

Heavy Metal Pollution Index of Surface Water and Groundwater Around Tongon Mine (Côte d'Ivoire)

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To cite this article:

Kagbagnan Kone, Kouakou Adjoumani Rodrigue, Konan Edmond Kouassi, Kopoin Adouby. Heavy Metal Pollution Index of Surface Water and Groundwater Around Tongon Mine (Côte d'Ivoire). *International Journal of Environmental Monitoring and Analysis*.

Vol. 7, No. 5, 2019, pp. 103-111. doi: 10.11648/j.ijema.20190705.12

Received: October 1, 2019; **Accepted:** October 28, 2019; **Published:** November 12, 2019

Abstract: Water is a valued resource, which is increasingly being threatened by mining activity. Monitoring of surface water and groundwater quality around gold mine is essential in terms of heavy metals and toxic substances. The northern zone of Côte d'Ivoire where located Tongon is a highly mineralised zone, with extensive mining of gold. The quality of water resources in this region may be affected by the activity of the Tongon mine, which is the main gold mine in the region. The objectives of this study were to determine the concentration of heavy metals and the Heavy Metal Pollution Index (HPI) in surface water and groundwater around Tongon mine. The concentrations of As, Zn, Pb, Cd, Cr, Cu, and Mn have been evaluated at 21 surface water and 16 groundwater sampling stations. The concentration of these metals were analysed using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) for heavy metal pollution indexing. The concentrations of As, Pb, Cr, Cu and Mn in surface water were found to be above the highest desirable limit of WHO drinking water standard with mean concentrations of 5.761, 0.016, 0.178, 2.939, and 0.684 mg/L, respectively. Excepted As (2.95 mg/L) and Mn (0.67 mg/L), the metal concentrations in groundwater were well below the permissible limits of WHO drinking water standard. The Heavy Metal Pollution Index was used to evaluate surface water and groundwater quality. The results showed that, in the groundwater samples, HPI values (48.56-72.49) were less than 100, indicating a low-level heavy metal. Concerning surface water, HPI values of Pongbe River are well below the index limit of 100, which suggest that it is generally no contaminated with respect to these metals. The mining activity of Tongon is carried out while protecting water quality against heavy metals. The quality of water resources in the area must be regularly monitored to avoid any dramatic situation.

Keywords: Surface Water, Groundwater, Heavy Metal Pollution, Tongon, Gold Mine

1. Introduction

Water is vital to the existence of all living organisms [1-4]. However, this valued resource is increasingly being threatened by human population's growth and anthropogenic activities such as mining activity. This is why it is necessary to monitor its quality [1]. Mineral extraction and processing is likely to contribute to the contamination of surface water and groundwater [2]. For example, waste water from non-ferrous metal ore mining and smelting, electroplating and

other industrial production process is an important contamination source of heavy metal [5]. The heavy metal contamination has the characteristic of the high toxicity, and difficult to degrade, and its migration brings about a broader range of hazards. The research indicated that mining and the smelting activities caused great destruction to the water environment. The heavy metals are difficult to clear away from the natural environment, or even form a secondary pollution [3-5].

Heavy metals can cause adverse effects to human health when their contents exceed the permissible limit in surface

water [6]. Thus, heavy metals assessment in surface water and groundwater used for drinking purpose is very significance from the human health viewpoint [7]. Heavy metals are usually present in trace amounts in natural water but many of them are toxic even at very low concentration though many of the metals are essential components of the biological system [8]. Heavy metals such as As, Pb, Cd, Cu, Cr, Zn and Mn are highly toxic even in minor quantity. Contaminated surface water when used for irrigation purpose affects soil quality and crop health of the agricultural system [7].

The pollution parameters monitored for the assessment of the quality of any system give an idea of the pollution with reference to these parameters individually. Quality indices are useful to obtain an idea of the synergistic action of all measured pollution parameters. They make it possible to synthesize the various data in the form of a single value. [9]. Quality indices use a set of quality criteria in a reproducible form and compile all pollution parameters in a simple approach, for evaluation of water quality contamination, the Heavy Metal Pollution Index (HPI) was developed [7, 9]. This index is used to assess the level of pollution of water resources by combining several water pollution parameters [7].

In Côte d'Ivoire, Tongon mine is located in north of the country. With an annual production of 8.5 tons of gold per year, the Tongon mine is the largest gold mine in Côte d'Ivoire. Its gold mine reserve is estimated at 3.16 million ounces, or more than 98 tons [10]. Mining in Tongon is an important source of income for Côte d'Ivoire, but it can affect

the environment around the mine. In fact, the surface and groundwater around the Tongon gold mine is an important water resource, which is used for crop irrigation and drinking water. Pollution of these waterways would have harmful consequences for populations. Unfortunately, to date, there are no data in the literature on surface and groundwater quality indices around the Tongon gold mine. Thus, it seems essential to assess the quality of these waters in terms of heavy metals. The main objective of this study is to assess the contamination of surface and groundwater around the Tongon gold mine by the Heavy metal Pollution Index (HPI).

