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Research article

Impact of artisanal small-scale (gold and diamond) mining activities on the Offin, Oda and Pra rivers in Southern Ghana, West Africa: A scientific response to public concern

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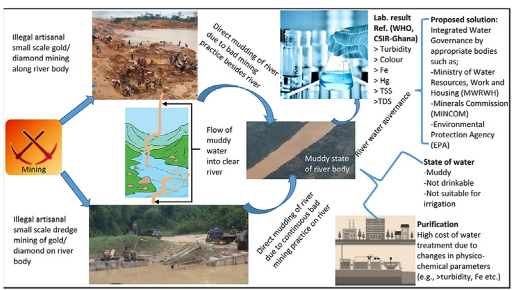
GRAPHICAL ABSTRACT



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ABSTRACT

The surface water systems of Ghana serve as a major source of drinking water, besides other multi-purpose benefit of hydro-electrical power generation and transportation. Thus, the dependence and benefits from such resources are of national interest. For instance, the Pra river of the South-Western surface water system of Ghana was a major consideration for a projected 5 billion m^3 water demand in the year 2020 and "African Water Vision 2025". In recent times, the colour state of the Pra river and similar surface water bodies of the Offin and Oda rivers has attracted intense public discussion. The prime issue relates to incessant illegal artisanal gold/diamond mining on or along these rivers. In order to assess the state of these rivers, water samples were taken, and analysed at the Council of Scientific and Industrial Research Laboratory (CSIR, Accra-Ghana) to investigate their physico-chemical quality. The research objective was to assess the extent of their water pollution by measuring physico-chemical parameters of turbidity, colour, pH and content of selected metals. A total of 18 preserved bottled samples [(5 from Offin river and 2 boreholes), 5 from Oda river and 5 from Pra river and 1 borehole)] were analysed, and results compared with portable water standards as defined by the WHO and CSIR (GS-175-1) of Ghana.

Results on turbidity, colour, mercury and iron from the river and water samples generally exceed WHO or GS-175-1 limit. The Pra river recorded the most alarming result; range for turbidity (2,010 to 2,745 NTU), colour (3,000 to 4,500 Hz), total suspended solutes (2,240 to 2,570 mg/L) and total dissolved solutes (97.80–99.60 mg/L, excluding 319.00 to 25,440 mg/L). The Oda river shows lowest parameter values among the three rivers, as the areas have been dormant from illegal gold mining for 5 years. Current data suggests polluted river bodies and boreholes, and that none of these water resources meets the portable water consumption criteria unless treated prior to usage. As the current state of the water bodies may incur higher cost of water treatment or purification, an

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integrated water governance under Ghana's Ministry of Water Resource, Work and Housing, and the Minerals Commission and Environmental Protection Agency are recommended for the management of these valuable water resources.

1. Introduction

Ghana is known globally for gold (and diamond) mining, and this activity contributes more than one-third of Ghana's export revenues. During the global COVID-19 pandemic, the mining sector was one major area that was largely considered as an essential sector, especially in Ghana (GCM, 2020), possibly due to its impact on the economy. Such consideration is a testament of a country whose economic growth is significantly influenced by the mining sector. For example, in 2013 and 2014, a respective gold production of 2.63 Moz and 3.48 Moz represent 95% of the country's revenue from mining (GCM-ICMM, 2015; Smith et al., 2016). Although, gold production declined from 2019 to 2020 at 4.577 Moz and 4.023 Moz respectively (GCM, 2020), such values made Ghana the largest gold producer in Africa; having taken over South Africa (Figure 1). The mining sector continues to expand, marked by an increased in exploration activities within the southern and northern segments of the nation (e.g. Griffis et al., 2002; Amponsah et al., 2015). Ghana is a prominent gold producer in West Africa (Pigois et al., 2003), and her stance comes as an output of large and small scale mining companies, and the artisanal miners (known locally in Ghana as "Galamsey").

Although, substantive revenues come from gold mining in Ghana, its operational effects on the environment or the ecosystem cannot be overlooked. According to Mengistu et al. (2012), mining is among the ventures of income worldwide with over a century of practice, and leaves huge volumes of mined tailings and abandoned mine sites. Andrea and John (2010) emphasized that mining operations often contaminate water bodies (both surface and groundwater), and causes life threatening diseases upon ingestion; ends up in the human body through eating or drinking, or by inhalation of associated dust particles. Likewise, Fungaro et al. (2012) have indicated that several mine wastes are radioactive, toxic and carcinogens, which affect primary health when consumed in water or indirectly by certain edible plants.

Over the past years, there have been serious concerns raised both in the Ghanaian media and public discussions regarding detrimental effects of artisanal scale gold mining activities in many parts of the country, especially on land degradation, destruction of arable lands and the quality of water in streams and rivers. In southern Ghana, streams and rivers including the Offin, Oda and Pra that drain mineralized gold and diamond-bearing areas have reportedly been drastically affected in various ways by artisanal gold and diamond mining. For example, Ellahi et al. (2021) reported that particulate matter, visible organisms, turbidity, and colour can be observed by users and may generate worries about the worth and suitability of drinking water supplies. Although the perceived pollution including change in colour and increased turbidity of the streams and rivers in many mining areas have often been attributed to artisanal scale mining activities, not much scientific data have been acquired and/or published to support many of the assertions made. This study primarily acquired (field) data from water samples taken in the Offin, Oda and Pra Rivers which were subsequently analysed and interpretations made as a contribution to the currently active discourse on the impacts of artisanal scale gold mining activities on the quality of water in southern Ghana. The obtained data or observation has been equally linked to existing National Water Policy of Ghana (MWRWH, 2007), and an integrated solution proposed.

2. Study area and geology

The study area is the domains drained by the Offin, Oda and the Pra rivers. The Oda and Offin sampled localities were in the Ashanti Region whiles the Pra samples are from the Western Region. Details on sampled localities have been provided in Table 1, and specific sampled points shown on Figure 2a and 2b. The Ashanti Region belongs to the wet semi-equatorial climatic region, with the mean annual rainfall between 125 and 200 cm. The heaviest rainfall occurs in June and a second rainfall

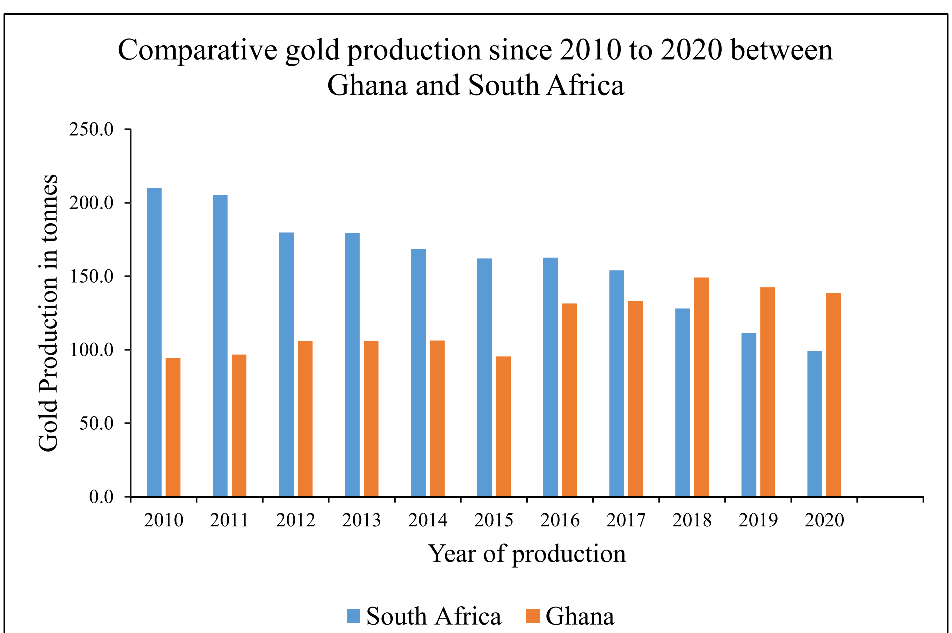

Figure 1. Ghana leads in gold production in Africa after a takeover from South Africa (World Gold Council, 2021).

