The AKOBEN programme as a tool towards responsible gold mining in Ghana, business as usual or a commitment towards sustainable development

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ABSTRACT

The AKOBEN Programme, an environmental performance rating and disclosure initiative that show the environmental performance of gold mining firms with reference to their daily activities post environmental impact assessment and issuance of an environmental permit was introduced in Ghana to serve as a monitoring and verification tool towards environmental compliance and responsible mining. As to whether the AKOBEN Programme is enhancing the environment and or safeguarding public health in Ghana needs to be investigated. A systematic multi-methods environmental audit approach comprising of comparative analysis, time series analysis, air and water quality indices were used within the framework of the Driver-Pressure-State-Impact-Response to answer the questions what is happening to the environment and what the consequences for the environment and humanity are. The quality and suitability of River Kwabrafo as a habitat for aquatic life, for agricultural, recreational and drinking purposes pre and post AKOBEN Programme introduction as well as the quality of agricultural soils and river sediments in gold mining communities was determined. The study revealed that the AKOBEN Programme rates gold mining firms based on variable-by-variable concentrations of toxic water pollutants such as As, Cd, Hg, CN and non-toxic water pollutants such as pH, suspended solids, dissolved solids and electrical conductivity without taking into account the cumulative effect of the pollutants and the various uses of water. Results on the quality of River Kwabrafo based on the Canadian Council of Ministers of the Environment Water Quality Index confirmed no differences in water quality concerning use for agriculture, recreation, drinking and as a habitat for aquatic life before and after the introduction of the AKOBEN Programme. The study also revealed the quality of air at Anyinam to be acceptable with reference to PM10 and unhealthy with reference to total suspended particulate (TSP). The AKOBEN Programme failed to delineate TSP into oxides of nitrogen, carbon dioxide, methyl mercury and oxides of sulphur for which reason the impacts of greenhouse gases and methyl mercury on the Obuasi Municipality could not be investigated under the AKOBEN Programme. Mean arsenic concentrations for all study sites exceeded the arsenic reference for Ghana with significant differences existing between mean soil Cd and Hg levels at AKOBEN sites, Non-AKOBEN sites and Control sites. This study will not only elucidate the environmental and health problems associated with gold mining operations at AKOBEN and Non-AKOBEN sites in Ghana, but will also present complex water quality data into simple communication format for easy understanding to policy makers and non-expert audience.

1. Introduction

Ghana, the second largest gold producer in Africa has made huge economic gains from gold since it was first mined in 1471[1] to date with environmental degradation also on the ascendency. Although Ghana has a Legal and Regulatory Framework that requires prospective miners to carrying out an environmental impact assessment, the extraction, recovery and refining of gold still results in the release of toxic and non-toxic pollutants. The toxic substances not limited to PM10, PM2.5, cyanide, copper, mercury, arsenic and cadmium and the non-toxic pollutants

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not limited to suspended solids and dissolved solids can have devastating impacts on flora and fauna.

These negative impacts which cover a scope of permanent toxicological ecosystem degradation, destruction of habitats with associated loss of biodiversity and the accumulation of contaminants in environmental media including water, sediment, air and soil can threaten community land use and cultural practices (Abdul-Wahab and Marikar, 2012; van der Voet et al., 2013). Notwithstanding the fact that humans possess mechanisms for the explosion of particulate matter that diffuse into their airways, subsequently getting into the bloodstream (Dockery and Pope, 1994; Anderson et al., 2012; Hinds, 2012) air pollutants emanating from gold mining activities be it gaseous or particulate in nature has the potential of causing tremendous health effects including respiratory, cardiac, and all-cause mortality to flora, fauna and humans (Miller et al., 2007; Environmental Law Alliance Worldwide, 2010; Choudhary, 2015; Nazif et al., 2016).

Gold mining effluent apart from contaminating surface and groundwater, arsenic and cadmium among other metals liberated during mining activities also has the potential of impacting dissolved oxygen levels and pH of receiving waters thereby diminishing the domestic, agricultural, industry, recreational uses and the capacity of water bodies to serve as a habitat for aquatic organisms (Armah et al., 2011; Jain et al., 2012, 2016).

