Journal of Environment Pollution and Human Health, 2020, Vol. 8, No. 1, 20-28
Available online at http://pubs.sciepub.com/jephh/8/1/3
Published by Science and Education Publishing
DOI:10.12691/jephh-8-1-3

Physical and Chemical Characterization of the Bagoue Watershed (North-Western Cote D'Ivoire) Impacted by Artisanal and Clandestine Gold Mining

Augustin KOUAME N'guessan[1,*], KOUAME Mathias Koffi[1,2], Marius Tanoh KAMELAN[1], Valentin N'DOUBA[1]

[1]Hydrobiology and Water Eco-technology Laboratory, Department of Biological Sciences,
Felix Houphouët Boigny University (Abidjan Côte d'Ivoire) 22 Box 582 Abidjan 22, Côte d'Ivoire
[2]National Agricultural Development Support Laboratory, Box 612 Abidjan, Côte d'Ivoire
*Corresponding author: augustkouame@yahoo.fr

Received December 26, 2019; Revised February 05, 2020; Accepted February 22, 2020

Abstract A study on some physical and chemical variables of water quality was conducted on North-western Ivory Coast. The objective was to assess the physico-chemical quality of Bagoue watershed subjected to artisanal and clandestine gold mining. Data were collected during four sampling campaigns at six stations from August 2018 to April 2019. Twelve physicochemical variables were measured in-situ and two (total mercury and total suspended solids) were measured in the laboratory. The principal component analysis was carried out in order to classify the watershed in an area. The Kruskall-wallis test was applied to determine spatial variation in physicochemical parameters. Spearman's test assessed the level of correlation between physicochemical variables. The results suggested a spatial variation in transparency and total suspended solids. In areas heavily impacted by illegal gold mining, in downstream, water is less oxygenated (3.86±0.42 mg/L), less transparent (25.25±4.24 cm) with heavy loads of suspended solids (92.62±26.81 mg/L). The average level of mercury was estimated at 0.68±0.03 µg/L for this study. Ultimately, strong correlations have been observed between dissolved substances and transparency (r = +0.84), between total phosphorus and resistivity (r = -1.00) among other things. In the overall, the results showed that Bagoue watershed has not yet reached the critical threshold of physicochemical pollution. Nevertheless, a greater pollution gradient downstream than upstream has been observed. In addition, waters of the basin are gradually enriching in mercury.

Keywords: *water quality, mercury, artisanal gold mining, Bagoue River, Côte d'Ivoire*

Cite This Article: Augustin KOUAME N'guessan, KOUAME Mathias Koffi, Marius Tanoh KAMELAN, and Valentin N'DOUBA, "Physical and Chemical Characterization of the Bagoue Watershed (North-Western Cote D'Ivoire) Impacted by Artisanal and Clandestine Gold Mining." *Journal of Environment Pollution and Human Health*, vol. 8, no. 1 (2020): 20-28. doi: 10.12691/jephh-8-1-3.

1. Introduction

The price of agricultural raw materials fell drastically in the north of Côte d'Ivoire with the socio-political crisis since 2002 resulting in the peasant mass' agricultural incomes decrease. In this situation, small-scale and clandestine gold mining became for people of Bagoue region as an alternative [1]. It's recognized as a major contributor to national income and a pillar of poverty reduction in developing countries [2] like Côte d'Ivoire. Unfortunately, these artisanal gold mining practices, which are one of the main causes of ecosystem pollution [3,4], are being done without any follow-up in this region. However, the persistence of this uncontrolled activity in watersheds leads to changes in physicochemical parameters of aquatic environments [5]. These changes have many implications for both aquatic organisms and human health [4,6,7].

In the Ivorian aquatic environment, several works relating to physical and chemical characteristics of waters have been carried out to assess the impact of anthropogenic activities. The results reveal in the majority of cases, the attainment of worrying levels of degradation, particularly surface waters [8,9,10,11]. Most of this work has been carried out in the southern part of the country. In the case of Bagoue River watershed, there has been little interest in physicochemical characteristics for scientific research, despite the growing anthropogenic pressures. The only work carried out in this basin is those of the "reference [12]" about the relation between zooplankton and environmental parameters and the "reference [13]" about the zooplankton diversity of Bagoue tributary. None of this work addressed the impact of human activities on physicochemical variables of the environment. To understand the scope and depth of the problems associated with artisanal mining, there is the need to study the levels of pollution in a location where artisanal mining takes place. Therefore, diagnosis of the current situation of level of pollution and rigorous monitoring of the variation of these parameters are of great necessity for preservation of this naturel heritage. So, the main goal of this study is to assess the physicochemical quality of Bagoue watershed, which is subject to the influence of artisanal gold mining.

2. Material and Methods

2.1. Study Area

The Bagoue River basin, tributary in the Niger stream, is situated in the North of Côte d'Ivoire between latitudes 9°15′-10°50′N and longitudes 5°40′-7°10′W (Figure 1). The Bagoue River system has a total catchment area of about 33 430 Km^2 [12] shared between Côte d'Ivoire, Mali and Niger. This basin has its source at west of Boundiali, in Madinani region and stretches for 350 km [14]. On Ivorian territory, this watershed covers Boundiali, Kouto and Tengrela departments. The Bagoue River watershed undergoes the influence Soudano-guineen climate characterized by two contrasting seasons ranging from a rainy season (May-October) to a dry season (November-April) [15]. The hydrologicalregime of the Bagoue River is experiencing major irregularities. It includes a period of low flows (stretching) from November to May, and a period of high flows (crude) from June to September. For the present study, surveys were carried out in 6 sampling sites (Figure 1).