2. Materials and Methods

2.1. The Studied Area and Sampling

Tongon gold mine is located at 9°57'5.76" N and 5°42'13.68" W (Figure 1). The mean temperature in this region is 27.6°C and the annual precipitation for the entire area is reported to be 1400 mm on average [11]. The sampling network consist of 37 sites, 21 of them surface water and 16 groundwater. The sampling sites are marked by a red point and numbered in Figure 1. Totally, 375 surface water and ground water samples were collected monthly from March 2017 to October 2018. The samples were collected in separate polyethylene bottles. Samples were collected and stored according to the method prescribed in the American Public Health Association manual [12]. A volume of 2 mL of 65% HNO₃ was added to prevent metal precipitation.

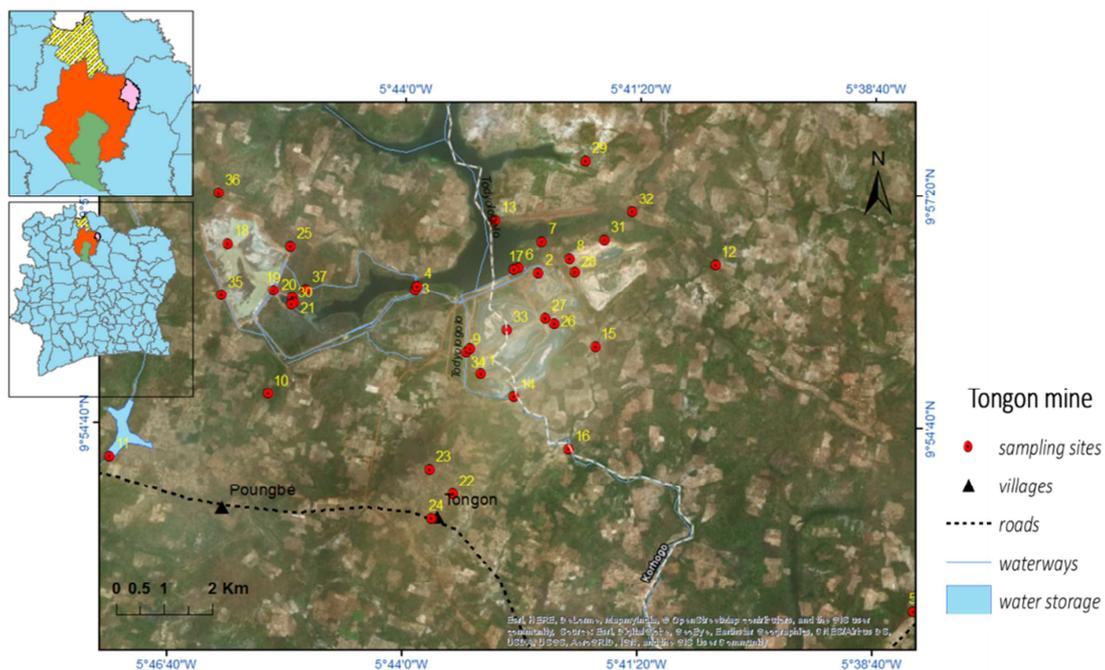


Figure 1. Location and sampling sites around Tongon mine, Côte d'Ivoire.

2.2. Analytical Methods

The concentrations of heavy metals were determined by Inductively Couple Plasma Mass Spectroscopy (NexION

2000 ICP-MS, USA), after the samples were concentrated and digested. The minimum limit of detection (LOD) for each heavy metal is resumed in Table 1.

Table 1. The limit of detection for As, Zn, Pb, Cd, Cr, Cu, and Mn.

Heavy metal	LOD (mg/L)
As	0.0005
Zn	0.005
Pb	0.0005
Cd	0.0001
Cr	0.001
Cu	0.001
Mn	0.002

The proposed HPI was developed by assigning a rating or weightage (W_i) for each selected parameter [7, 9, 13-15]. The rating is a value between zero and one, reflecting the relative importance of individual quality considerations, and can be defined as inversely proportional to the recommended standard (S_i) for each parameter. For this study, the highest permissible value for drinking water (S_i) and maximum desirable value (I_i) for each parameter were taken according to WHO guidelines (Table 2). The highest permissible value for drinking water (S_i) refers to the maximum allowable concentration in drinking water in absence of any alternate water source. The desirable maximum value (I_i) indicates the standard limits for the same parameters in drinking water. The heavy metal pollution index is expressed by equation (1)

Table 2. Applied parameters and constants for calculation of HPI and Q_i (according to WHO guidelines).