With the study area the Obuasi Municipality being a major Proterozoic gold belt where gold deposits occur within greenstones mineralized in quartz veins with gold trapped in arsenopyrite and sulphide ore[2,3], heavy metal and metalloid pollution is an ever present danger. The use of an adapted version of the Solway Water Quality Index (WQI) by the Water Resources Commission of Ghana as an index to characterize the overall raw water quality in Ghana into good, fairly good, poor, and grossly polluted without recourse to the key uses of water including recreation, drinking, irrigation and as a habitat is woefully inadequate. This study ascertained if the quality of River Kwabrafo, air quality, soil quality and sediment quality in the Obuasi Municipality has improved post AKOBEN Programme implementation using the driver-pressure-state-impact-response (DPSIR) approach to uniquely elucidate the impact of the AKOBEN Programme on four key environmental media in an easy to comprehend form, which is a paucity in Ghana.

Since the implementation of her first public disclosure in the late 1980's in response to the right to know mentality of the United States citizenry as well as addressing the potential impacts toxic substances cause to the environment, public disclosure has been in vogue (Lopez et al., 2009; Kathuria, 2009). Europe, Australia, Canada, Mexico, South Korea, China and Indonesia have subsequently disclosed environmental information to the public via rating the environmental performance of industries as a means of complimenting and strengthening conventional regulation (Paliwal, 2006; Kathuria, 2009; Jin et al., 2010).

The AKOBEN Programme an "environmental performance rating and disclosure initiative" instituted by the Government of Ghana and the Environmental Protection Agency (EPA) in the year 2010 follows the general rules of public disclosures albeit having a scope of indicators reflecting the Ghanaian concept of the environment. Five colours namely gold, green, blue, orange and red are used in a "five-colour rating scheme" to show the environmental performance of gold mining firms with reference to their daily processes after an environmental impact assessment has been undertaken and environmental permit issued[4]. The input for the evaluation of the AKOBEN Progmamme include quantitative data, qualitative data and visual information based on which gold mining firms are rated from excellent for the best performance and poor for the worst performance.

There four (4) main stages in the AKOBEN Programme include Data Collection, Evaluation, Ratings Report Card and Disclosure. To ensure the accuracy of AKOBEN ratings, EPA inspectors conduct site assessments to ascertain at first-hand environmental and social issues, which may be difficult to capture using quantitative approaches. To ensure optimum accuracy, the methodology used by the AKOBEN Programme include rating criteria, rating concept and rating rules through a computerized system[5]. The rating criteria based on which the public disclosure of the AKOBEN Programme is announced consist of seven parameters viz legal issues, hazardous waste management, toxic and non-toxic releases, monitoring and reporting, environmental best practices, community complaints and corporate social responsibility[6]. A RED rating is assigned if a gold mining company: (a) is noncompliant with all requirements of the Environmental Assessment Regulations LI 16522; (b) is noncompliant with all criteria for safe on-site management of toxic and hazardous waste; (c) discharges effluent with any of the toxic parameter exceeding permissible discharge levels as stipulated by the EPA. To avoid a RED rating, a compliance rate of more than 98% is required for toxic parameters during a twelve month period. A gold mining company is assigned an ORANGE rating if: (a) compliance rate of the mining firm is <75% for conventional or non-toxic environmental parameters; (b) "compliance rate the gold mining company is <75% for noise pollution", (c) best practices adoption rate of the mining firm is <75%, (d) reporting rate of the mining company is <75% for monthly monitoring data. A mine is rated BLUE if: (a) there are no RED or ORANGE in relation to any criteria, (b) "the compliance rate is >=75% for all environmental categories during the rating period of twelve months", (c) "the reporting Rate is >=75% for monthly monitoring data after adjusting for months when sampling was not possible", (d) the best practices adoption rate is >=75%[7]. A GREEN rating is assigned if: (a) "It has secured a BLUE rating with 90% or higher compliance and reporting rates", (b) "Meets >=90% of the complaints management criteria, and has no unresolved issue for a complaint which has been validated by EPA". Environmental complaints covered by the AKOBEN Programme, include the complaints in relation to: (a) water resources of the communities in the catchment area of a mining project; (b) ambient air quality due to particulate matter (PM10) and total suspended particulate TSP; (c) noise pollution; (d) vibrations caused by blasting at mining sites and (e) any other environmental issue likely to hamper the welfare of the communities in the proximity of the project area of a mining firm. A gold mining company is credited with a GOLD rating if: (a) the mining company has secured a BLUE rating with 100% compliance and reporting rates; (b) the mining company meets 100% of the GREEN criteria; and (c) the mining company properly follows its corporate social responsibility (CSR) policies and meets 100% of the GOLD criteria[8].