2.2. Sample Collection

Environmental variables were collected during the rainy season (August-November 2018) and the dry season (January-April 2019)

The physical and chemical parameters (temperature, pH, dissolved oxygen, electrical conductivity, resistivity, redox potential, total dissolved solids) were measured, with a portable multi-parameter probe, *HANNA HI* 9828.Water transparency was measured using a Secchi disk. Nutrients (NO_2^-, PO_4^{3-}, total-PO_4 and total-Cl^-) have been measured in-situ with *HANNA*-branded digital mini-photometers and *HANNA* kits. For dosage of total solids suspended, 1000 ml water samples were collected and packaged in polyethylene vials. Total mercury was analysed by taking water samples using sterile gloves [16] at a depth of 10 cm [17,18]. Water collected was first filtered through a 45 µm porous filter and packaged in 1000 ml sterilized vials. It was then stabilized by addition of 1% concentration hydrochloric acid [19]. All samples were labelled, wrapped in aluminium foil and stored in an ice chest at 4 °C and transported to the laboratory according to "reference [20] and [19]". Total solids suspended were balanced using vacuum filtration method with a fiberglass filter of nominal porosity estimated at 1,5 µm according to [21]. Total mercury was analysed by atomic absorption spectrophotometry equipped with a cold vapour system (VGA 77). All analyses were done in three remnants per parameter.

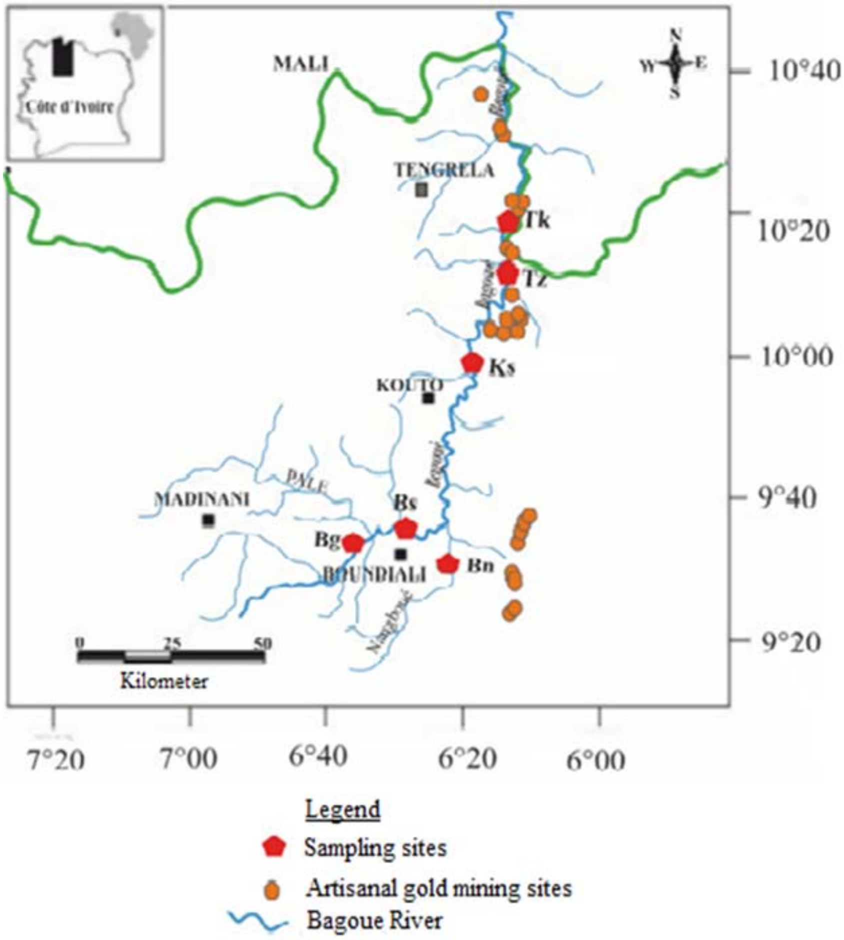

Figure 1. Map of the Bagoue River watershed in Côte d'Ivoire with sampling position sites

2.3. Statistical Analysis

Descriptive analysis was applied to physicochemical data. Before performing comparison test, normality of data was verified by Shapiro-wilk test at critical probability value of 0.05.The Kruskall-wall is test, was used to verify the significance of spatial variations in environmental parameters [22]. Significance was tested at an alpha value of 0.05. Spearman's analysis was used to estimate the correlation between variables. In order to establish a zonation of watershed, all the physicochemical parameters were ordinated using principal components analysis (PCA). All statistical analyses were performed using *XLSTAT 2018* software.

3. Results

3.1. General Trend of Environmental Parameters in the Whole River

The average values of environmental variables measured in the watershed are presented in Table 1.

Table 1. Annual data of environmental parameters measured in Bagoue watershed from August 2018 to April 2019.

Variables	Min	Max	Median	Average	Std error
Hg-t (µg.L^{-1})	0.64	00.72	00.69	00.68	00.03
T (°C)	23.64	27.46	26.24	26.01	01.33
DO (mg.L^{-1})	03.42	04.92	04.04	04.07	00.51
pH	06.26	07.01	06.57	06.57	00.28
EC (µs.cm^{-1})	39.02	55.02	46.78	47.03	07.43
TDS (mg.L^{-1})	22.62	30.45	26.16	26.46	03.86
ER (kΩ.cm)	19.62	30.75	22.31	23.57	04.21
TSS (mg.L^{-1})	07.61	111.58	28.67	43.53	41.58
Eh (mV)	16.00	118.50	68.59	68.65	36.63
trans (cm)	19.87	55.75	35.25	35.89	14.55
Cl-t (µg.L^{-1})	41.66	118.33	62.46	69.43	27.51
NO_2 (µg.L^{-1})	05.33	152.33	66.66	68.08	54.03
PO_4^{3-} (µg.L^{-1})	73.66	340.00	121.66	167.71	112.69
PO_4-t (µg.L^{-1})	34.66	155.33	71.00	87.74	50.88

Hg-t= total mercury, DO = dissolved oxygen, EC = electrical conductivity, TDS = total dissolved solids,
ER = electrical resistivity, TSS = total suspended solids, Eh = redox potential, Cl-t = total chlorine, NO_2 = nitrite, PO_4^{3-} = orthophosphate, PO_4-t = total phosphorus