Heavy metal	Permitted value (mg/L)	Unit weightage, W_i	Desirable maximum value (mg/L) for drinking water (I_i)	Highest permitted value (mg/L) for drinking water (S_i)
As	0.05	0.02	0.01	0.05
Zn	5	0.0002	3	5
Pb	0.015	0.7	0.01	0.1
Cd	0.05	0.3	0.003	0.005
Cr	0.003	0.02	0.05	0.001
Cu	0.05	0.001	2	1
Mn	1	0.02	0.5	0.100

Geographic information system (GIS) is widely used for collecting, analysing and presenting all types of spatial and geographical data [15]. The spatial distribution maps were prepared using ArcGIS- 10.2.2 software. The analysis of variance (ANOVA one way) was used to evaluate the difference in metal concentrations between surface water and groundwater sampling sites. Differences were considered significant at p values <0.05 . Statistical analyses (mean value, minimum, maximum) were carried out with Statistica 7.1 software.

3. Results and Discussion

3.1. Distribution of Heavy Metals in Water

The heavy metal concentrations of the surface water and groundwater samples collected in different sampling sites are given in Table 3 and Table 4, respectively.

The metal concentrations (mg/L) in surface water samples ranged from 0.009 to 53.508 for As, 0.005 to 0.625 for Zn, 0.001 to 0.228 for Pb, $<LOD$ to 0.00403 for Cd, 0.006 to 2.505 for Cr, 0.004 to 14.275 for Cu, and 0.021 to 10.9 for Mn, respectively (Table 3). The heavy metal concentrations of all surface water samples were (5.761 ± 19.099), ($0.081 \pm$

and (2) as follows [9, 13]:

$$HPI = \frac{\sum_{i=1}^n W_i Q_i}{\sum_{i=1}^n W_i} \quad (1)$$

Where Q_i is the sub index of the i th parameter. W_i is the unit weightage of i th parameter, and n is the number of parameters considered. The sub index (Q_i) of the parameter is calculated by

$$Q_i = \frac{\sum_{i=1}^n \frac{M_i(-)I_i}{S_i - I_i}}{S_i - I_i} \times 100 \quad (2)$$

Where M_i is the monitored value of heavy metal of i th parameter, I_i is the ideal value of i th parameter, and S_i is the standard value of the i th parameter, in mg/L. The sign (-) indicates the numerical differences of the two values, ignoring the algebraic sign. Generally, the critical pollution index value is 100. HPI index less than 100 indicates that it is a low-level heavy metal and has no adverse health effects. When the value of HPI is equal to 100, it indicates that the threshold risk and adverse health effects are possible. If the HPI value is more than 100, water cannot be used for drinking and is unsuitable for consumption [7, 9, 13-15].

0.252), (0.016 ± 0.123), (0.0004 ± 0.0017), (0.178 ± 0.889), (2.939 ± 6.751) and (0.684 ± 2.325) mg/L, for As, Zn, Pb, Cd, Cr, Cu, and Mn respectively (Figure 2). Based on these results, it was observed that concentrations of As, Pb, Cr, Cu and Mn were above the highest desirable limit of WHO drinking water standard (Table 3). It has been observed that concentrations of heavy metals such as Cd and Zn were well below the permissible limits of WHO drinking water standard. The high concentrations of heavy metals in the samples could be explained by the release of heavy metals from mining waste throughout the Tongon mine area. Concerning the groundwater samples (Table 4), the metal concentrations (mg/L) ranged from 0.002 to 0.263 for As, 0.019 to 0.071 for Zn, 0.002 to 0.034 for Pb, $<LOD$ to 0.00019 for Cd, 0.017 to 0.040 for Cr, 0.005 to 0.198 for Cu, and 0.008 to 4,025 for Mn. The mean concentrations of all groundwater samples were (0.036 ± 0.112), (0.037 ± 0.048), (0.009 ± 0.025), (0.000024 ± 0.000152), (0.021 ± 0.026), (0.025 ± 0.117) and (0.662 ± 1.283) mg/L, for As, Zn, Pb, Cd, Cr, Cu, and Mn respectively (Figure 3). Excepted As and Mn, the metal concentrations were well below the permissible limits of WHO drinking water standard (Table 3).