2. Materials and methods

2.1. Study areas

The Obuasi Municipality of sixty-three (63) Communities is situated between latitudes 5.35 °N and 5.65 °N and longitudes 6.35 °N and 6.90 °N and hosts the Obuasi Gold Mine, now Anglo Gold Ashanti in Obuasi its administrative capital (GSS, 2014). The Obuasi Municipality, which spans an area of about 162.4 km^2, is located in the southern section of the Ashanti Region. The Municipality shares precincts to the west with Amansie Central District, to the east and south with Adansi South and to

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[2] District Profile Obuasi.

[3] Minerals Commission, Ghana.

[4] www.epaghanaAKOBEN.org/AKOBEN/methodolgy.

[5] www.epaghanaakobe.org.

[6] www.epaghanaakobe.org.

[7] Due to the very technical nature of the rating methodology, the text referenced 7 could not be completely paraphrased. See www.epaghanaAKOBEN.org/AKOBEN/methodolgy for information on the AKOBEN Programme.

[8] Due to the very technical nature of the rating methodology, the text referenced 8 could not be completely paraphrased. See www.epaghanaAKOBEN.org/AKOBEN/methodolgy for information on the AKOBEN Programme.

the north with Adansi North District[9,10]. The climate is of the semi-equatorial type with a double rainfall regime. Mean annual rainfall ranges between 1250 mm and 1750 mm. Mean annual temperature is 25.5 °C and relative humidity is 75%–80% in the wet season (GMET, 2014). The vegetation is predominantly degraded semi-deciduous forest. The forest consists of limited species of hard wood, which are harvested as lumber[11,12]. Several communities in the Obuasi Municipality prefer to consume water from boreholes or hand dug wells due to the popular belief that the water flowing through taps is often contaminated with heavy metals associated with mining[13]. Tontokrom a hotbed for artisanal and small-scale mining is located about 14.2 km from Manso Nkwanta, the district capital of Amansie West District. Totonkrom can be found between Latitude 6°15'0"N and Longitude 2°0'0"W and host communities including Mmredani, Bogum and Komkowu. Tontokrom is categorised as a wet semi-equatorial climatic zone with double rainfall maxima regime. Mean annual rainfall in Tontokrom ranges between 855 mm and 1,500 mm for the minor and major rainy seasons respectively. December-March in Tontokrom are characterized by early morning mist/fog and cold weather conditions. Mean monthly temperature is 27 °C and vegetation is mainly rain forest with moist semi deciduous characteristics. To be able to situate the environment in relation to sustainable development issues, to establish clearly cause-effect relationships and to answer the question what is happening to the environment and why it is happening, air, soil, sediment and water quality analysis were undertaken at locations under AKOBEN monitoring (Obuasi), Non-Akoben (Tontokrom) locations and control sites.

2.2. Water quality assessment

Toxic water quality parameters including cadmium, copper, mercury and arsenic as well as non-toxic toxic water quality parameters including dissolved solids, suspended solids, electrical conductivity and pH were selected for assessment in order not to go out of the scope of the AKOBEN Programme water quality indicators. Data on water sampled monthly between 2003-2010 (pre AKOBEN Programme period) and 2011–2017 (post AKOBEN Programme period) from the upstream section (S1) and three (3) other locations (S2, S3, S4) downstream River Kwabrafo taking into consideration proximity of communities, tailings footprints, tailings dam and how to obtain a true representation of River Kwabrafo was gathered (Fig. 1). An Excel macro of the Canadian Council of Ministers of Environment Water Quality Index (1.0) based on a formula developed by the British Columbia Ministry of Environment, Lands and Parks and modified by Alberta Environment (Fig. 2) was used to assess the quality of River Kwabrafo pre and post AKOBEN Programme periods taking cognizance of the key uses of water. The key uses of water with reference to River Kwabrafo considered in this study included the suitability of the water for use in agriculture, as a habitat for aquatic organisms and for use by humans and wildlife for which ranges for the categorization is shown in Table 1 (CCME, 2001; Saffran et al., 2001).

2.3. Sediment quality assessment

Composite sediment samples were collected using standard protocol from River Kwabrafo (river under AKOBEN Monitoring) and River Offin (control). The composite sediment samples were labelled and transported to the Soil Research Institute (SRI) of the Center for Scientific and Industrial Research (CSIR) laboratory where Atomic Absorption Spectrometer (AAS) with a graphite and vapour kit units were used to measure cadmium and mercury/arsenic concentrations respectively. A

certified reference material was prepared the same way as the samples as a way of ensuring quality control. A comparative analysis between sediments from River Kwabrafo and sediments from River Offin was used to assess the impact of the AKOBEN Programme on sediment quality.

