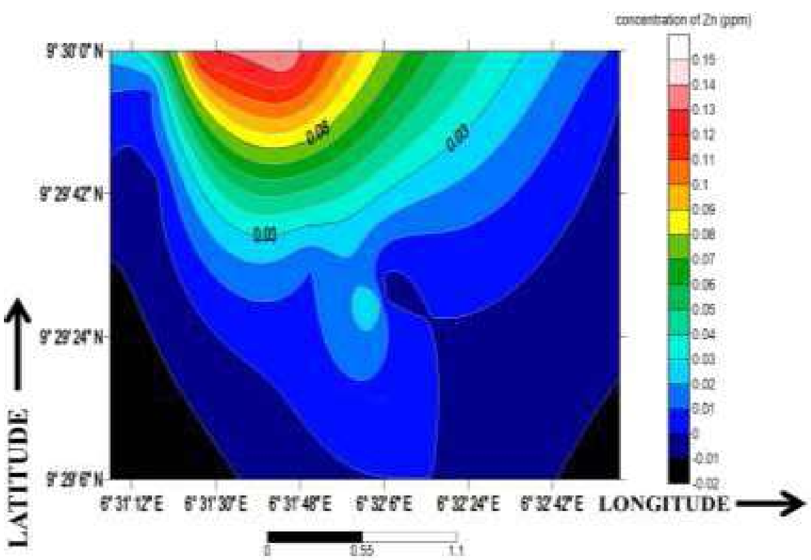

Figure 12. Concentration map for zinc in Bariki and environs

Copper and zinc have highest concentration within Latitude N9°29'50" to N9°30'00" and Longitude E6°31'20" to E6°32'06", in the neighbourhood of abandoned mine site 1. Copper concentration is 0.019 ppm while that of zinc is 0.14 ppm. Both concentrations are yet to reach the limit prescribed by WHO (2011), 2.0 ppm for copper and 3.0 ppm for zinc.

Table 4 presents the average concentration of each metal (X_{Ave}), the WHO (2011) maximum admissible concentration for each metal used or a normalizer (MAC), individual metal enrichment value ($\frac{X_{Ave}}{MAC}$), and metal pollution index (MPI)

$$\mathrm{MPI} = \mathrm{Log} \sum_{i=1}^{6} \frac{X_{Ave}}{MAC}$$

METAL	SERIAL NUMBER	AVERAGE CONCENTRATION OF EACH METAL (X_{Ave}) After Taylor (1964)	WHO (2011) ADMISSIBLE CONCENTRATION FOR EACH METAL OR NORMALISER (MAC)	INDIVIDUAL METAL ENRICHMENT VALUE ($\frac{X_{Ave}}{MAC}$)
Co	1	0.1454	0.005	29.08
Zn	2	0.02	0.03	0.0067
Cd	3	0.0745	0.002	37.25
Cu	4	0.00018	2	0.00009
Ni	5	0.249	0.02	12.45
Cr	6	1.11	0.05	22.2
				$\sum_{i=1}^{6} \frac{X_{Ave}}{MAC} = 100.99$
				$MPI = \text{Log} \sum_{i=1}^{6} \frac{X_{Ave}}{MAC} = 2.004$

Table 4: Metal Pollution Index and its Computation Parameters

The MPI value of 2.004 indicates elevated concentration of the heavy metals, which reveals that groundwater is polluted in the study area. This is in conformity with MPI interpretation by Thambavani and Uma (2013).

IV. Electrical Resistivity of the Overburden

Figure 13 is the apparent resistivity map produced for the regolith within Bariki and environs