Table 1. Sample identification and location.

Sample ID	Water source	GPS Coordinates		Nearest location/Town
		Northern	Western	
OF1	Offin*	6°38′27″	2°00′22″	NE of Nyinahin
OF2	Offin*	6°37′30″	2°01′14″	NE of Nyinahin
OF2BH	Borehole	6°37′30″	2°01′14″	
OF3	Offin*	6°36′11″	2°02′26″	Adiembra
OF4	Offin*	6°32′11″	2°02′51″	Ntobroso
OF4BH	Borehole	6°32′11″	2°02′51″	Ntobroso
OF5	Offin*	6°28′38″	2°02′29″	Achiase
ODA1	Oda*	6°27′09″	1°38′08″	
ODA2	Oda*	6°27′47″	1°37′47″	
ODA3	Oda*	6°42′21″	1°27′37″	Odaho
ODA4	Oda*	6°42′21″	1°27′37″	Ejisu
ODA5	Oda*	6°46′33″	1°26′54″	Ejisu
PR1	Pra*	5°01′09″	1°37′44″	Shama
PR2	Pra*	5°07′25″	1°37′00″	Beposo
PR3	Pra*	5°14′36″	1°35′51″	Sekyere-Krobo
PR4	Pra*	5°17′00″	1°35′34″	Didiso
PR4BH	Borehole	5°17′00″	1°35′34″	Didiso
PR5	Pra*	5°05′03″	1°37′05″	Atweaboanda

* Major river.

from September to October. The Western Region is part of the southwestern equatorial climatic region and is the wettest area in Ghana, with a mean annual rainfall above 190 cm (Dickson and Benneh, 2004).

The sampled areas are part of the Birimian geological terrane of southern Ghana, which constitute deformed and metamorphosed volcano-sedimentary rocks intruded by granitoids (Oberthür et al., 1998; Feybesse et al., 2006). The metavolcanic rocks include basalts and andesites with minor volcaniclastic rocks (Dampare et al., 2008). The metasedimentary rocks comprise greywacke, phyllitic siltstone and shale, locally rich in graphite, interbedded with volcaniclastic rocks (e.g., Adadey et al., 2009; Nunoo et al., 2016). The intruded granitoids include granite, tonalite, trondhjemite and granodiorite (TTGs) pulses, and are coeval with the 2.2–2.0 Ga Eburnean orogeny (Leube et al., 1990; Taylor et al., 1992; Feybesse et al., 2006).

3. Materials and methods

A total of 18 preserved bottled samples (7 from the Offin catchment (of which 5 were along the river and 2 from boreholes), 5 from the Oda river and 6 from the Pra catchment (of which 5 were along the river and 1 borehole) were collected and analysed at the Council for Scientific and Industrial Research Laboratory (CSIR, Accra–Ghana). The data was excel-treated and results compared to World Health Organization (WHO) and CSIR (GS-175-1) standards on potable water for human consumption. Descriptive statistical method was as well deployed to define the minimum, maximum, range and standard deviations of obtained results. The original meta data obtained on samples has been included as appendix 1 for reference purposes. Sampling protocols were dully observed to avoid any form of contamination. For instance, all the 500 mL polyethylene bottles for sample storage were pre-conditioned prior to sampling. Rivers were sampled at where there was a steady continuous flow and reasonable distance (e.g. mid-way) from the river bank. Sampling was done in May, 2021, and mostly in the morning. For selected boreholes samples, each borehole was pumped for a minimum duration of 5 min before sampling. In other to avoid bare hand interaction with bottle and water, disposable gloves were used. Samples were stored in ice-coolers and transported to the laboratory within 12 h. CSIR standard methods used in analysing for each parameter have been provided in Table 2. In all, ten standard methods were deployed in the analysis of the twenty-nine physico-chemical parameters. The inclusion to test for the presence of mercury, zinc and lead for only Pra samples, was later suggestion due to restricted project budget.

4. Results

4.1. Offin river

Results from seventeen measured parameters (Table 3) have been compared to WHO and CSIR standards. Descriptive statistical summary of the measured parameters from river and borehole water samples has been presented respectively in Tables 4 and 5. The values of parameter recorded from each river sample follow a decreasing order of turbidity (126.00–469.00 NTU), colour (75.00–400.00 Hz), TDS (157.00–166.00 mg/L), total hardness as $CaCO_3$ (73.60–78.60 mg/L), Na (21.00–25.00 mg/L), Ca (21.00–23.10 mg/L), Cl (18.70–23.80 mg/L), total Fe (3.66–12.30 mg/L), SO_4 (7.00–10.00 mg/L), pH (7.04–7.20), K (5.00–5.80 mg/L), Mg (5.03–5.47 mg/L), NH_4–N (<0.001–0.89 mg/L), NO_3–N (0.23–0.86 mg/L), NO_2–N (0.02–0.16 mg/L), Mn (<0.005–0.04 mg/L) and F (<0.005 mg/L). Borehole samples (OF2BH and OF4BH, Table 3) have lower values relative to river samples and standards, except few variations for Mn, F, Cl, total Fe content and total hardness as $CaCO_3$ (Table 3). For example, sample OF2BH has Mn content of 0.53 mg/L, which is highest in all samples and the standards. Also Cl content of this sample measures 30.00 mg/L that is lower than standards but higher relative to all analysed samples.

Visual observation of the river shows an obvious change in colour of water from possibly clean to muddy (Figure 3a) due to increase of sediment input. Stacked bar graph plot (Figure 3b) of selected parameters, show higher value or content of colour, turbidity and total Fe of most samples, except TDS when compared to the adopted standards. The mean and minimum values of colour, turbidity and total iron (Table 4) still show higher relative to the standards. For boreholes, all parameters are lower, except total iron content for borehole water sample OF4BH, which is higher relative to standards (Figure 3b). However, the minimum and mean values (Table 5) from the borehole samples are generally lower relative to standards and river samples.

4.2. Oda river

Table 6 presents seventeen measured parameters compared to WHO and CSIR standards. A summary descriptive statistic of parameter, that covers minimum, maximum, range and deviations has also been tabulated (Table 7). Decreasing order of value measured for various parameters follow a sequence of TDS (93.60–412.00 mg/L), turbidity (12.70–245.00 NTU), colour (20.00–125.00 Hz), total hardness as $CaCO_3$ (50.60–112.00 mg/L), Na (10.00–75.00 mg/L), Cl (12.00–55.00 mg/L), Ca (9.14–33.80 mg/L), SO_4 (4.00–30.00 mg/L), K (3.00–10.20 mg/L), NH_4–N (0.55–7.99 mg/L), pH (6.39–7.40), Mg (4.75–6.76 mg/L), NO_3–N (0.06–6.40 mg/L), total Fe (0.53–3.15 mg/L), NO_2–N (0.03–1.66 mg/L), Mn (0.004–0.14), and F (<0.005–0.09 mg/L). Turbidity and colour values either individually (Table 6) or respective mean 73.92 mg/L and 55.00 Hz show higher values compared to the standards. Sample OD2 show higher nitrite of 1.66 mg/L relate to all samples and standards, but the average value of 0.58 (Table 7) is 42% less compared with WHO and GS 175-1 standards. This same sample shows the lowest total iron content compared to all samples.

The physical observation of the Oda River around Odaho (Figure 4a) showing a muddy brown colouration. The stack bar graph of selected parameters (Figure 4b) shows all samples have lower TDS relative to the used standards. However, the parameters of colour, turbidity and total iron recorded higher values compared to the standards, except sample ODA2 with lowest total Fe content (Figure 4b). From the samples, ODA1 and ODA2 show higher values in most measured parameters, but the former surpasses the later.