2.4. Soil quality assessment

Eighteen (18) soil samples from eight (8) holes from rehabilitated sites under the AKOBEN Programme and control sites outside of the footprints of mining activities (Fig. 3) were collected using a combination of hand-auger, and power-auger methods to a maximum depth of 40 cm. Soil samples were bagged in sterilized plastic containers labelled and analyzed for arsenic, chromium, cadmium, copper and mercury using X-ray Fluorescence (XRF) as described by (Fitton, 2014) at a temporary field laboratory in Obuasi. The labelled bagged samples were stored in a cool box and transported to the accredited laboratory of Maxxam in Canada where samples were again analyzed by inductively coupled plasma mass spectrometry (ICP-MS)[14] following aqua-regia digestion for quality-control purposes.

2.5. Air quality assessment

Twenty–four hour monitoring data on Particulate Matter (PM 10) and Total Suspended Particulate (TSP) sampled over a 48 month period at two air quality monitoring stations S6 (under AKOBEN Programme monitoring) and S7 (control) as shown in Fig. 1 was obtained from the Environmental Department of AngloGold Ashanti Obuasi Mine. The monitoring data was inputted into an Excel macro of the Air Quality Index (AQI) calculator developed by the United States Environmental Protection Agency (Fig. 4) to generate a number that was interpreted using Table 2 to inform the residents at Anyinam and Mampamhwe how clean and or unhealthy the air is and what the associated health effects could be. AQI values in the range of 0–50 and 51–100 (Table 2) represents good air quality that poses little or no risk threat to the health of individuals and moderate air quality with moderate public health concern for a very small number of the population respectively (CIESE, 2016; USEPA, 2016). Air Quality Index values in the range 101–150 (Table 2) are generally thought of as unhealthy for sensitive groups while AQI values above 300 is an indication of the fact that the air quality is unhealthy (Eder et al., 2010; Arora et al., 2015).

2.6. Quality control

All analyses of soil, sediment, water and air were performed in conjunction with a range of standard quality control measures to enable the calculation of sampling variance, analytical variance and instrumental accuracy/precision. The quality control measures used included regular verification of instrument calibration against independent standards; regular measurement of blank samples; regular measurement of laboratory control samples; consistent measuring of duplicate samples and regular measurement of spiked matrix samples and matrix certified reference materials. Additional quality control measures used for the study included collecting and analyzing field duplicate samples at a frequency of 5% of total samples and repeating analysis of samples at a frequency of 1 in 20 analyses.

2.7. Analysis

Site-specific objectives as well as guidelines from CCME for parameters including cadmium, copper, mercury and arsenic, dissolved

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[9] [Online] Available from: http://www.ghanadistricts.com/.

[10] 2010 Population and Housing Census, District Analytical Report.

[11] Ghana Statistical Services (GSS).

[12] District Profile Obuasi Municipality.

[13] District Profile Obuasi Municipality.