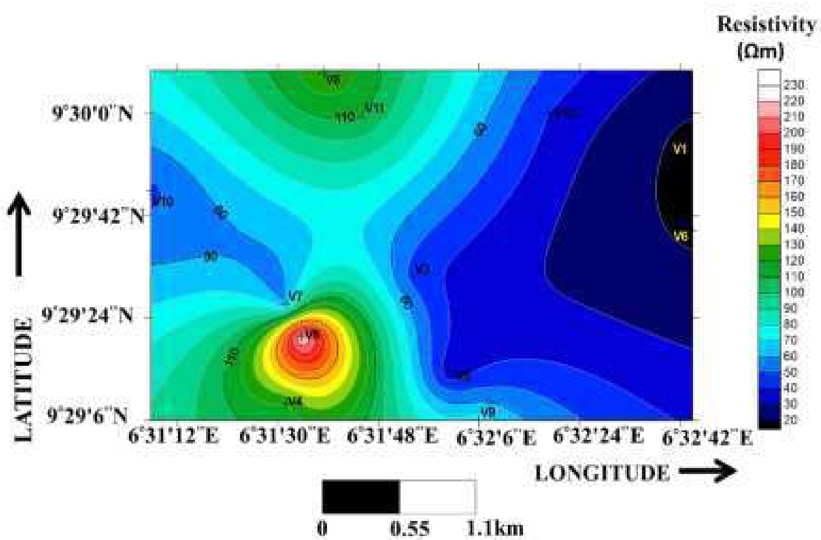

Figure 13. Regolith apparent resistivity map for Bariki and environs

Very low regolith apparent resistivity values are seen in the area within Latitudes N9°29'24.0" to N9°30'0.0" and Longitudes E6°32'24" to E6°32'42". This area is the location of abandoned mine site 2 and its immediate vicinity. Cadmium and nickel concentrations as well TDS and EC values are very high in this area, with concomitant fairly low pH (6.4). This is in conformity with the very low regolith apparent resistivity values. Very low regolith apparent resistivity values are also noticed in the area within Latitudes N9°29'24.0" to N9°30'0.0" and Longitudes E6°32'0.0" to E6°32'24". This area is within the location of activemine site 6 and its immediate vicinity. Cobalt, chromium, cadmium and nickel have very high concentrations in this area. Associated TDS and EC values are also high, in line with the observed regolith low apparent resistivity. The regolith resistivity becomes high within Latitudes N9°29'06" to N9°29'24.0" and Longitudes E6°31'30" to E6°31'48' where heavy metal concentration becomes low due to adsorption by the regolith in a relatively high pH(8.2 -9.0) or alkaline environment. The very low TDS and EC values observed within this area accounts for the high regolith apparent resistivity.

V. Status of Groundwater Pollution

The groundwater pHis lower than 7.0 at locations L1, L2, L3, L4, L5 and L6. It exceeds the WHO (2011) prescription of 7 -8.5 pH value at these locations. Concentrations of Cd, Cr, Ni, and Co respectively are one hundred and ten, sixty-eight, thirty, and four multiples of the WHO (2011) prescribed concentration for harmless drinking water within the neighbourhood of the mine sites. Outside the mine sites, the respective metal concentrations remain higher than the WHO (2011) prescription for potable water. The lower than 7.0 pH value and toxically high concentrations of Cd, Cr, Ni, and Co indicate that the groundwater is polluted within Bariki and environs. This indication is validated by obtained MPI of 2.004. According to Thambavani and Uma (2013), 2.004 MPI value confirms heavy metal related groundwater pollution. The polluted status of the groundwater manifested as very low regolith apparent resistivity values in the neighbourhood of the mine sites.

CONCLUSION

Elevated values of TDS and EC, as well as toxic level concentrations of Cd, Cr, Ni and Co were found in groundwater within immediate neighbourhood of the mine sites. Groundwater pH is between 6.4 and 6.8 around the mine sites, revealing slightly acidic conditions. The pH increases southwards away from the mine sites, in the groundwater flow direction, to between 7.6 and 10.2. This is concomitant with southward attenuation of TDS and EC values, as well as southward lowering of concentrations of Cd, Cr, Ni and Co.

Mine tailings were generated as the mines were worked to wean gold from the rocks. Chemical reaction of the tailings' Sulphur content with surface runoff from rain water produced acidic surface water that leached out Cd, Cr, Ni and Co into aqueous solution. The aqueous solution infiltrated groundwater within immediate neighbourhood of the mine sites to elevate TDS and EC values, as well as concentrations of Cd, Cr, Ni and Co. Alkaline groundwater environment, reflected by pH values between 7.6 and 10.2, caused adsorption of Cd, Cr, Ni and Co on regolith material and thereby attenuated their concentration in groundwater. Despite the attenuation, their concentration remains higher than WHO prescribed concentration for potable water. The polluted status of the groundwater is validated by metal pollution index of 2.004. The neighbourhood of the mining sites is characterised by very low regolith resistivity values, which validate observed elevated TDS, EC and concentrations of Cd, Cr, Ni and Co around the sites.

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