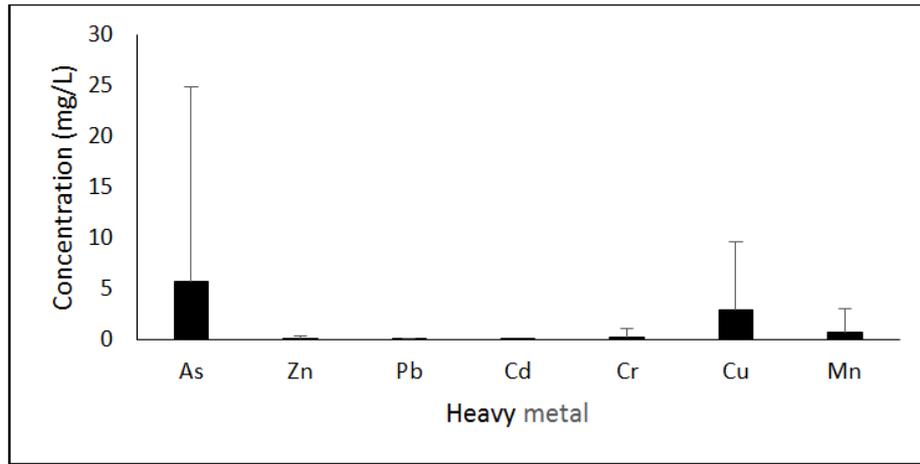


Figure 2. Heavy metal concentrations of all surface water samples.

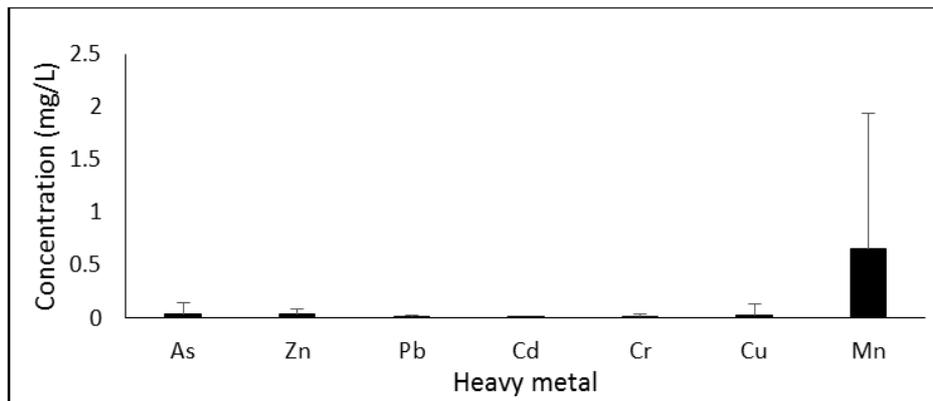


Figure 3. Heavy metal concentrations of all groundwater samples.

Table 3. Concentration of heavy metals in surface water samples (mg/L).

Sstation	As		Zn		Pb		Cd		Cr		Cu		Mn	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1	0.068	0.054	0.060	0.035	0.002	0.002	0.00004	0.00005	0.018	0.022	0.006	0.005	0.094	0.079
2	3.265	3.290	0.039	0.016	0.003	0.002	0.00020	0.00040	0.024	0.014	8.300	5.683	0.060	0.000
3	3.672	7.062	0.055	0.088	0.002	0.001	0.00005	0.00015	0.028	0.033	1.085	3.283	0.353	0.349
4	0.055	0.129	0.042	0.033	0.003	0.004	0.00000	0.00000	0.016	0.016	0.015	0.029	0.324	0.272
5	0.294	0.437	0.031	0.040	0.003	0.003	0.00014	0.00021	0.019	0.018	0.011	0.005	0.070	0.081
6	0.015	0.012	0.050	0.021	0.002	0.001	0.00008	0.00010	0.037	0.005	0.011	0.006	0.068	0.043
7	0.032	0.021	0.042	0.021	0.003	0.002	0.00020	0.00040	0.042	0.008	0.027	0.031	0.112	0.062
8	0.146	0.051	0.009	0.002	0.002	0.001	0.00002	0.00004	0.015	0.016	0.008	0.002	0.056	0.019
9	0.657	0.675	0.059	0.085	0.002	0.001	0.00024	0.00032	0.035	0.048	0.018	0.032	0.074	0.096
10	6.650	1.066	0.005	0.004	0.001	0.001	0.00005	0.00010	0.006	0.001	0.024	0.029	10.900	0.000
11	0.012	0.007	0.035	0.034	0.002	0.001	0.00000	0.00000	0.012	0.013	0.008	0.005	0.214	0.134
12	0.011	0.016	0.040	0.027	0.001	0.001	0.00000	0.00000	0.012	0.017	0.004	0.001	0.920	0.000
13	0.009	0.017	0.029	0.025	0.001	0.001	0.00000	0.00000	0.016	0.016	0.007	0.006	0.086	0.046
14	0.219	0.214	0.035	0.041	0.001	0.001	0.00017	0.00030	0.016	0.017	0.006	0.004	0.062	0.044
15	0.132	0.137	0.036	0.029	0.002	0.001	0.00016	0.00029	0.016	0.017	0.007	0.005	0.217	0.128
16	0.106	0.095	0.041	0.056	0.002	0.001	0.00015	0.00029	0.016	0.016	0.007	0.003	0.398	0.490
17	0.011	0.013	0.034	0.028	0.001	0.001	0.00004	0.00014	0.018	0.018	0.005	0.003	0.094	0.019
1	15.862	12.024	0.107	0.220	0.002	0.002	0.00032	0.00058	0.036	0.024	13.539	11.008	0.030	0.021
19	10.800	4.525	0.007	0.000	0.009	0.012	0.00000	0.00000	0.023	0.023	14.275	8.096	0.001	0.002
20	9.172	8.567	0.041	0.054	0.001	0.001	0.00022	0.00037	0.028	0.035	13.646	8.143	0.326	0.321
21	53.508	54.914	0.625	0.817	0.228	0.455	0.00403	0.00596	2.505	2.711	9.526	9.420	6.718	6.086

Table 4. Concentrations of heavy metal in groundwater samples (mg/L).