[14] ICP-MS is a type of mass spectrometry capable of detecting metal concentrations as low as one part in 10^{15}.
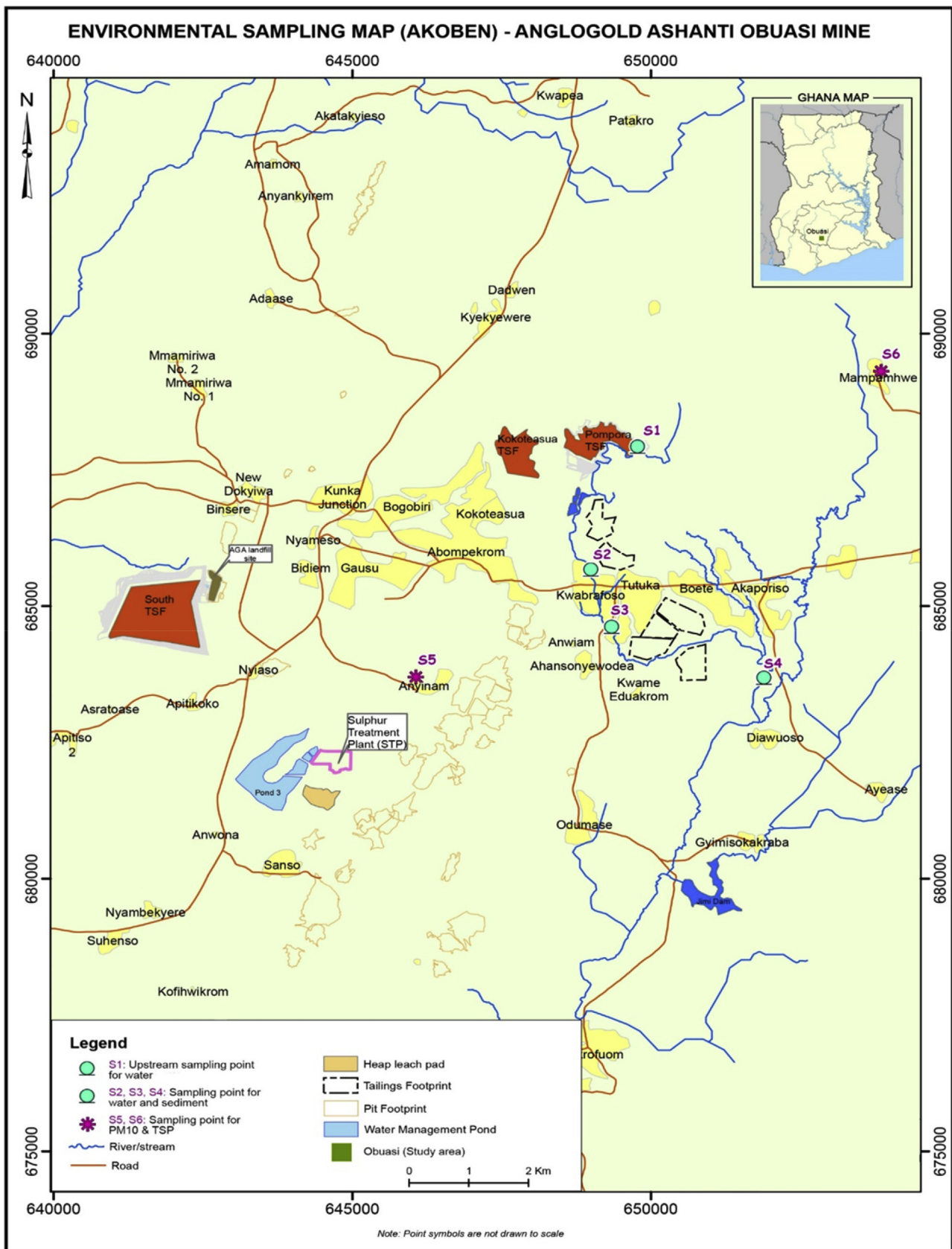
Fig. 1. Map of Study Area Showing Sampling Points for Air and Water Quality Assessment. Source: Rebeca Amoah Addae and reproduced by Edwin Gyamfi.
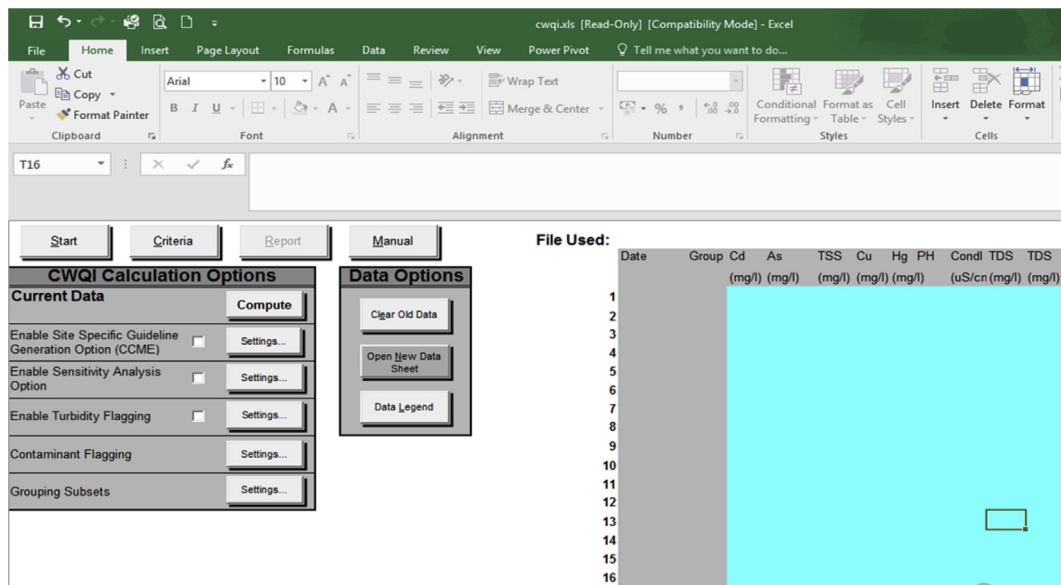
Fig. 2. Water Quality Index Calculator used for Water Quality Assessment of River Kwabrafo Pre and Post AKOBEN Programme Monitoring.