4.3. Pra river

Nineteen physico-chemical parameters were measured, and quantitative values are presented in Table 8, and their summary descriptive statistic also in Table 9. The values as measured are presented here in a decreasing order; TDS (97.80–25,440 mg/L), Cl (18.50–12,499 mg/L), Na (8.80–7,000 mg/L), total hardness as $CaCO_3$ (58.00–5,420 mg/L), colour (30.00–4,500 Hz), turbidity (15.00–2,750 NTU), Mg (6.21–1,078 mg/L), SO_4 (5.00–445.00 mg/L), Ca (8.26–393.00 mg/L), K (4.00–300.00 mg/L), pH (7.00–7.42), total Fe (0.83–3.37 mg/L), F (<0.005–1.64 mg/L), NO_3–N (0.32–1.65 mg/L), Mn (0.004–0.54), NH4–N (0.07–0.29 mg/L), NO_2–N (0.03–0.17 mg/L), Zn (0.01–0.24 mg/

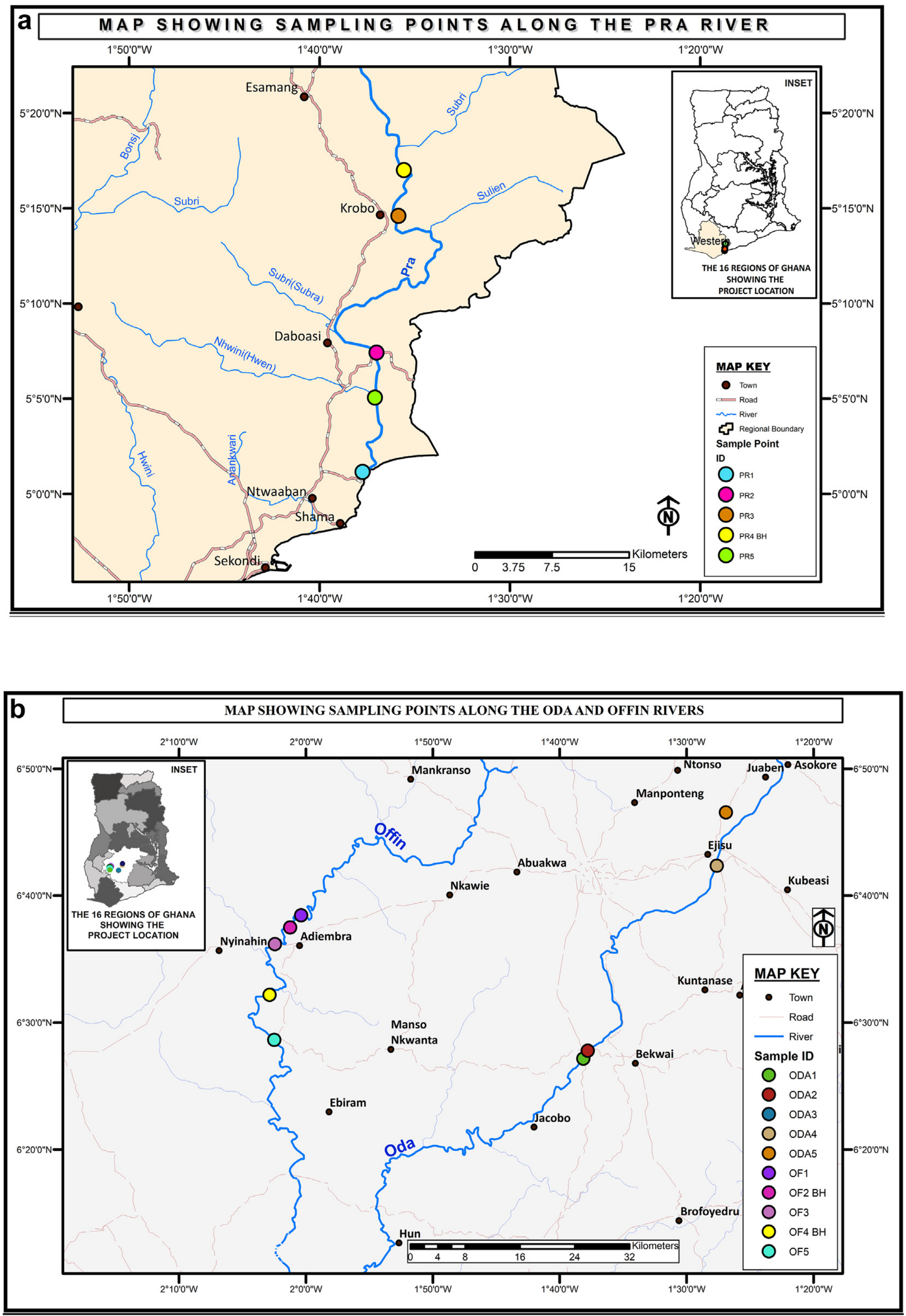

Figure 2. Map showing sample points along the rivers or tributaries of the (a) Pra and (b) Offin and Oda rivers.

Table 2. CSIR instruments/methods used in analysing the parameters.

Parameter	Unit	Standard Method
Turbidity	NTU	Nephelometric
Colour (apparent)	Hz	Visual comparison
pH	pH Units	pH meter
Conductivity	μS/cm	Electrometric
Total Suspended Solids (TSS)	mg/L	Gravimetric
Total Dissolved Solids (TDS)	mg/L	Gravimetric
Sodium	mg/L	Flame photometric
Potassium	mg/L	Flame photometric
Calcium	mg/L	Titrimetric
Magnesium	mg/L	EDTA Titrimetric
Total Iron	mg/L	Spectrophotometric
Ammonia (NH_4–N)	mg/L	Spectrophotometric
Chloride	mg/L	Argentometric
Sulphate (SO_4)	mg/L	Spectrophotometric
Phosphate (PO_4–P)	mg/L	Spectrophotometric
Manganese	mg/L	Spectrophotometric
Nitrite (NO_2–N)	mg/L	Spectrophotometric
Nitrate (NO_3–N)	mg/L	Spectrophotometric
Total Hardness (as $CaCO_3$)	mg/L	Spectrophotometric
Total Alkalinity (as $CaCO_3$)	mg/L	Titrimetric with acid
Calcium Hardness (as $CaCO_3$)	mg/L	EDTA Titrimetric
Mag. Hardness as $CaCO_3$)	mg/L	EDTA Titrimetric
Fluoride	mg/L	Spectrophotometric
Bicarbonate (as $CaCO_3$)	mg/L	EDTA Titrimetric
Carbonate (as $CaCO_3$)	mg/L	EDTA Titrimetric
Mercury	mg/L	Mercury Analyser
Lead	mg/L	Spectrophotometric
Zinc	mg/L	Spectrophotometric
Copper	mg/L	Spectrophotometric

L) and Hg (0.003–0.004 mg/L). The astronomical values in TDS, Cl, Na, Mg and total hardness as $CaCO_3$ content for sample PR1 is due to proximity to the sea, where the river enters the sea. But values of such parameters decrease upstream (Table 8 and Figure 2a). From the descriptive statistic result, such parameters respectively have higher standard deviations to the calculated mean (i.e. Std. Deviation in Table 9). In Table 9, mercury (Hg) values show zero, and not as recorded of 0.003–0.004 mg/L (Table 8). These zeros in Table 9 relates to decimal places defect, and the mean for Hg is 0.0032 mg/L, three-times of WHO and GS 175-1 standard value (Table 8).

Aerial view (Figure 5a) and on-site (Figure 5b) observation of the river show muddy brown colouration. The stack bar graph (Figure 5c) of selected parameters shows similar trend for turbidity, colour and total iron, as higher values in river relative to WHO and GS 175-1 standards. Mercury content shows higher values in river and borehole samples compared to standards (Figure 5c). TDS content varies in samples, for example PR1 and PR2 show higher values in all samples (including borehole sample), and when compared to standards (Figure 5c). Total Fe is only lower in PR4BH compared to all samples and standards (Figure 5c).