Station	As		Zn		Pb		Cd		Cr		Cu		Mn	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
22	0.006	0.007	0.029	0.023	0.002	0.005	0.00002	0.00004	0.017	0.017	0.016	0.019	0.096	0.014
23	0.002	0.003	0.019	0.016	0.003	0.006	0.00002	0.00006	0.017	0.017	0.009	0.009	0.113	0.033
24	0.003	0.003	0.023	0.017	0.002	0.001	0.00001	0.00004	0.018	0.017	0.007	0.003	0.261	0.249
25	0.006	0.005	0.023	0.015	0.013	0.012	0.00002	0.00006	0.017	0.018	0.023	0.062	2.474	0.409
26	0.024	0.027	0.071	0.138	0.006	0.003	0.00001	0.00003	0.034	0.020	0.009	0.008	0.075	0.080
27	0.004	0.005	0.034	0.032	0.002	0.002	0.00004	0.00011	0.023	0.017	0.010	0.003	0.312	0.642
28	0.263	0.291	0.034	0.029	0.034	0.078	0.00019	0.00054	0.040	0.077	0.198	0.408	1.013	0.978
29	0.098	0.046	0.050	0.044	0.025	0.031	0.00001	0.00003	0.022	0.018	0.023	0.037	1.687	0.294
30	0.002	0.002	0.058	0.022	0.001	0.001	0.00000	0.00000	0.018	0.017	0.009	0.006	0.008	0.008
3	0.025	0.007	0.045	0.034	0.008	0.004	0.00001	0.00003	0.020	0.016	0.013	0.007	0.113	0.132
32	0.078	0.195	0.045	0.057	0.006	0.005	0.00003	0.00009	0.020	0.019	0.013	0.014	4.025	2.523
33	0.003	0.004	0.033	0.035	0.002	0.002	0.00001	0.00000	0.018	0.018	0.007	0.006	0.014	0.011
34	0.009	0.019	0.030	0.039	0.003	0.003	0.00001	0.00000	0.017	0.016	0.009	0.006	0.010	0.006
35	0.005	0.003	0.041	0.034	0.019	0.020	0.00002	0.00004	0.019	0.018	0.005	0.002	0.269	0.802
36	0.009	0.014	0.033	0.027	0.016	0.023	0.00002	0.00006	0.018	0.017	0.009	0.011	0.021	0.024
37	0.007	0.012	0.022	0.024	0.007	0.006	0.00001	0.00001	0.017	0.017	0.006	0.003	0.065	0.153

The analysis of variance was performed using metal data to compare heavy metal concentrations in surface water samples with those in groundwater. It was observed that concentrations of As, Zn, Cd, Cd, Cr and Cu in surface water samples were statistically higher than those in groundwater (Table 5). This difference is due to the absorption of metals by the different components of the soil and sediments such as carbonates, oxides and organic matter.

Table 5. ANOVA test for significance between surface water and groundwater (difference are significant at $P < 0.05$).

	SC	dl	MC	SC	dl	MC	F	p
As	3071.370	1	3071.370	69308.85	373	185.8146	16.52922	0.000058
Zn	0.162	1	0.162	11.45	343	0.0334	4.85819	0.028179
Pb	0.004	1	0.004	2.97	373	0.0080	0.48765	0.485413
Cd	0.000	1	0.000	0.00	373	0.0000	6.85664	0.009191
Cr	2.293	1	2.293	150.47	373	0.4034	5.68437	0.017616
Cu	796.423	1	796.423	8663.16	373	23.2256	34.29070	0.000000
Mn	0.026	1	0.026	690.13	225	3.0672	0.00842	0.926973

Table 6 gives the reported concentration range of metals in surface water and groundwater by various studies conducted in Cote d'Ivoire. It can be seen that the concentrations of heavy metals reported in the present investigation are below

than the high concentration range reported by Bakary et al., and Coulibaly et al [17, 18]. It is observed that the concentration range of Zn, Cd and Pb are similar to the low concentration range reported by Naminata et al [16].

Table 6. Heavy metal concentrations (mg/L) reported in Cote d'Ivoire water samples in other studies.