Sampling sites are characterized by total mercury (Hg-t) levels that vary from 0.64 to 0.72 µg.L^{-1} with an average of 0.68±0.03 µg.L^{-1}. Water temperature varied between 23.64 and 27.46°C. Dissolved oxygen concentration varied between 3.42 to 4.92 mg.L^{-1}. Its average value is 4.07±0.51µg.L^{-1}. Water pH was generally acid (< 7) and varied from 6.26to 7.01. Conductivity values are between 39.02 and 55.02 µS.cm^{-1}with an average of 47.03±7.43 µS.cm^{-1}, while those of resistivity range from 19.62 to 30.75kΩ. cm. Generally, water total dissolved solids concentration varied between 22.62 and 30.45 with an average of 26.46±3.86 mg.L^{-1}. In the Bagoue River basin, the concentration of total suspended solids in water ranged from 7.61 to 111.58 with an average of 43.53±41.58 mg.L^{-1}. On the other hand, water transparency is measured between 19.87 and 55.75 with an average of 35.89±14.55 cm. In addition to these parameters, some ion characteristics have been determined. Thus, total chlorine values obtained fluctuated between 41.66 and 118.33 µg.L^{-1}, while those of nitrites varied from 5.33 to 152.33 µg.L^{-1}. Orthophosphate concentrations were higher than total phosphorus with averages of 167.71±112.69 and 87.74±50.88 µg.L^{-1} respectively.

3.2. Spatial Variation of Physicochemical Parameters

With the data obtained for water physical and chemical variables, a Principal Component Analysis was performed. Only the first two components were considered since they together explained 65.46% of the total variance (Figure 2).

The first principal component was responsible for 42.47% of the total variance. The second principal component represented 22.99% of the variance. When diagram is analysed considering axis 2, the separation of the stations in two zones, downstream and upstream, can be observed. The downstream watershed includes Tengrela (Tk, Tz) and Kouto (Ks) stations. At these stations, values of total mercury, total suspended solids, potential redox, temperature and nitrite are higher. Upstream stations in Boundiali (Bs, Bg et Bn) are characterized generally by higher values of conductivity, transparency, phosphorus, total dissolved solids, dissolved oxygen and chlorine, notably at Samorosso (Bs) and Guinguereni (Bg) stations. Also in upstream areas, the N'dara station (Bn) located on the tributary of the Bagoue River's characterized by high orthophosphate levels and higher resistivity.

The first principal component was responsible for 42.47% of the total variance. The second principal component represented 22.99% of the variance. When diagram is analysed considering axis 2, the separation of the stations in two zones, downstream and upstream, can be observed. The downstream watershed includes Tengrela (Tk, Tz) and Kouto (Ks) stations. At these stations, values of total mercury, total suspended solids, potential redox, temperature and nitrite are higher. Upstream stations in Boundiali (Bs, Bg et Bn) are characterized generally by higher values of conductivity, transparency, phosphorus, total dissolved solids, dissolved oxygen and chlorine, notably at Samorosso (Bs) and Guinguereni (Bg) stations. Also in upstream areas, the N'dara station (Bn) located on the tributary of the Bagoue River's characterized by high orthophosphate levels and higher resistivity.

The results of the spatial distribution of environmental variables are recorded in Table 2.

Analysis of the results based on Kruskall-wall is comparison's test revealed a significant spatial variation in suspended materials (*p= 0.004*) and water transparency (*p= 0.037*). Highest total suspended solids ((111.58±188.29 mg.L^{-1}) were observed at Zanikaha (Tz) and Kanakono (T_K) sites, downstream, whereas lowest (7.61±6.78 mg.L^{-1}) were obtained at Kouto site (Ks), still downstream. It was also verified that transparency averages values were generally lower for the sampling sites located downstream system (22.25±13.5 cm at Zanikaha (Tz) site and 28.5±19.46 cm at Tk site), as well as for a tributary to the Bagoue River (19.87±9.04 cm). Considering transparency, the greater values (55.75±8.73 cm) occurred at Samorosso site (Bs), located upstream. No significant variation (p > 0.05) was observed for the other parameters. Nevertheless, the apparent fluctuations of a few variables should be noted. As observed averages values of Hg-t, the highest concentrations (0.70±0.19 µg.L^{-1} and 0.72±0.19 µg.L^{-1}) have been observed respectively in the sites Tk and Tz, at downstream. Low temperature value (23.63±0.16°C)was measured at N'dara (Bn) station, on the tributary of Bagoue River. Values were roughly the same (26- 27°C) on other stations.pH value of water was neutral (7.01±0.55) at Bs station and slightly acidic on the other stations. The dissolved oxygen level was generally low at all stations but the lowest rate (3.90±1.76 mg.L^{-1}) was obtained at Tk station. The highest value of redox potential (118.50±58.15 mV) was recorded upstream, at Guinguereni (Bg) station and the lowest value (16.00±85.99 mV) downstream (Tz site). Fluctuation were not marked for resistivity, conductivity total dissolved solid from one station to another. In terms of nutrients, the results showed that values of total chlorine (118.33±115.57 µg.L^{-1}), nitrite (152. 33±240.69 µg.L^{-1}), phosphate (340.00±385.74µg.L^{-1}) and total phosphorus (155±65.61 µg.L^{-1}) were higher at Bg, Ks, Bn and Ks stations respectively.