Table 4. Descriptive statistical summary of measured parameters of water samples from the Offin river.

Parameter	N	Range	Minimum	Maximum	Mean	Std. Deviation
Turbidity	5	343.00	126.00	469.00	275.00	169.46
Colour	5	325.00	75.00	400.00	205.00	120.42
pH	5	0.08	7.04	7.12	7.07	0.04
TDS	5	9.00	157.00	166.00	162.00	3.81
Sodium (Na)	5	4.00	21.00	25.00	22.80	1.48
Potassium (K)	5	0.80	5.00	5.80	5.52	0.30
Calcium (Ca)	5	2.10	21.00	23.10	22.12	0.97
Magnesium (Mg)	5	0.44	5.03	5.47	5.19	0.16
Total Iron (Fe)	5	8.64	3.66	12.30	7.38	4.05
Ammonia (NH_4–N)	5	0.89	0.00	0.89	0.53	0.32
Chloride (Cl)	5	5.10	18.70	23.80	20.96	1.98
Sulphate (SO_4)	5	3.00	7.00	10.00	8.00	1.22
Manganese (Mn)	5	0.04	0.00	0.04	0.02	0.02
Nitrite (NO_2–N)	5	0.19	0.02	0.21	0.10	0.08
Nitrate (NO_3–N)	5	0.63	0.23	0.86	0.55	0.23
Total Hardness (as $CaCO_3$)	5	5.00	73.60	78.60	76.68	2.10
Fluoride (F)	5	0.00	0.004	0.004	0.004	0.00

Table 3. Measured parameter of water samples from along the Offin River and nearby boreholes compared with adopted standards. All parameters were measured in mg/L, except turbidity, colour and pH as NTU, Hz and pH units, respectively.

Parameter	OF1	OF2	OF3	OF4	OF5	OF2BH	OF4BH	GS 175-1	WHO Guideline
Turbidity	126.00	155.00	175.00	450.00	469.00	1.15	3.66	5.00	5.00
Colour	75.00	150.00	200.00	400.00	200.00	2.50	10.00	5.00	15.00
pH	7.04	7.10	7.12	7.04	7.06	6.08	5.05	6.50–8.50	6.50–8.50
TDS	164.00	164.00	166.00	159.00	157.00	205.00	63.00	1000.00	1000.00
Na	21.00	23.00	25.00	22.00	23.00	24.00	6.50	200.00	200.00
K	5.60	5.60	5.60	5.00	5.80	6.20	2.00	30.00	30.00
Ca	21.20	22.90	22.40	23.10	21.00	24.80	1.52	200.00	200.00
Mg	5.47	5.17	5.17	5.03	5.13	13.90	7.63	150.00	150.00
Fe-total	4.44	3.66	5.32	12.30	11.20	0.05	3.14	0.30	0.30
NH_4–N	0.89	0.61	0.58	0.58	<0.001	0.05	0.06	0.00–1.50	0.00–1.50
Cl	18.70	19.60	21.80	20.90	23.80	30.00	19.30	250.00	250.00
SO_4	8.00	8.00	10.00	7.00	7.00	8.30	2.00	250.00	250.00
Mn	0.03	<0.005	<0.005	0.01	0.04	0.52	0.21	0.40	0.40
NO_2–N	0.21	0.02	0.05	0.06	0.16	0.02	0.02	1.00	1.00
NO_3–N	0.23	0.86	0.53	0.66	0.46	0.42	0.62	10.00	10.00
Total Hardness (as $CaCO_3$)	75.60	78.60	77.20	78.40	73.60	119.00	35.20	500.00	500.00
F	<0.005	<0.005	<0.005	<0.005	<0.005	0.69	<0.005	1.50	1.50

*river samples (OF1, OF2, OF3, OF4 and OF5), borehole samples (OF2BH and OF4BH), GS 175-1 = standard from Council for Scientific and Industrial Research Lab.

Table 5. Descriptive statistical summary of measured parameters of water samples from boreholes closer to the Offin river.

	N	Range	Minimum	Maximum	Mean	Std. Deviation
Turbidity	2	2.51	1.15	3.66	2.41	1.77
Colour (apparent)	2	7.50	2.50	10.00	6.25	5.30
pH	2	1.03	5.05	6.08	5.57	0.73
TDS	2	142.00	63.00	205.00	134.00	100.41
Sodium (Na)	2	17.50	6.50	24.00	15.25	12.37
Potassium (K)	2	4.20	2.00	6.20	4.10	2.97
Calcium (Ca)	2	23.28	1.52	24.80	13.16	16.46
Magnesium (Mg)	2	6.27	7.63	13.90	10.77	4.43
Total Iron (Fe)	2	3.09	0.05	3.14	1.59	2.19
Ammonia (NH_4–N)	2	0.01	0.05	0.06	0.05	0.01
Chloride (Cl)	2	10.70	19.30	30.00	24.65	7.57
Sulphate (SO_4)	2	6.30	2.00	8.30	5.15	4.45
Manganese (Mn)	2	0.32	0.21	0.52	0.36	0.22
Nitrite (NO_2–N)	2	0.00	0.02	0.02	0.02	0.00
Nitrate (NO_3–N)	2	0.20	0.42	0.62	0.52	0.14
Total Hardness (as $CaCO_3$)	2	83.80	35.20	119.00	77.10	59.26
Fluoride (F)	2	0.69	0.00	0.69	0.35	0.49

5. Discussion

Data collected from the three major rivers and a number of boreholes identified closer to the river course is considered here as a scientific basis to ascertain if such water bodies and associated borehole water are polluted. Activities that may have contributed to higher levels of the measured physico-chemical parameters are discussed as well as the possible health implications likely to arise from the intake of such water, as these water bodies or boreholes serve as sources of drinking water or for domestic usage.

5.1. *The extent of river pollution and likely sources*

A common trend observable in all rivers sampled is the variable degrees of muddy brown colouration (e.g. Figures 3a, 4a and 5a and 5b). According to Lehmann et al. (2018), colour is based on the sensual perception of the human eye and is an intuitive and a broadly applicable water measurement. For instance, such an approach has often been used by people to discern water's suitability for consumption, recreation and aesthetic value (Smith and Davies-Colley, 1992; West et al., 2016; Ellahi et al., 2021). From the aerial view of the Pra river (i.e. Figure 5a) and on-site observation, the muddy brown colouration could be seen by the eye. Colour is one of the oldest measurement of water quality, hence, the current colour of the Oda, Offin and Pra rivers possibly indicate saturated presence of sediments and other dissolved materials. Colour judgement mostly does not require knowledge of inherent optical properties of