solids, suspended solids, electrical conductivity and pH from River Kwabrafo were inputted into a "user-friendly Excel based model programme using Visual Basic for Applications" of the CCME. A vector is scaled to range between 0 and 100, and deducted from 100 to give an index with zero (0) and hundred (100) representing worst water quality and best water quality respectively with associated risks (Table 1 and Fig. 2). Microsoft Excel macro of the Air Quality Index calculator (Fig. 4) developed by the United States Environmental Protection Agency (USEPA, 2016) was used to undertake a time series of PM10 and TSP and to determine the quality of air (state) within in the context of the driver-pressure-state-impact-response framework and the results interpreted using (Table 2). The student's T-Test in Graphpad Prism Version 5.0 was used to compare the means of cadmium, copper lead, mercury and arsenic present in sediments from River Kwabrafo (under AKOBEN Programme monitoring) and control sediments (sediments from River Offin) for significance. The student's T-Test in IBM SPSS Statistics Version 22.0 was used to compare the means of heavy metals present in treatment soils (soils at reclaimed sites) and control soils (soils from sites outside the footprints of reclaimed sites) for significance.

Table 1
Categorization of water quality.

WQI Value	Colour	Category	Water Quality Description
95–100	Purple	Excellent	water quality is protected with a virtual absence of threat/impairment; conditions very close to natural or pristine levels.
80–94	Dark red	Good	water quality is protected with only a minor degree of threat or impairment; conditions rarely depart from natural or desirable levels
65–79	Dark green	Fair	water quality is usually protected but occasionally threatened or impaired; conditions sometimes depart from natural or desirable levels
45–64	Blue	Marginal	water quality is frequently threatened or impaired; conditions often depart from natural or desirable levels
0–44	Green	Poor	water quality is almost always threatened or impaired; conditions usually depart from natural or desirable levels.

Adapted from CCME, 2001 and Saffran et al. (2001).

3. Results and discussion

3.1. Trends in water quality parameters for River Kwabrafo

All arsenic concentrations monitored in River Kwabrafo during the pre-AKOBEN periods of 2003 and 2004 and the post-AKOBEN periods of 2010–2017 exceeded the EPA's guideline value of 0.05 mg/L (Fig. 5). The elevated levels of arsenic in River Kwabrafo has been corroborated by the incidence of elevated levels of arsenic (0.90–8.25 mg/L) in water bodies far exceeding the EPA'S and World Health Organizations guideline values 0.05 mg/L and 0.01 mg/L respectively in Prestea a mining community in Ghana (Serfor-Armah et al., 2006). Surface water in Obuasi have also been reported by (Smedley et al., 1996) as affected by mining activities with observed arsenic concentrations of 0.5 mg/L ten times greater than the EPA guideline. Awuah (2016) reported of mean arsenic levels of 0.07 mg/L and 0.06 mg/l in River Tano in the Brong Ahafo Region and River Ankobra in the Western Region of Ghana exceeding the EPA'S guideline of 0.05 mg/L. Asamoah-Boateng (2009) reported of arsenic concentrations in the range of 0.010–0.090 mg/L from surface water samples in the Brong Ahofo Region of Ghana where Newmont Ghana owns a gold mining concession in support of Awuah's assertions which are largely in agreement with outcome of the study. The results of these two studies are in agreement with the results on the arsenic levels in River Kwabrafo albeit the maximum arsenic value (3.97 mg/L) recorded in River Kwabrafo being significantly higher. Arsenic levels in River Kwabrafo was significantly higher (p < 0.05) than arsenic levels reported by (Hadzi et al., 2015; Attiogbe and Nkansah, 2017) in River Pra, Bosomkese Forest River, Atiwa Range River and the Ankasa Forest River. All studies so far had not categorized the quality of water bodies in mining communities in Ghana into the suitability of water for uses such as irrigation, recreation among others which the present study focuses on.