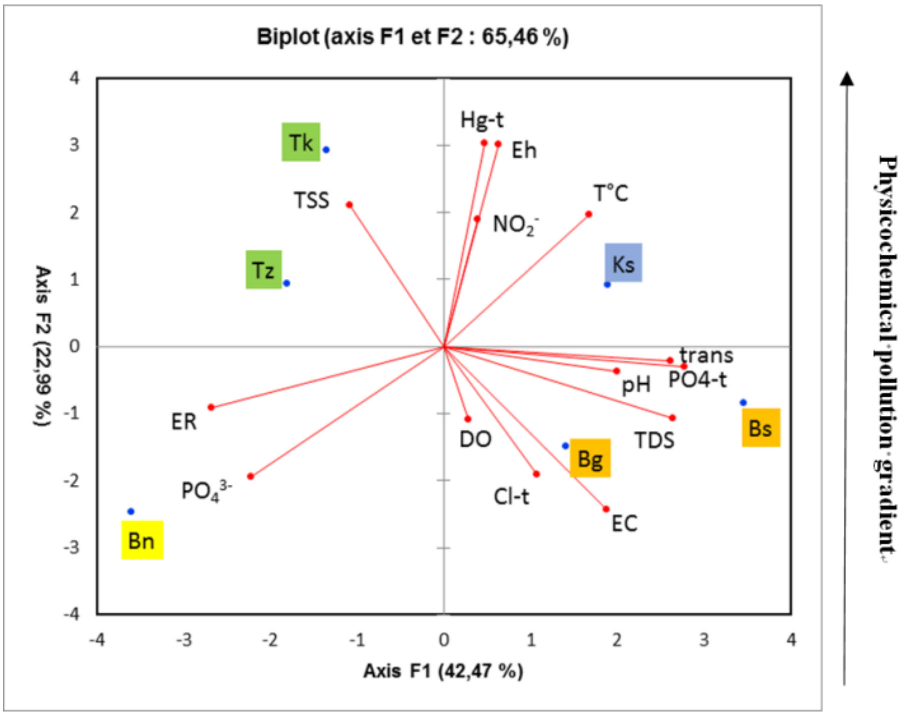

Figure 2. Principal Components Analysis of data from environmental factors in the Bagoue watershed (Côte d'Ivoire) from August 2018 to April 2019 (Tk = Kanakono, Tz = Zanikaha (Tengrela stations) ; Ks = Kouto station; Bs = Samorosso, Bg = Guinguereni, Bn = N'dara (Boundiali stations))

Table 2. Values of environmental factors measured in Bagoue watershed during August 2018 and April 2019

Areas	Sites	Parameters							
			THg (µg.L^{-1})	T (°C)	DO(mg.L^{-1})	pH	Con.(µs.cm^{-1})	res. (kΩ.cm)	TSS (mg.L^{-1})
Downstream	Tk	Min	0.45	21.64	1.91	4.83	33.00	22.00	11.27
		Max	0.88	29.40	5.95	7.70	45.50	26.30	243.00
		median	0.73	27.55	3.87	6.27	38.80	23.60	20.18
		Average	0.70	26.53	3.90	6.27	39.02	23.87	73.66
		St-error	0.19	3.38	1.76	1.35	5.31	2.03	113.10
	Tz (b)	Min	0.55	21.97	3.34	5.97	27.00	20.40	14.18
		Max	0.88	29.75	5.91	7.55	48.10	37.20	394.00
		median	0.72	27.88	3.92	6.54	43.35	22.85	19.07
		Average	0.72	26.87	4.27	6.75	40.45	25.82	111.58(c)
		St-error	0.18	3.40	1.21	0.67	9.24	7.67	188.29
	Ks(c)	Min	0.54	21.40	1.94	5.96	40.60	13.30	0.950
		Max	0.87	28.74	4.50	7.30	75.00	25.20	17.000
		median	0.67	26.25	3.63	6.56	46.15	22.05	6.240
		Average	0.69	25.66	3.42	6.59	51.97	20.65	7.610(b)
		St-error	0.15	3.23	1.08	0.54	15.58	5.12	6.78

Upstream	Bs	Min	0.64	22.80	3.70	6.520	39.200	13.00	8.00
		Max	0.76	30.00	5.53	7.80	77.00	24.90	20.16
		median	0.72	28.53	5.24	6.87	50.25	20.30	20.05
		Average	0.71	27.46	4.92	7.01	54.17	19.62	16.07
		St-error	0.06	3.35	0.84	0.55	17.13	5.46	6.98
	Bg	Min	0.16	21.94	1.98	5.92	39.60	10.40	3.94
		Max	0.93	28.57	5.60	7.30	94.00	25.30	114.00
		median	0.74	26.65	4.75	6.50	43.25	23.65	23.58
		Average	0.64	25.95	3.75	6.55	55.02	20.75	41.27
		St-error	0.33	2.97	1.60	0.59	26.04	6.97	51.62
	Bn	Min	0.45	19.40	0.39	5.25	21.00	12.00	5.65
		Max	0.85	25.22	6.41	7.10	83.00	47.80	16.07
		Median	0.64	24.95	5.45	6.36	31.20	31.60	11.18
		Average	0.64	23.64	4.19	6.26	41.60	30.75	11.02(a)
		St-error	0.16	2.79	2.62	0.79	28.06	14.74	4.50

Areas	Sites	Parameters						
			Eh (mV)	trans (cm)	Cl-t (µg/L)	NO^{2-}(µg/L)	PO_4^{3-}(µg/L)	PO_4^-t (µg/L)
Downstream	Tk	Min	-22.70	5.00	20.00	16.00	0.00	6.00
		Max	220.00	48.00	110.00	200.00	320.00	91.00
		Median	93.00	30.00	23.00	33.00	150.00	71.00
		Average	96.76	28.25	51.00	83.00	156.66	56.00
		Std-error	121.39	19.46	51.11	101.68	160.10	44.44
	Tz(b)	min	-78.80	5.00	10.00	3.00	80.00	3.00
		max	89.00	38.00	126.00	190.00	460.00	98.00
		Median	37.80	23.00	68.000	96.500	270.00	80.00
		Average	16.00	22.25(d)	68.00	96.50	270.00	50.50
		Std- error	85.99	13.50	82.02	132.22	268.70	67.17
	Ks	Min	-50.700	39.00	10.00	3.00	70.00	80.00
		Max	183.600	51.00	80.00	430.00	87.00	200.00
		median	84.200	43.00	35.00	24.00	81.00	186.00
		Average	72.367	41.00	41.66	152.33	79.33	155.33
		Std-error	117.59	5.47	35.47	240.69	8.622	65.61
Upstream	Bs (d)	Min	15.90	45.00	50.00	9.00	70.00	124.00
		Max	103.10	66.00	120.00	29.00	100.00	167.00
		Median	75.50	56.00	72.00	25.00	90.00	141.00
		Average	64.83	55.75(bf)	80.66	21.00	86.66	144.00
		Std-error	44.56	8.73	35.79	10.58	15.27	21.65
	Bg	Min	60.30	19.00	10.00	2.00	60.00	62.00
		Max	176.60	64.00	240.00	8.00	81.00	99.00
		Median	118.60	43.00	105.00	6.00	80.00	97.00
		Average	118.50	42.25	118.33	5.33	73.66	86.00
		Std-error	58.15	24.59	115.57	3.05	11.84	20.80
	Bn (f)	Min	32.60	9.00	0.900	19.00	60.00	23.00
		Max	55.30	31.00	140.00	70.00	780.00	46.00
		Median	42.50	19.75	30.00	62.00	180.00	35.00
		Average	43.46	19.87 (d)	56.96	50.33	340.00	34.66
		Std-error	11.38	9.04	73.36	27.42	385.74	11.50