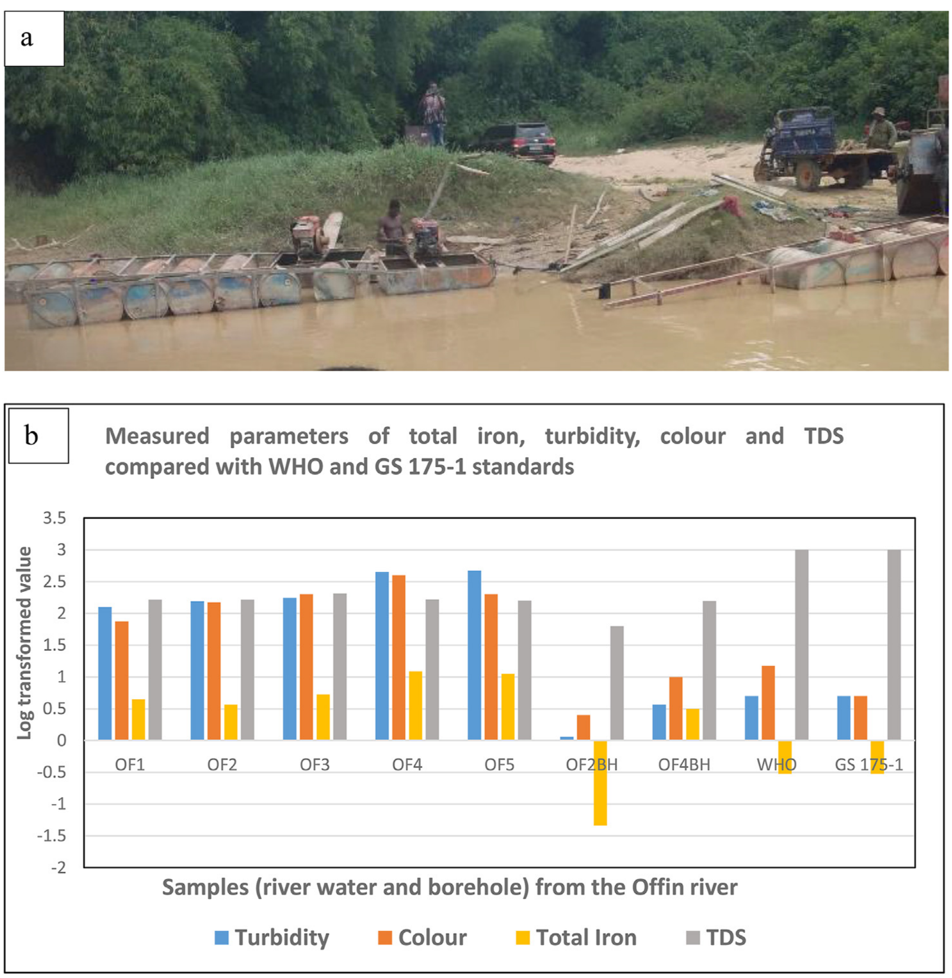

Figure 3. The state of the Offin River at Achiase and selected parameters compared with WHO. (a) Muddy river show brown colouration and dredge miners at the bank of the river. (b)Except TDS (Total Dissolved Solids), other parameters of colour, turbidity and total iron values of river samples exceed WHO and GS 175-1 standards values. For boreholes, all parameters are lower, except total iron content for borehole water sample OF4BH, which is higher relative to standards.

Table 6. Measured parameters of water samples from along the Oda River compared with adopted standards. All parameters were measured in mg/L, except turbidity, colour and pH as NTU, Hz and pH units, respectively.

Parameter	ODA1	ODA2	ODA3	ODA4	ODA5	GS 175-1	WHO Guideline
Turbidity	245.00	75.40	12.70	12.70	23.80	5.00	5.00
Colour	125.00	75.00	25.00	20.00	30.00	5.00	15.00
pH	7.40	7.36	7.08	6.61	6.39	6.50–8.50	6.50–8.50
TDS	394.00	412.00	113.00	146.00	93.60	1000.00	1000.00
Sodium	90.00	95.00	10.00	28.00	7.50	200.00	200.00
Potassium	10.20	10.00	3.80	6.40	3.00	30.00	30.00
Calcium	33.70	33.80	13.00	12.90	9.14	200.00	200.00
Magnesium	6.76	6.71	5.43	4.75	6.74	150.00	150.00
Total Iron	0.53	0.18	2.70	1.89	3.15	0.30	0.30
Ammonia (NH_4–N)	7.93	7.99	0.60	0.55	0.72	0.00–1.50	0.00–1.50
Chloride	52.50	55.00	13.00	23.60	12.00	250.00	250.00
Sulphate (SO_4)	25.00	30.00	5.00	15.00	4.00	250.00	250.00
Manganese	0.11	0.004	0.03	0.02	0.14	0.40	0.40
Nitrite (NO_2–N)	0.78	1.66	0.03	0.21	0.21	1.00	1.00
Nitrate (NO_3–N)	0.06	6.40	0.54	0.80	0.85	10.00	10.00
Total Hardness (as $CaCO_3$)	112.00	112.00	54.80	51.80	50.60	500.00	500.00
Fluoride	$<$0.005	$<$0.005	$<$0.005	$<$0.005	0.09	1.50	1.50

*river samples (ODA1, ODA2, ODA3, ODA4 and ODA5), GS 175-1 = standard from Council for Scientific and Industrial Research Lab.

Table 7. Descriptive statistical summary of measured parameters of water samples from the Oda river.

Parameter	N	Range	Minimum	Maximum	Mean	Std. Deviation
Turbidity	5	232.30	12.70	245.00	73.92	99.09
Colour	5	105.00	20.00	125.00	55.00	44.86
pH	5	1.01	6.39	7.40	6.97	0.45
TDS	5	318.40	93.60	412.00	231.72	157.60
Sodium	5	87.50	7.50	95.00	46.10	43.13
Potassium	5	7.20	3.00	10.20	6.68	3.37
Calcium	5	24.66	9.14	33.80	20.51	12.19
Magnesium	5	2.01	4.75	6.76	6.08	0.93
Total Iron	5	2.97	0.18	3.15	1.69	1.31
Ammonia (NH_4–N)	5	7.44	0.55	7.99	3.56	4.02
Chloride	5	43.00	12.00	55.00	31.22	21.08
Sulphate (SO_4)	5	26.00	4.00	30.00	15.80	11.65
Manganese	5	0.13	0.00	0.14	0.06	0.06
Nitrite (NO_2–N)	5	1.63	0.03	1.66	0.58	0.67
Nitrate (NO_3–N)	5	6.34	0.06	6.40	1.73	2.63
Total Hardness (as $CaCO_3$)	5	61.40	50.60	112.00	76.24	32.68
Fluoride	5	0.09	0.00	0.09	0.02	0.04

water, but directly measurable by any optical imager with bands within the visible spectrum (e.g. Giardino et al., 2001; Van der Woerd and Wernand, 2018). The measured laboratory data of colour from the samples compared with WHO (15 Hz) and CSIR (5 Hz) standards indicates several folds of intense colour obliteration. Comparatively, average values for river colour increase from the Oda river (average 55.00 ± 20.00 Hz) through Offin river (average 205.00 ± 54.00 Hz) to Pra river (2,286 ± 928.00 Hz).

In addition to the above higher values of colour, river samples (Oda, Offin and Pra) are marked by respective excessive average turbidity values of 74.00 ± 44.00, 275.00 ± 76.00 and 1,428 ± 565.00 NTU, and total Fe contents of 1.69 ± 0.58, 7.38 ± 1.81 and 2.11 ± 0.52 mg/L. Such values are suggestive of huge amount of suspended materials (e.g., sediments and charged iron). Elsewhere (e.g., Health Canada, 2012), a combination of colour and turbidity has been a way in measuring water quality, which gets influenced by factors such as sediments traps, soil run-off and algae incubators (e.g. Vörösmarty et al., 2003; Gardner et al., 2021). Parameters of colour and turbidity are often observable by humans, and may induce worries about the suitability of the water for consumption or other usage (e.g. Ellahi et al., 2021).

Current data as exemplified by the measured physico-chemical parameters (e.g. colour, turbidity, pH, total iron and TDS among others) may be largely through the activities of illegal artisanal mining (*locally called "Galamsey"),* as such practices are common in the upstream and along the banks of river bodies. Illegal miners adopt unprofessional rudimentary style of mining, for example, dredging on rivers (Figure 3a) using pressure-regulated tubes to mine the gold-bearing river-beds. The geology (Figure 6) and the tropical climatic condition that characterized the area make availability of the alluvial forms of Birimian-Tarkwaian gold from a highly weathered metamorphosed ferruginous-shales or Fe-rich sedimentary rocks (e.g., Manu et al., 2013; Asiedu et al., 2019). In addition, the elevated contents of mercury in Pra samples, ~ three to four times higher compared to standards (Fig, 5c), likely relates to excessive usage of Hg in gold processing by artisanal miners, a known practise among illegal miners. The higher levels of ammonia and nitrite (*relative to standards*) in some Oda samples (Table 7) and sulphate in two Pra samples (Table 8) are likely related to run-off of excess usage of fertilizers from cocoa farmlands or sources yet to be known. Run-off of excess fertilizers from farmland is possible through heavy-down pours, which is climate dependant. According to Murphy and Sprague (2019) and Stets et al. (2020), changes in hydroclimate is an effective driver for river colour change, as all manner of materials (e.g. sediments and chemicals) could be washed into water bodies. Alternatively, farmlands closer to river bodies may have been mined directly by illegal miners, and thereby getting such substances into the river. The Pra river among the three sampled rivers shows the highest amount of pollutant. Such pollutants arise from vigorous and continues illegal mining operations, and or likely sampling from the downstream part of Pra; acting as a sink that receives pollutant from upstream.