Conductivity/pH levels, copper and free cyanide concentrations recorded during both the pre-AKOBEN Programme monitoring period (conductivity 2007, pH 2003 & 2004, Cu, 2003 & 2004, free cyanide 2003 & 2004) and the post-AKOBEN Programme period from 2010-2017 for River Kwabrafo were within guideline limits set by the EPA of Ghana (Figs. 6, 7, 8, and 9). This results on River Kwabrafo is generally in agreement with the results of a water quality study for the Afosu Stream (pH 7.2, TDS 165.7 and TSS 18.8) and River Pra (pH: 7.3, TDS: 172.2, TSS: 125) in a study conducted in the Eastern Region of Ghana by (Attiogbe and Nkansah, 2017). Results of a study by (Hadzi
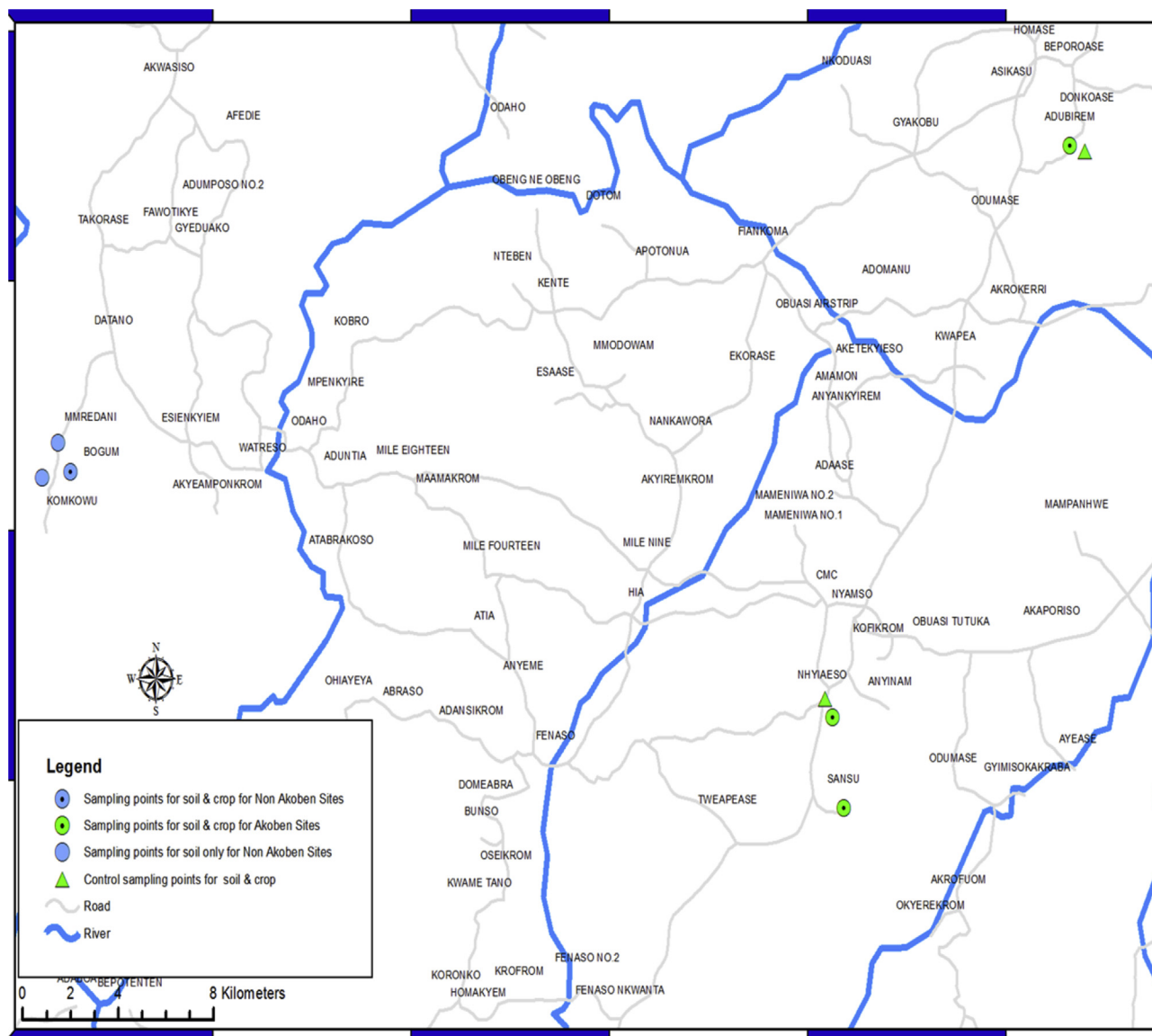
Fig. 3. Map showing sampling sites for soil for Akoben, non-Akoben & control sites source: Patrick awortwe.

et al., 2015) on Rivers in close proximity to gold mining activities recorded conductivity ranges of 2790–2890 µs/cm (Bonsa River) and 2070–2079 µs/cm (Subri River) exceeding the EPA guidelines with measurements for the Birim River 442–1890 µs/cm falling within the EPA guideline. The pH values recorded in River Kwabrafo corroborates (Hadzi et al., 2015) findings of pH ranges of 7.0–7.2 (Bonsa River), 6.9–7.2 (Subri River) and 5.7–7.0 (Birim River) all within the EPA guideline. The pH results for River Kwabrafo all of which fall within the EPA guidline (6.5–8.5) is an indication of the water being generally neutral to slightly alkaline. With a neutral to alkaline pH, metals which are generally soluble in acidic environment will not be readily available for uptake and bioaccumulated by aquatic organisms in River Kwabrafo (ATSDR, 2001).