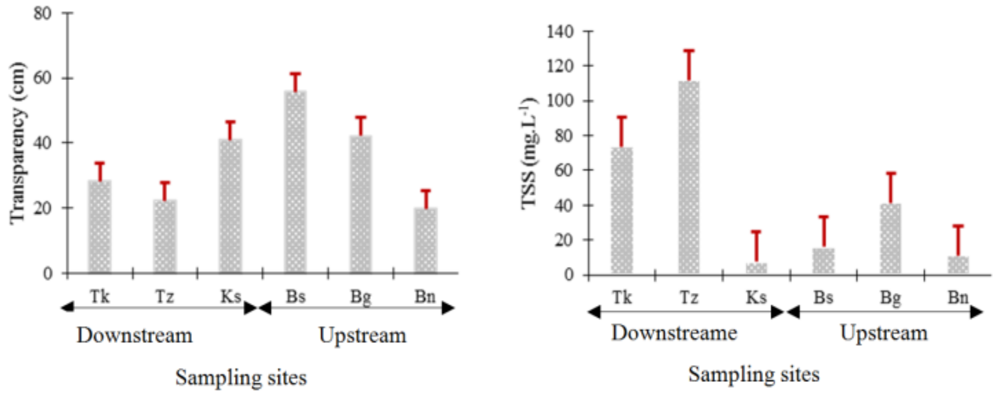

Figure 3. Bar diagram of spatial variation of transparency and total suspended solids (TSS) in the Bagoue watershed

Table 3. Correlation matrix of fourteen different physical and chemical parameters measured in Bagoue watershed from August 2018 to April 2019.

Variables	Hg-t	T°C	DO	pH	EC	TDS	ER	TSS	Eh	Trans	Cl-t	NO_2^-	PO_4^{3-}	PO_4-t
Hg-t	**1**													
T°C	0,37	**1**												
DO	0,08	0,65	**1**											
pH	0,14	0,77	0,42	**1**										
EC	-0,82	-0,02	-0,14	0,31	**1**									
TDS	-0,37	0,46	-0,02	0,69	**0,83**	**1**								
ER	0,08	-0,42	0,08	-0,65	-0,60	**-0,84**	**1**							
TSS	0,42	0,60	0,37	0,14	-0,42	-0,05	0,31	**1**						
Eh	0,54	0,02	-0,65	-0,08	-0,25	0,08	-0,25	0,20	**1**					
Trans	-0,08	0,42	-0,08	0,65	0,60	**0,84**	**-1,00**	-0,31	0,25	**1**				
Cl-t.	-0,77	-0,02	0,02	-0,14	0,71	0,46	-0,31	-0,20	-0,25	0,31	**1**			
NO_2^-	0,25	-0,48	-0,54	-0,37	-0,20	-0,29	-0,20	-0,65	0,42	0,20	-0,14	**1**		
PO_4^{3-}	0,02	-0,08	0,60	0,02	-0,31	-0,52	0,48	-0,14	-0,77	-0,48	-0,37	-0,14	**1**	
PO_4-t.	-0,08	0,42	-0,08	0,65	0,60	**0,84**	**-1,00**	-0,31	0,25	**1,00**	0,31	0,20	-0,48	**1**

Significance was tested at an alpha value of 0,05 for bold values

Figure 3 shows diagrams of parameters presenting significant variation.

The correlation coefficient values of environmental factors are presented in Table 3.

According to Spearman correlation (Table 3), total dissolved solids showed a positive correlation with transparency (r = +0.84) and electrical conductivity (0.83), electrical resistivity showed strong negative correlation with transparency (r = -1) and TDS (r =-0.84). Total phosphorus, on the other hand, showed a significant positive correlation (r = +1.00) with transparency and TDS, while it showed strong negative correlation (r = -1.00) with electrical resistivity.

Table 4. Mercury in freshwater in gold mining areas of Sub-Saharan Africa

Watersheds or Rivers	Hg-t ($\mu g.L^{-1}$)	Country	Authors
Bagoue watershed	0.64-0.72	Côte d'Ivoire	Present study
Pra River	0.028-0.420	Ghana	[23]
Gold mining watershed	0.440	Ghana	[24]
Tank	0.021	Burkina	[25]
Gold mining basin	0.02-2.4	Senegal	[26]
Gambia River	0.005-0.973	Senegal	[27]
Gold mining watershed	0.02-0.65	Zimbabwe	[28]
Witwatersrand basin	0.22	South Africa	[29]
Mining areas	0.001-6.78	Tanzania	[30]

4. Discussion

This work represents the first study on impact of anthropogenic activities, including activities related to artisanal gold mining on the environmental parameters of the Bagoue watershed. In reference to work in Sub-Saharan Africa (Table 4), total mercury (Hg-t) concentrations in the watershed are in the same order of magnitude as previous work.