For the boreholes, the higher content of certain chemical parameters, for example, Hg in the Pra samples (i.e. PR4BH, Table 8), and total iron and colour in the Offin borehole sample (i.e. OF4BH, Table 3) suggest certain degree of interconnectivity between the river bodies and groundwater closer to the catchment areas. The seepage of source water or polluted materials into groundwater is a higher possibility within the Birimian terrane, as rocks are characterized by fractures, foliations and folds

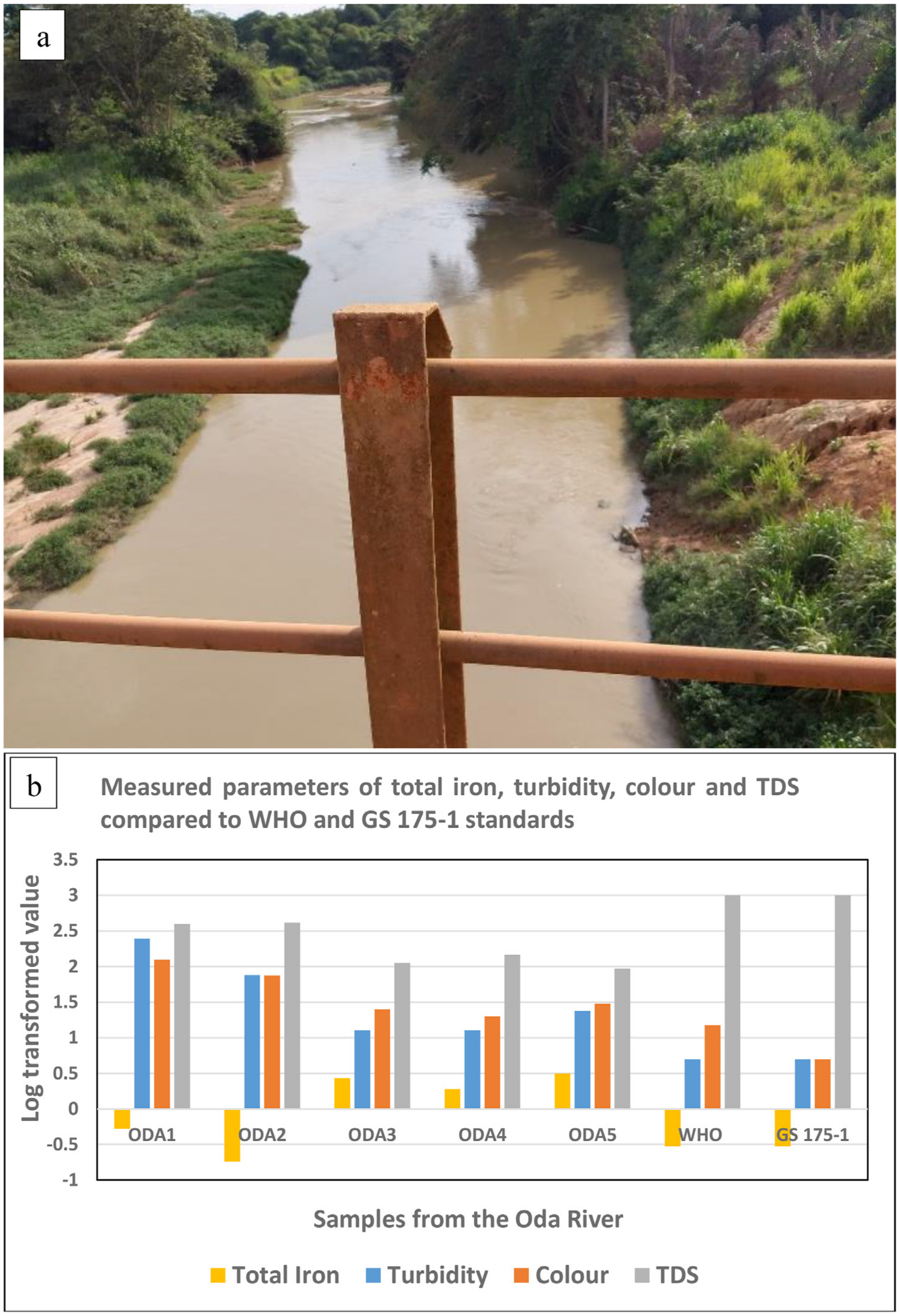

Figure 4. The state of the Oda River and plotted parameters compared with WHO. (a) River shows light brown colouration. (b) Stack bar graph of selected parameters shows samples recorded lowest TDS relate to standards, but turbidity and colour values of samples exceed WHO. Total Fe content of samples exceed WHO, except sample ODA2.

structures, which serves as weak zones or conduits suitable for fluid infiltration (e.g., Perrouty et al., 2012; Nunoo et al., 2016). Comparatively to the river samples, the borehole samples are less polluted, and may be due to the adsorption of pollutants into soils as water percolates into aquifers.

5.2. Portability of the water and possible health implications

Selected physico-chemical parameters of turbidity, colour and iron content from all rivers samples, pH of all boreholes and variable levels of fluoride, mercury, zinc, ammonia, sulphate and nitrite in all samples suggest contamination, which makes neither river nor borehole ideal for human consumption or domestic usage. These parameters compared with both the WHO and CSIR (GS-175-1) standards are often higher, although few lower values do occur that indicate deficiency relative to the standards. In all the areas where existing boreholes are being used, perhaps the colour of the water is based on eye judgement as a measure to know whether the water is clean without any form of contamination. However, the laboratory results indicate that none of the samples from the river and borehole make them suitable for human consumption, and could induce possible health issues when consumed in their current state.

For instance, water samples from boreholes recorded pH from 4.72 to 6.08 (Tables 3 and 8) but these values are lower than the WHO

Table 8. Measured parameters of water samples from along the Pra River and nearby borehole compared with adopted standards. All parameters were measured in mg/L, except turbidity, colour and pH as NTU, Hz and pH units respectively.

Parameter	PR1	PR2	PR3	PR4	PR5	PR4BH	GS 175-1	WHO Guideline
Turbidity	15.00	2235.00	2010.00	2745.00	138.00	<1.00	5.00	5.00
Colour	30.00	3750.00	3000.00	4500.00	150.00	<2.50	5.00	15.00
pH	7.42	7.15	7.00	7.03	7.36	4.72	6.50–8.50	6.50–8.50
TDS	25440.00	98.40	99.60	97.80	3444.00	319.00	1000.00	1000.00
Sodium (Na)	7000.00	9.00	8.80	9.00	850.00	60.00	200.00	200.00
Potassium (K)	300.00	4.50	4.00	4.00	26.00	9.00	30.00	30.00
Calcium (Ca)	393.00	13.10	12.80	8.26	33.30	23.40	200.00	200.00
Magnesium (Mg)	1078.00	6.21	8.30	9.08	115.00	17.90	150.00	150.00
Total Iron (Fe)	1.06	2.19	3.12	3.37	0.83	0.01	0.30	0.30
Ammonia (NH_4–N)	0.25	0.12	0.20	0.07	0.40	0.29	0.00–1.50	0.00–1.50
Chloride (Cl)	12499.00	18.50	20.80	18.90	1310.00	180.00	250.00	250.00
Sulphate (SO_4)	445.00	5.00	5.00	5.00	285.00	6.35	250.00	250.00
Manganese (Mn)	0.54	0.13	0.16	0.17	0.004	0.01	0.40	0.40
Nitrite (NO_2–N)	0.03	0.08	0.05	0.17	0.05	0.01	1.00	1.00
Nitrate (NO_3–N)	0.46	1.52	1.65	1.33	0.32	1.36	10.00	10.00
Total Hardness (as $CaCO_3$)	5420.00	58.40	66.20	58.00	612.00	132.00	500.00	500.00
Fluoride (F)	1.64	<0.005	<0.005	<0.005	<0.005	<0.005	1.50	1.50
Mercury (Hg)	0.003	0.003	0.004	0.003	0.003	0.003	0.001	0.001
Zinc (Zn)	0.02	0.24	0.02	0.01	0.03	0.13	-	-

*river samples (PR1, PR2, PR3, PR4 and PR5), borehole (PR4BH), GS 175-1 = standard from Council for Scientific and Industrial Research Lab.