Location	As	Zn	Pb	Cd	Cr	Cu	Mn	Reference
Surface water and groundwater water (MBadon)	-	0.03 – 0.06	0.26-0.86	0.04-0.24	-	0.007-3.93	-	[16]
Milliardaires Bay	-	1.14 - 4.33	0.31 - 1.73	0.03 - 0.17	-	0.04 - 0.14	-	[17]
Bietri Bay	-	12.05 - 19.87	2.40 - 4.80	0.02 - 0.26	-	9.05 - 9.68	-	[18]
Surface and ground water around Tongon mine	< LOD - 13.91	0.01 - 2.63	< LOD - 1.60	< LOD - 0.02	< LOD - 9.00	< LOD - 39.00	< LOD - 14.30	present study

A number of significant correlations were obtained in the Study (Table 7). The correlation at 5% level of significance ($P < 0.05$) shows significant correlation between the following pairs As and Zn, Pb, Cr; Cd, Cu and Mn; Zn and As, Pb, Cd, Cr and Mn; Pb and As, Zn, Cd, Cr, and Mn; Cd and As, Zn, Pb, Cr, and Mn; Cr and As, Zn, Cd and Mn; Mn and As, Zn, Cd and Cr. Cu shows significant correlation with As. Overall the convergent results indicated that the significant correlation was correlated with a common source. The source of these elements is the gold mining activity.

Table 7. Correlation matrix between heavy metals (bold correlations are significant at $P < 0.05$).

	As	Zn	Pb	Cd	Cr	Cu	Mn
As	1,00						
Zn	0,85	1,00					
Pb	0,48	0,47	1,00				
Cd	0,89	0,91	0,39	1,00			
Cr	0,88	0,90	0,48	0,99	1,00		
Cu	0,39	0,03	0,01	0,05	0,05	1,00	
Mn	0,63	0,63	0,39	0,67	0,66	-0,01	1,00

3.2. Heavy Metal Pollution Index

Mean concentrations of the analysed metals were used to calculate the HPI values. The HPI values of surface water sampling sites ranged from 50.03 to 794.51 (Table 8) Sampling sites N° 10, 18, 19, 19, 20 and 21 have HPI values higher than the critical HPI threshold value (100). These sampling sites are contaminated. The higher values of HPI may be attributed to the gold mining activity [13]. The water in these sampling sites come from directly of the mine plant, the artificial dam, and the artificial lake, which is created to collect runoff water during rainfall in the mine. It is

important to note that the Tongon mine has a water reusing system. This system uses the contaminated surface water in the processes of the mine plant. The sampling site N°8 is located at the site where the mine water is discharged into the environment. The HPI value of the sampling station N° 8 was below 100 (Figure 4). It is far below the critical HPI threshold value (Table 8). It indicates that the sampling site N° 8 is not contaminated by the heavy metals studied. It shows that the water reusing system in the Tongon mine is operating. It is confirmed by HPI values of the sampling station N°12, 15 and 16 which were below 100. These sampling stations are located at the Pougbe River.