The rate observed in this study is higher than the level normally found in surface waters, according to "reference [31]". It’s almost similar to the threshold value for protection aquatic wildlife from chronic effects as indicated by the "reference [32]" directive. From the above, it follows that waters of the basin are undergoing an enrichment of Hg-t. Less excessive enrichment likely related to the gravity amalgamation method used by mine operators [33], method requiring only small amounts of Hg-t. Nevertheless, the frequency of its use, the increasing number of mine operators and sites associated time factor, will necessarily contribute to a large accumulation of this metal trace in the aquatic environment. Beyond observations made on Hg-t, other factors are environmental risks. Suspended materials and transparency are part of it [34]. Downstream of watershed, the influx of migrant miners has increased the scale of artisanal mining around and even in the streambed. As a result, water mass degradation processes in terms of increased turbidity and total suspended solids [35] have reached unacceptable levels. As [36] points out, suspended solids and turbidity are among the known impacts of gold mining. Dues to dredging techniques using mobile rigs for alluvial exploitation, river system disturbance is common in this stretch where miners operate. Disturbance causes increased particulate load, hence decreased turbidity [37,38]. These observations are comparable to those reported by [2] in the Bonsa River (Ghana), as well as [39], in a mining basin in California (USA). Upstream of watershed, considered a reference zone, the relatively high level of transparency and low suspension load linked to the limited influence of anthropogenic activities, including gold activities. In any case, the low level of transparency observed at the Bn station, on the tributary of the River is due to the high density of vegetation cover, limiting the penetration of sun's rays. The environmental anoxic trend accelerates the decomposition process of plant debris abundant in the water. According to [37], the organic matter resulting in decomposition helps to increase the load of solid particles suspended and subsequently turbidity.

Clearly, the increase of downstream pollution gradient demonstrates high anthropization of the aquatic system. Indeed, a comparative study conducted by [40] in an undisturbed stream and another, affected by gold mining in South America revealed a pollution of stream impacted by gold mining, notably by high rates of suspended particulates and turbidity. Chronic pollution of a particulate or organic nature, beyond its influence on water quality, disrupts aquatic life [41]. Thus, according to "reference [42]", the persistence of high level of suspended particles in environment induced in fish, clogging of gills and egg-laying habitats, a limitation of sight hunting and a flight of area due to lack of food. Also, it has been observed a reduction of diversity of fish species as well as a decrease of proportion of young fish in environments with high loads of suspended solids [40]. In addition, high turbidity reduces the amount of oxygen in water [38]. For coastal populations, high turbidity makes it impossible to use water for common domestic needs.

The correlation matrix revealed significant links between some variables. In this study, transparency weighs 70,56% on the value of dissolved substances. Indeed, the transparent of aquatic environment offers more possibility for solubility of ion particles, at the same time, an increase in conductivity. Correlatively, electrical resistivity decreases [43]. The results are in accordance with those of [38] in Kinyankonge River, Burundi. "Reference [44]″ also reported similar relationship between transparency and total dissolved solids in Sô River, Benin. They are also in line with findings of [45] in Omoku Creek River, Nigeria. On the other hand, these results contrast with those reported in the Baldi River, India, by [46], including the links between transparency and dissolved substances. The significant and positive correlation of total dissolved solids with available phosphorus might be due to a contribution of phosphorus compounds to the concentration of nutrient in the aquatic environment. The presence of these phosphorus compounds could likely be due to leaching and runoff from fertilized farmland. These correlations were raised by [47] in Ratuwa River, Nepal. On other hand, "reference [48]" could not establish such links between these parameters in Culiacan Basin River, Mexico. The strong correlation of transparency with total phosphorus suggests the presence of the dissolved form of phosphorus, especially the mineral form of phosphate ion. Contrary to our observations, "reference [48]" revealed a negative but very weak (r= -0,367) correlation between these variables in Culiacan Basin River, Mexico. The role of phosphorus compounds in controlling the chemical quality of water has been highlighted in several studies [49,50,51]. In excessive quantities, total phosphorus promotes abnormal growth of aquatic flora resulting in serious dysfunction of aquatic ecosystems [48]. This growth can accelerate the proliferation of cyanobacteria and their degradation releases toxins harmful to human health.

Conclusion

The study provided data on the level of physical and chemical pollution in the Bagoue watershed. The results show that almost all of the variables measured still meet WHO standards for drinking water quality. However, suspended matter, turbidity and dissolved oxygen have values susceptible to obvious threats, mainly to aquatic wildlife and possibly for humans. The presence of these pollution indicators testifies the ever-increasing influence of artisanal and clandestine gold mining on the waters quality from the Bagoue basin. To reduce the environmental and health risks associated with human activities, one solution is to integrate small-scale mining into the formal sector. This requires a participatory approach, through certain priority areas including awareness, promoting other complementary production activities.

Acknowledgements

We wish to thank Professor N'douba V., for the moral endorsement of this research work. Particular thanks are also due to Dr. Koffi M., for his involvement in data analysis at LANADA research Laboratory, as well as to Dr. Kamelan, who worked on statistical analysis data. The role played by the chiefs of Kanakono and Guinguereni villages is acknowledged in terms of availability and accessibility of sampling sites.

References

[1] Koné, B. "Gold fever and the future of rural activities in the department of Tengrela (North Côte d'Ivoire). Geography Tropical Institute, Félix Houphouët-Boigny University, Abidjan-cocody, Côte d'Ivoire", *Revue Ivoirienne de Géographie des Savanes*, 2, 2521-2535, 2017.

[2] Bansah, K.J.; Yalley, A.B.; Dumakor-Dupey, N. "The hazardous nature of Smal Scale Underground Mining in Ghana", *Journal of Sustainable Mining,* 15 (1), 8-25, 2016.

[3] United Nation Environment Programme (U.N.E.P.). "*Global Mercury Assessment*"; Geneva, Switzerland, 2002, 270p.

[4] Word Health Organization (WHO). "*Preventing disease through healthy environments; Exposure to mercury: a major public health concern*", Production Services Document, Geneva, Switzerland, 2007, 167p.

[5] Gammons, C.H.; Slotton, D.G.; Gerbrandt, B.; Weight, W.; Young, C.A.; McNearny, R.L.; Cámac, E.; Calderón, R.; Tapia, H. "Mercury concentrations of fish, river water, and sediment in the Río Ramis-Lake Titicaca watershed, Peru", Sciences of the Total Environment, 368, 637-648, 2006.

[6] Taylor, H.; Appleton, J.D.; Lister, R.; Smith, B.; Chitamweba, D.; Mkumbo, O." Environmental assessment of mercury contamination from the Rwamagasa artisanal gold mining centre, Geita District, Tanzania", *Sciences of the Total Environment*.,343, 111-133, 2005.