Table 9. Descriptive statistical summary of measured parameters of water samples from the Pra river.

	N	Range	Minimum	Maximum	Mean	Std. Deviation
Turbidity	5	2730.00	15.00	2745.00	1428.60	1263.44
Colour (apparent)	5	4470.00	30.00	4500.00	2286.00	2074.06
pH	5	0.42	7.00	7.42	7.19	0.19
TDS	5	25342.20	97.80	25440.00	5835.96	11054.32
Sodium (Na)	5	6991.20	8.80	7000.00	1575.36	3054.26
Potassium (K)	5	296.00	4.00	300.00	67.70	130.20
Calcium (Ca)	5	384.74	8.26	393.00	92.09	168.49
Magnesium (Mg)	5	1071.79	6.21	1078.00	243.32	468.90
Total Iron (Fe)	5	2.54	0.83	3.37	2.11	1.16
Ammonia (NH_4–N)	5	0.33	0.07	0.40	0.21	0.13
Chloride (Cl)	5	12480.50	18.50	12499.00	2773.44	5465.40
Sulphate (SO_4)	5	440.00	5.00	445.00	149.00	205.13
Manganese (Mn)	5	0.54	0.00	0.54	0.20	0.20
Nitrite (NO_2–N)	5	0.14	0.03	0.17	0.08	0.05
Nitrate (NO_3–N)	5	1.33	0.32	1.65	1.05	0.62
Total Hardness (as $CaCO_3$)	5	5362.00	58.00	5420.00	1242.92	2347.22
Fluoride (F)	5	1.64	0.00	1.64	0.33	0.73
Mercury (Hg)	5	0.00	0.00	0.00	0.00	0.00
Zinc (Zn)	5	0.23	0.01	0.24	0.06	0.10

recommended range of 6.50–8.50, which indicate an acidic nature of the water from the boreholes. The presence of calcium carbonate acts as natural buffer to make pH close to alkalinity (e.g. McNally and Mehta, 2004), yet the borehole sample shows higher acidity. Limited neutrality may be due to lower content of the $CaCO_3$ content in the borehole water samples (35.20, 119.00 and 132.00 mg/L) relative to the WHO standard of 500.00 mg/L. The $CaCO_3$ content of samples is significantly small, and may contribute less to increasing pH close to neutrality, especially for sample PR4BH (pH 4.72). In addition, others (e.g. Griffiths et al., 2006) have emphasized the occurrence of volcanic ash and sulphate that lowers pH.

According to WHO (1996, 2003), waters with pH values not within their range, when consumed, can lead to skin disorders, redness of the eye and damage to epithelium. Although, the number of samples may be relatively small for an in-depth health-related deduction, higher levels of iron and mercury particularly in the Pra river samples relative to the WHO and CSIR standards cannot be overlooked. For example, WHO compilation of mercury data emphasized its potent to cause severe disruption of any tissue (*concentration dependant*), however, the main effects of mercury poisoning are neurological and renal disturbances. It has long been reported (e.g. Stockinger, 1981) that the ingestion of mercury could result in swelling of the salivary glands, stomatitis, loosening of the teeth, nephritis, anuria and hepatitis. From the results of this research, Hg levels range from 0.003 to 0.004 mg/L as against WHO and CSIR recommended value of 0.001 mg/L; such increment close to quadruple could be detrimental. For example, Skerfving and Vostal (1972) indicated that hours of exposure to 1–3 mg/m^3 of Hg may give rise to pulmonary irritation and destruction of lung tissue and

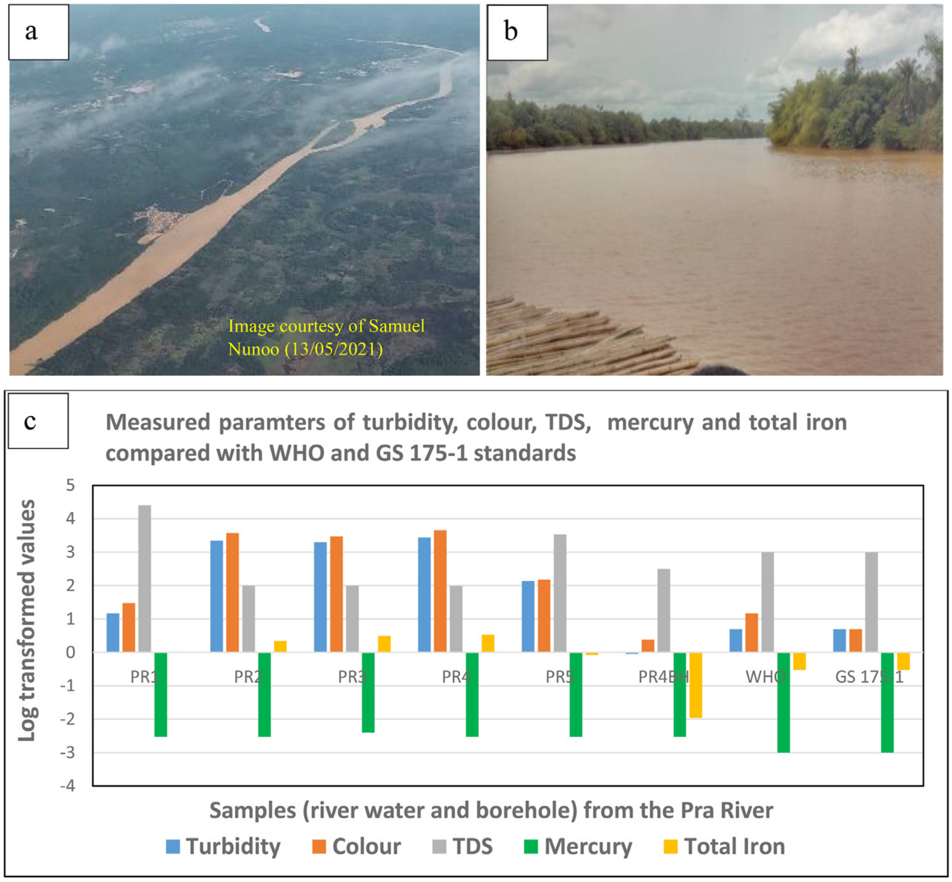

Figure 5. The muddy state of the Pra River and selected parameters compared with WHO. (a & b) Muddy river show brown colouration from an aerial view and at the bank of the river. (c) Respective turbidity, colour and total iron values of samples exceed WHO, except for borehole PR4BH. The TDS of PR1 and PR2 measures higher relative to samples and standards. Mercury content of both river and borehole sample exceed WHO.

occasionally to central nervous system disorders. The health discussion of this current work requires comprehensive data and an approach of some medical data which is an aspect for future research. However, the current state of the water bodies and borehole water when consumed could pose health issues.