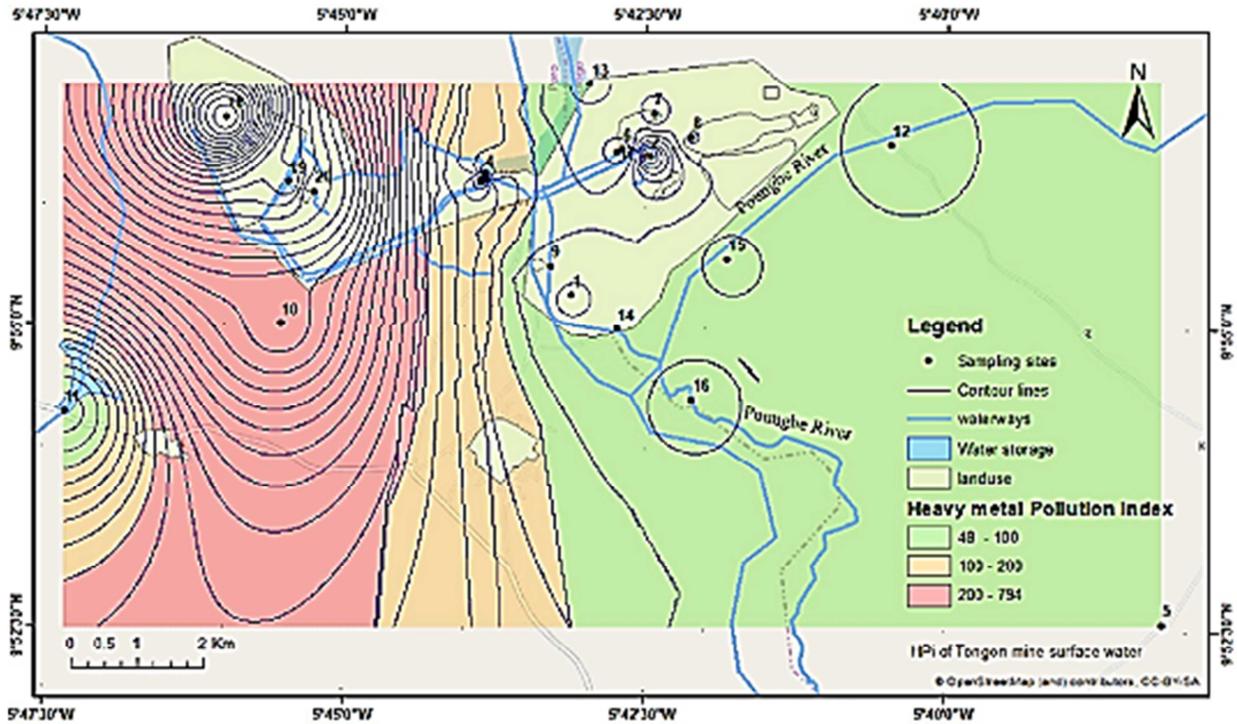


Figure 4. HPI map of surface water around Tongon mine.

Table 8. Heavy metal pollution index of surface water sampling stations.

Station	Qi-As	Qi-Zn	Qi-Pb	Qi-Cd	Qi-Cr	Qi-Cu	Qi-Mn	Wi×Qi-As
1	145.00	146.98	8.78	148.00	64.49	199.42	101.50	2.90
2	8137.50	148.03	7.43	140.00	53.06	630.00	110.00	162.75
3	9153.85	147.25	9.07	147.31	45.37	91.53	36.79	183.08
4	111.58	147.88	7.72	150.00	70.17	198.47	44.08	2.23
5	709.75	148.44	8.18	143.13	64.03	198.95	107.50	14.20
6	11.88	147.50	8.67	146.25	26.02	198.88	108.13	0.24
7	53.75	147.91	7.89	140.00	17.35	197.33	97.00	1.08
8	340.50	149.56	9.36	149.00	71.43	199.20	111.13	6.81
9	1617.92	147.07	9.14	137.92	31.46	198.24	106.46	32.36
10	16600.00	149.77	9.92	147.50	90.82	197.58	2600.00	332.00
11	4.09	148.25	8.49	150.00	76.81	199.15	71.56	0.08
12	2.88	147.99	10.28	150.00	77.55	199.63	105.00	0.06
13	3.21	148.55	9.56	150.00	68.92	199.27	103.46	0.06
14	521.29	148.24	9.96	141.54	68.76	199.39	109.50	10.43
15	303.96	148.22	8.97	142.08	70.41	199.32	70.65	6.08
16	240.81	147.93	8.82	142.50	68.54	199.32	25.40	4.82
17	1.50	148.31	10.00	147.92	65.48	199.51	101.63	0.03
18	39628.85	144.66	8.83	134.23	28.89	1153.92	117.42	792.58
19	26975.00	149.65	1.67	150.00	55.10	1227.50	125.00	539.50
20	22903.85	147.97	9.54	139.23	43.96	1164.62	43.50	458.08
21	133745.83	118.75	242.75	51.25	5010.71	752.58	1554.50	2674.92

Table 8. Continued.

Station	Wi×Qi-Zn	Wi×Qi-Pb	Wi×Qi-Cd	Wi×Qi-Cr	Wi×Qi-Cu	Wi×Qi-Mn	ΣWi×Qi	HPI
1	0.03	6.14	44.40	1.29	0.20	2.03	56.99	53.71
2	0.03	5.20	42.00	1.06	0.63	2.20	213.87	201.54
3	0.03	6.35	44.19	0.91	0.09	0.74	235.38	221.81
4	0.03	5.40	45.00	1.40	0.20	0.88	55.15	51.97
5	0.03	5.73	42.94	1.28	0.20	2.15	66.52	62.68
6	0.03	6.07	43.88	0.52	0.20	2.16	53.09	50.03
7	0.03	5.52	42.00	0.35	0.20	1.94	51.11	48.16
8	0.03	6.55	44.70	1.43	0.20	2.22	61.94	58.37
9	0.03	6.40	41.38	0.63	0.20	2.13	83.12	78.32
10	0.03	6.94	44.25	1.82	0.20	52.00	437.24	412.02
11	0.03	5.95	45.00	1.54	0.20	1.43	54.22	51.10
12	0.03	7.19	45.00	1.55	0.20	2.10	56.13	52.90
13	0.03	6.69	45.00	1.38	0.20	2.07	55.44	52.24
14	0.03	6.97	42.46	1.38	0.20	2.19	63.65	59.98
15	0.03	6.28	42.63	1.41	0.20	1.41	58.03	54.69
16	0.03	6.18	42.75	1.37	0.20	0.51	55.85	52.63
17	0.03	7.00	44.38	1.31	0.20	2.03	54.98	51.81
18	0.03	6.18	40.27	0.58	1.15	2.35	843.14	794.51
19	0.03	1.17	45.00	1.10	1.23	2.50	590.53	556.47
20	0.03	6.68	41.77	0.88	1.16	0.87	509.47	480.09
21	0.02	169.93	15.38	100.21	0.75	31.09	2992.30	719.73

The HPI values of groundwater ranged from 48.56 to 72.49 (Table 9). All groundwater-sampling sites have HPI values below the critical HPI limit value (Figure 5). It shows, in general, that the groundwater samples are not contaminated with respect to heavy metals pollution.