[7] Tarras-Wahlberg, N.H.; Flachier, A.; Lane, S.N.; Sangfors, O. "Environmental impacts and metal exposure from aquatic ecosystems in Rivers contaminated with small gold mining: Puyango Basin River, South Equator", *Sciences of the total environment,* 278 (1), 239-261, 2001.

[8] Ahoussi, K.E.; Koffi, Y.B.; Kouassi, A.M.; Soro, G.; Soro, N.; Biémi J. "Study of the chemical and microbiological characteristics of the water resources of the N'zi watershed: Case of N'zianouan commune (South of Côte d'Ivoire)", *International Journal of Biological and Chemical Sciences*, 6 (4), 1854-1873, 2012.

[9] Ouffoué, K.S.; Salla, M.; Kicho, D. Y.; Soro, D.; Da, K.P.; Tonzibo, Z.F. "Water Quality Assessment of the Coastal Tropical River's Boubo (Côte d'Ivoire): Physico-Chemical and Biological Aspects", *Journal of Environment Pollution and Human Health,* 1 (2), 9-15, 2013.

[10] Eblin, S.G.; Sombo, A.P.; Soro, G.; Aka, N.; Kambiré, O.; Soro, N. "Hydrochemistry of surface waters in the Adiake region (southeastern Côte d'Ivoire)",*Journal of Applied Biosciences,* 75, 6259-6271, 2014.

[11] Tohouri, P.; ADJA, G.M.; SORO, G.; AKE, E.G.; KONAN, I.N.; BIEMI, J. "Physicochemical quality in rainy season water surface area, Bonoua (southeast Côte d'Ivoire)", *International Journal of Innovation and Applied Studies*,20 (1), 28-41, 2017.

[12] N'da, S.A.; Etilé, R.N.; N'zi, K.G.; Berté, S.; N'douba, V. "Composition and Distribution of Zooplankton Relationship to Environmental Factor in a Tropical River: (Bagoe, Côte d'Ivoire)", *International Research Journal of Biological Sciences*, 4(11), 1-11, October, 2015.

[13] Berté, S.; N'Doua, R.E.; Kamelan, M.T., Kouamelan, E.P. "First Data on Zooplankton Community Structure and Abundance of Kankelaba River in Côte d'Ivoire (Bagoe Tributary, Basin Niger)", *Nature et Sciences,* 17 (8), 125-135, July, 2019.

[14] Sanogo, Y.; Samaké, F.; Koné, A.; Traoré, D. "Diversity of the Ichthyological settlement of Bagoue River (Basin Niger, Mali)", *Agronomie Africaine*, 27 (1) 47-56, 2015.

[15] Tanina, D.S.; Bernard, D.K; Ernest, A.K.; Gbombélé, S.; Amani, M.K.; Konan, E.K.; Marie-Solange, O.Y.; Nagnin, S. "Hydroclimatology and land use dynamics in the upper Sassandra watershed, Tortiya (North Côte d'Ivoire)", *Revue électronique en sciences de l'environnement*,13 (3), 104-144, 2013.

[16] Ghestem J.P., Crouzet C. & Girardot N."*Geochemical bottons estimation in trace elements of continental surface water and groundwater: Charge book for analysis and collection*". Final report, 2008, 47p.

[17] Canadian Council of Ministers of the Environment. (CCME). "*Manual of sampling protocols for water quality analysis in Canada*". In CCME, Water-publication, 2011, 219p.

[18] Morel, F.M.M.; Kraepiel, A.M.L.; Amyot, M. "The Chemical cycle and bioaccumulation of Mercury", *Annual Review of Ecology and Syst*ematics, 29 (24), 543-566, 1998.

[19] French Standards Association (AFNOR). "*Water quality, collection of French standards*", AFNOR Editions, Paris, 1997, pp. 46.

[20] Quebec Center of Environmental Expertise and Analysis. Centre d'Expertise (CEAEQ). "Conductivity determination: Electrometric method", Ministry of Sustainable Development, Environment and Climate Change, Québec, 2015, 9p.

[21] French Standards Association (AFNOR). "*Water quality-Determination of suspended matter- Filtering method on fiberglass filter*", 2005, pp. 1-10.

[22] Zar J.H. "*Biostatistical analysis*", 4th Edition, Prentice Hall, Upper Saddle River,1999, 663p.

[23] Donkor, A.K.; Nartey, V.K.; Bonzongo, J.C.; Adotey, D.K. "Artisanal Mining of Gold with Mercury in Ghana", *West Africa Journal of Applied Ecology,* 9 (1), 2-18, June, 2006.

[24] Nartey, V.K.; Raphael, K.;Klake, R.K.;Hayford, E.H.; Louis, K.; Doamekpor, L.D.;Appoh, R.K. "Assessment of Mercury Pollution in Rivers andStreams around Artisanal Gold Mining Areas of the Birim North District of Ghana", *Journal of Environmental Protection*, *2,* 1227-1239, November, 2011.

[25] Ouedraogo, O.; Amyot, M. "Mercury, arsenic and selenium concentrations in water and fish from sub-Saharan semi-arid freshwater reservoirs (Burkina Faso)", *Science of the Total Environment*, 444, 243-254, 2012.

[26] Gerson, J.R.; Charles, T.; Driscoll, H.H.-K.; Emily, S. B. "Senegalese artisanal gold mining leads to elevated total mercury and methylmercury concentrations in soils, sediments, and rivers", *Elementa Science Anthroponece*, 6, 11-25, 2018.

[27] Niane, B.; Moritz, R.; Guédron, S.; Ngom, P. M.; Pfeifer, H.R.; Mall, I.; Poté, J. "Effect of recent artisanal small-scale gold mining on the contamination of surface river sediment: Case of Gambia River, Kedougou region, south-eastern Senegal", *Journal Geochemical Explor*., 144, 517- 527, 2014.

[28] Van Straaten P. "Mercury contamination associated with small-scale gold mining in Tanzania and Zimbabwe", *The Sciences of the total Environment*, 259, 105-113, 2000.