5.3. Current data in relation to Ghana water policy

The water policy of Ghana is driven by the United Nation (UN) Millennium Development Goals (MDGs) and the New Partnership for African Development (NEPAD), both explore strategic ways to harness growth and reduce poverty (MWRWH, 2007). For instance, a core feature recognized in both strategies is the improvement in the provision of water supply and sanitation services. Specifically, regarding the MDGs, the Government of Ghana has endorsed a number of principles for water (MWRWH, 2007), which include (i) improving access to safe water supply and sanitation to reduce the proportion of population without access to basic water supply and sanitation by 50% by 2015 and 75% by 2025, (ii) promoting efficient and sustainable use of water to address food security and income generation, and (iii) using integrated water resource management (IWRM) to promote cooperation in national and shared water basins for the mutual benefit of all water users and their communities, (iv) acting to prevent, mitigate and manage water related disasters by developing a prevention based culture, strengthening capacity to monitor and mitigate the effects of climate variability and to manage disasters.

The current illegal mining along river courses as mentioned earlier, and supplemented by the obtained data defeat the outlined principles by the Ministry of Water Resources Work and Housing (MWRWH, 2007) of Ghana. According to MWRWH (2007), the Pra river forms a major river body under the South-Western surface river systems under surface water of Ghana, and was considered a major source of water for projected 5 billion m^3 water demand in the year 2020. Thus, Pra and the other surficial water sources (e.g., Offin and Oda) are valuable water resources that should be protected from all manner of pollution. The current states of the investigated rivers also challenge the NEPAD vision of an “African Water Vision 2025” that focuses on more equitable and sustainable use of water resources for poverty alleviation, socio-economic development, regional cooperation and the environment ((MWRWH, 2007). In addition, the data as well questions Ghana's Water Vision for 2025 aimed to “promote an efficient and effective management system and environmentally sound development of all water resources in Ghana” (Section 1.2 of MWRWH, 2007). The current state of the examined river bodies is likely to register ripple effects such as a higher purification and maintenance cost, health-related crises from consumption and non-suitable as a source water for irrigation. For instance, it has been demonstrated elsewhere that the quality of irrigation water has effect on crop yield, internal and external qualities of the product (Rusan et al., 2007; Zavadil, 2009; Mzini and Winter, 2015).

In recent times, the Ghana Water Policy of 2007 has been review by Frimpong et al. (2021). The team (Frimpong et al., 2021) drew attention to ineffective expectation of the policy as supposed to turn fortunes of the country around in the context of water resource management. Highlighted setbacks since implementation include inadequate institutional capacity and ineffective enforcement of existing regulations among others (Frimpong et al., 2021). The recent observation (this study) of the surface water, especially in the south-western sector of the nation attest

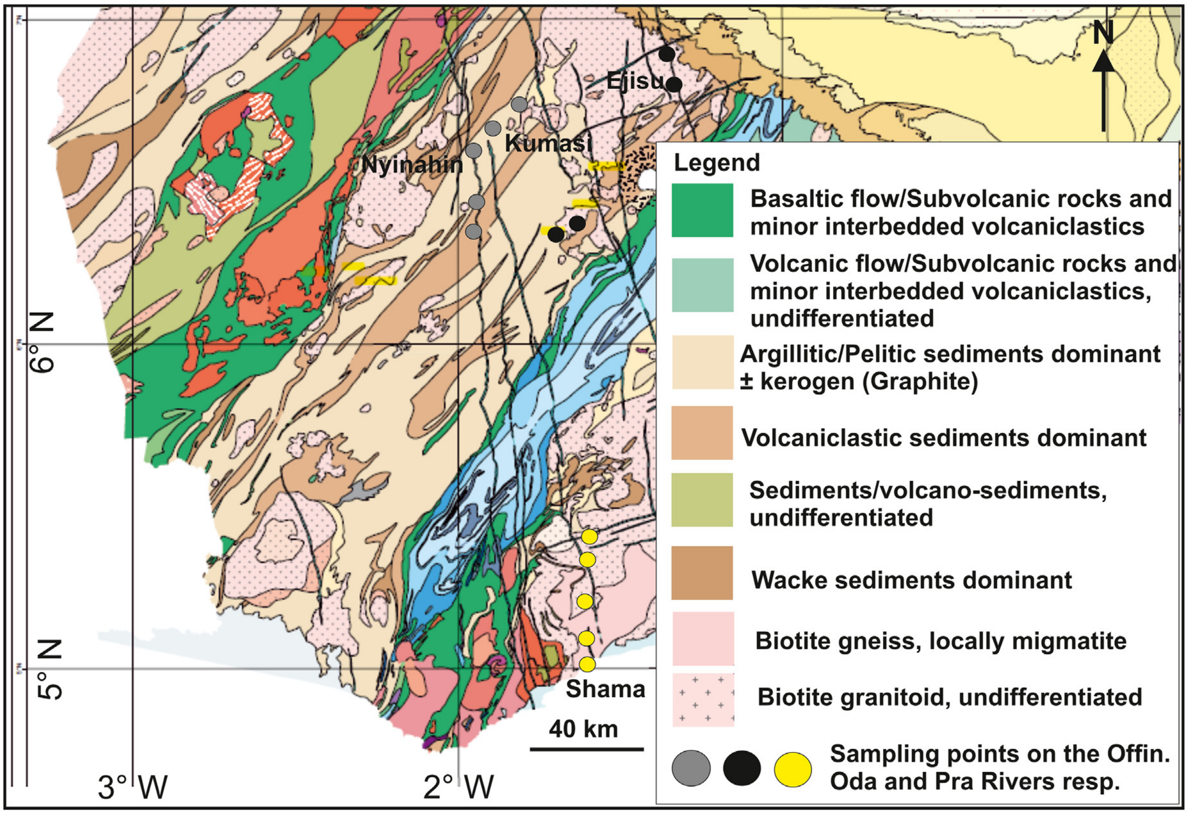

Figure 6. Geological map of Southern Ghana (GSD, 2009) showing the sampling points in relation to the underlying rocks incised by the Offin, Oda and Pra Rivers.

to a major problem of ineffectiveness governance of the investigated surface water resources. For effective governance, an integrated effort and measures are required from major relevant policy making bodies such as the Water-related institutions under MWRWH, the Inspectorate Division of the Minerals Commission and the Environmental Protection Agency of Ghana.

6. Conclusion and recommendations

6.1. Conclusion

Major rivers of the Offin, Oda and Pra basins and few nearby boreholes were sampled and analyzed to ascertain if polluted, as colour of the rivers observed posed worries to the public. The data obtained from 15 river samples and 3 borehole samples offer three main deductions:

- The current state of the three rivers and nearby borehole waters indicates contamination as values of colour, turbidity, total Fe, mercury, ammonia and sulphates exceed potable water limits by the WHO and Ghana CSIR standards.
- Potential activity believed to have largely necessitated the observed trends in the apparent colour, suspended sediments level and other chemical constituents can be related to practices of illegal alluvial gold mining. In some samples, especially in the Pra and Oda rivers, high values of ammonia, nitrite and sulphate could come from excess run-off from farmland fertilizers or other sources yet to be established.
- Among the three rivers, the data indicate an increase of pollution from the Oda through Offin to the Pra Rivers. The current state of these rivers are not desirable for human consumption without any treatment, particularly, that of the Pra River and the associated boreholes which are much acidic with extreme high levels of chlorine and mercury likely to pose health issues.

6.2. Recommendations

- The need to monitor all the rivers and associated borehole water should be of a national concern and for this reason regular or periodic sampling is needed to check levels of contamination and give advice on the suitability of using the water especially for drinking.
- Future research should be focused on other major rivers, such as the Birim, Ankobra and the Tano within the country, which drain areas with some mining activities.
- Future work should consider soil analysis, especially, the likelihood of pollutants adsorbed by soil during the percolation of water into aquifers.

Declarations

Author contribution statement

Samuel Nunoo; Francis K.B Owusu-Akyaw: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Frank K. Nyame; Johnson Manu: Analyzed and interpreted the data; Wrote the paper.

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Data availability statement

Data will be made available on request.

Declaration of interest's statement

The authors declare no competing interests.

Additional information

No additional information is available for this paper.

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