Figure 5. HPI map of groundwater around Tongon mine.

Table 9. Heavy metal pollution index of groundwater sampling stations.

Station	Qi-As	Qi-Zn	Qi-Pb	Qi-Cd	Qi-Cr	Qi-Cu	Qi-Mn	Wi×Qi-As
22	9.67	148.53	8.38	149.23	66.56	198.36	100.95	0.19
23	19.67	149.07	8.17	149.23	66.88	199.14	96.80	0.39
24	17.25	148.86	8.97	149.38	65.31	199.34	59.68	0.35
25	9.63	148.84	2.85	149.17	66.67	197.67	493.50	0.19
26	34.90	146.46	4.97	149.62	32.65	199.15	106.38	0.70
27	16.06	148.31	8.61	148.13	54.34	198.98	46.95	0.32
28	633.27	148.30	27.10	140.38	19.94	180.19	128.25	12.67
29	221.04	147.48	16.43	149.58	57.48	197.68	296.67	4.42
30	21.15	147.08	9.49	150.00	66.16	199.08	122.93	0.42
31	37.71	147.74	2.70	149.58	60.88	198.73	96.64	0.75
32	169.02	147.76	4.98	148.64	62.15	198.67	881.25	3.38
33	17.37	148.33	9.12	150.00	66.25	199.26	121.55	0.35
34	3.13	148.50	8.24	150.00	67.01	199.08	122.58	0.06
35	12.58	147.93	9.67	149.17	63.61	199.49	57.80	0.25
36	2.83	148.35	6.96	149.23	64.68	199.12	119.78	0.06
37	7.44	148.91	3.77	150.00	67.19	199.37	108.75	0.15

Table 9. Continued.

Station	Wi×Qi-Zn	Wi×Qi-Pb	Wi×Qi-Cd	Wi×Qi-Cr	Wi×Qi-Cu	Wi×Qi-Mn	ΣWi×Qi	HPI
22	0.03	5.87	44.77	1.33	0.20	2.02	54.41	51.27
23	0.03	5.72	44.77	1.34	0.20	1.94	54.38	51.25
24	0.03	6.28	44.81	1.31	0.20	1.19	54.17	51.04
25	0.03	2.00	44.75	1.33	0.20	9.87	58.37	55.00
26	0.03	3.48	44.88	0.65	0.20	2.13	52.07	49.07
27	0.03	6.03	44.44	1.09	0.20	0.94	53.04	49.98
28	0.03	18.97	42.12	0.40	0.18	2.57	76.93	72.49
29	0.03	11.50	44.88	1.15	0.20	5.93	68.10	64.18
30	0.03	6.64	45.00	1.32	0.20	2.46	56.08	52.84
31	0.03	1.89	44.88	1.22	0.20	1.93	50.90	47.97
32	0.03	3.49	44.59	1.24	0.20	17.63	70.55	66.48
33	0.03	6.38	45.00	1.32	0.20	2.43	55.72	52.50
34	0.03	5.77	45.00	1.34	0.20	2.45	54.85	51.69
35	0.03	6.77	44.75	1.27	0.20	1.16	54.43	51.29
36	0.03	4.87	44.77	1.29	0.20	2.40	53.61	50.52
37	0.03	2.64	45.00	1.34	0.20	2.18	51.54	48.56

suggestions to the draft manuscript.

4. Conclusion

In this research, the heavy metal concentrations were first evaluated, and then a Heavy Metal Pollution Index was calculated for surface water and groundwater around the Tongon gold mine. The findings of the present research are summarized as follows:

- i. The concentration of As, Pb, Cr, Cu and Mn has been found more than the highest desirable limit of WHO drinking water standard in the majority of sampling stations for surface water.
- ii. The surface water of the sampling site, which has the HPI values above the critical index value of 100 was used by the water reusing system of the mine.
- iii. In general, the groundwater is not contaminated with respect to heavy metals pollution.

Acknowledgements

The authors want to thank authorities of Tongon gold mine for their support for this study. Thanks to Dr Julien Bahino in atmospheric physics laboratory of FHB University, Abidjan, Côte d'Ivoire, for their help and

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