[29] Lusilao-Makiese, J.G.; Cukrowska, E.M.; Tessier, E.; Amouroux, D.; Weiersbye, I. "The impact of post gold mining on mercury pollution in the West Rand region, Gauteng, South Africa", *Journal of Geochemical Exploration*, 134, 111-119, August, 2013.

[30] Ikingura, J.; Akagi, H.; Mujumba, J.; Messo, C. "Environmental assessment of mercury dispersion, transformation and bioavailability in the lake Victoria goldfields, Tanzania", *Journal of Environmental Management*,81, 167-173, 2006.

[31] Word Health Organization (WHO). "*Guidelines for Drinking-water QualityRecommendations*" (4th edn), 2011, ISBN 978 92 4 154815 1, 541p.

[32] Environmental Protection Agency (EPA) US. "*National Recommended Water Quality Criteria*", United States Environmental Protection Agency, Office of Water, Office of Science and Technology. www.epa.gov/ost/criteria/wqctable/,2009,28p.

[33] Marcello, M.V.; Peter, A.M.; Lars, D.H. "Origin and consumption of mercury in small-scale gold mining" *Journal of Cleaner Production*, 14, 436-447, 2006.

[34] Maurice-Bourgoin, L.; Quiroga, I.; Chincheros, J.; Courau, P."Mercury distribution in waters and fishes of the upper Madeira rivers and mercury exposure in riparian Amazonian populations" *Sciences of the Total Environment*, 260, 73-86, 2000.

[35] Bamba, O.; Souleymane, P.; Aboubakar, S.;Kagambega, N.; Miningou, M.Y.W. "Impact of mining crafts on the soils of a developed agricultural environment in Burkina Faso", *Journal des Sciences*,13 (1), 1-11, October, 2013.

[36] Younger, P. L.; Wolkersdorfer, C. "Mining impacts on the fresh waterenvironment: technical and managerial guidelines for catchment scalemanagement",*Mine water and the environment*, 23, 2-80, 2004.

[37] Decamps, H.; Casanova-Batut. "Suspended matter and water turbidity in the Lot River", *Annales de Limnologie*, 14 (1-2), 59-84, 1978.

[38] Buhungu S., Montchowui E., Barankanira E., Sibomana C., Ntakimazi G. & Bonou C.A. "A spatio-temporal characterization of the water quality of the Kinyankonge River, a tributary of Tanganyika Lake, Burundi",*International Journal of Biology and Chemistry Sciences*, 12 (1), 576-595, 2018.

[39] Whyte, D.C.; James, W. K. "Assessing water quality impacts and clean-up effectiveness in streams dominated by episodic mercury discharges" *The Science of the Total Environment*,260, 1-9, February, 2000.

[40] Jan, H.M.; Paul, E. O. "Downstream effects of erosion from small-scale gold mining on the Instream habitat and fish community of a small Neotropical Rainforest Stream", *Conservation Biology*,18 (1), 201-214, 2004.

[41] Hebert, S.; Légré S."*Monitoring water quality of rivers and small-streams*",Directorate of Environmental Monitoring, Ministry of the Environment, Government of Quebec,2005, 5 p.

[42] Laperche, V.; Maury-Brachet, R.; Blanchard, F.; Dominique, Y.; Durrieu, G.; Massabuau, J.C.; Bouillard, H.; Joseph, B.; Laporte, P.; Mesmer-Dubons, N.; Duflo, V.; Callier, L. "*Regional distribution of mercury in the sediments and fish of six Rivers in Guyana*", Final report, 2007,201p.

[43] Werban, U.; Kuka, K.; Merbach, I. "Correlation of electrical resistivity, electrical conductivity and soil parameters at a long-term fertilization experiment", *Near Surface Geophysics*, 7 (32), 5-14, 2009.

[44] Koudenoukpo, Z.C.; Chikou, A.; Adandedjan, D.; Hazoume, R.; Youssao, I.; Mensah, G.A.; Laleye, A. P."Physicochemical characterization of a tropical-regional lotic system: Sô River, South Benin, West Africa"*Journal of Applied Biosciences*, 113, 11111-11122, 2017.

[45] Ewa, E.E.; Iwara, A.I.; Adeyemi, J.A.; Eja, E.I.; Ajake, A.O.; Out, C.A. "Impact of Industrial Activities on Water Quality of Omoku Creek",*Sacha Journal of Environmental Studies*, 1 (2), 8-16, 2011.

[46] Neetu, S.; Ramesh, C.S. "Assessment of physicochemical parameters of Mountain River Baldi, Garhwal Himalayas", *International Journal of Fisheries and Aquatic Studies*,4 (2), 88-93, 2016.

[47] Arun, K.S.; Nabin, B. “The Correlation and regression analysis of physicochemical parameters of River water for the evaluation of percentage contribution to electrical conductivity”, *Journal of Chemistry*, Article ID 8369613, 9p, 2018.

[48] Li, X.; Nan R. "Biometric analysis of eutrophication literatures: A growing and changing center", *Science de l’Environnement et de la Recherche sur la Pollution*, 24, 17103-17115, 2017.

[49] Baron, J.S.; Poff, N.L.; Angermeier, P.L.; Dahm, C.N.; Gleick, P.H.; Hairston, N.G.; Jackson, R.B.; Johnston, C.A.; Richter, B.D.; Steinman, A.D. "Sustaining healthy freshwater ecosystems", *Issues in Ecology*, 10, 1-17, 2003.

[50] Conley, D.J.; Paerl, H.W.; Howarth, R.W.; Boessch, D.F.; Seitzinger, S.P.; Havens, K.E.; Lancelot, C.; Likens, G.E. "Controlling eutrophication :Nitrogen and Phosphorus", *Science*, 323, 1014-1015, 2009.

[51] Tchakonté, S; Ajeagah, G; Diomandé, D; Camara, A; Konan, M.; Ngassam, P. "Impact of anthropogenic activities on water quality and Freshwater Shrimps diversity and distribution in five rivers in Douala, Cameroun", *Journal of Biodiversity and Environmental Sciences*, 4, 183-194, 2015.