TSS concentrations for (2013, 2015 & 2017) and TDS concentrations for (2012 & 2013) for River Kwabrafo exceeded the EPA guidelines (Figs. 10 and 11). The reasons for the TDS and TSS exceeding the EPA guidelines could probably be due to an upsurge in artisanal and small-scale mining activities within the catchment area of River Kwabrafo, the use of limestone during the neutralization in the BIOX process at AngloGold Ashanti (Michaud, 1991) and the infusion of wastewater with

high dissolved salts from septic systems from residents of Apitikoko, Tutuka, Diawuoso and Kwabrafo all communities in close proximity to River Kwabrafo (Fig. 1). The AKOBEN Programme through it rating criteria, which demand that gold mining companies properly manage hazardous and toxic waste, comply with environmental quality standards, monitor and report on environmental issues and apply best environmental management practices has only resulted in a decreasing trend in copper concentrations in River Kwabrafo with other water quality parameters seeing no improvement.

3.2. State of River Kwabrafo Pre and post AKOBEN periods

With the exception of Arsenic (As), all other water quality parameters analyzed for River Kwabrafo were below the stipulated EPA permissible levels. The high levels of Arsenic can be attributed to the geology of the Obuasi Municipality which is categorized arsenopyrite (arsenic and iron). Although the arsenic concentration exceeded the permissible levels, there has been a significant reduction in the arsenic concentration post-AKOBEN Programme introduction (Fig. 5). The decreasing concentrations of arsenic in River Kwabrafo Post AKOBEN Programme

Fig. 4. Air Quality Index Calculator used for Air Quality Assessment at Anyinam and Mampamhwe.

periods could be attributed partly to the AKOBEN Programme and largely to the BIOX process, which pre-treats refractory sulphide gold ores including arsenopyrite, pyrite and pyrrhotite[15].

Per the variable-by-variable permissible levels of pollutants in River Kwabrafo, all the toxic pollutants but arsenic and all non-toxic water quality concentrations met the Environmental Protection Agency of Ghana's permissible guidelines for the AKOBEN Programme. The state of River Kwabrafo based on the variable-by-variable concentrations appeared to be okay. However, an analysis of River Kwabrafo using the Canadian Council of Ministers of Environment (CCME) Water Quality Index (WQI) model, which uses a cumulative approach of all the toxic and non-toxic water quality indicators of the AKOBEN Programme to assess water quality, revealed River Kwabrafo as having serious pollution issues.

The water quality of the upstream section of River Kwabrafo S1 (Fig. 12) that has had no infusion of mining waste with a CCME WQI value of sixty one (61) can be said to be frequently threatened or impaired; with conditions often departing from natural or desirable levels (CCME, 2001) and hence categorized marginal for drinking (Table 1). Even though people in the Obuasi Municipality hardly drink from River Kwabrafo, ascertaining the quality of River Kwabrafo with reference to drinking is very relevant. This is because close to 60% of water bodies in Ghana which are considered critically polluted serve poor rural communities downstream[16]. The water quality of the upstream section of River Kwabrafo can also be said to be almost always threatened or impaired; with conditions usually departing from natural or desirable levels with reference to the survival of aquatic life (CCME WQI value of 40) with a categorization of poor (CCME, 2001). A CCME WQI of seventy-two (72) for irrigation and sixty-eight (68) for use by

livestock of the upstream section of River Kwabrafo is an indication that the water quality is usually protected but occasionally threatened or impaired with conditions sometimes departing from natural or desirable levels[17][18] [19](CCME, 2001). The quality of water vis-à-vis irrigation and livestock rearing at the upstream section of River Kwabrafo can thus be said to be fair (Fig. 12). For recreation purposes, the water quality of the upstream section of River Kwabrafo per the CCME WQI model (WQI of 82) can be said to be good and protected with only a minor degree of threat or impairment, with conditions rarely departing from natural or desirable levels (CCME, 2001). These variations in the five uses of the upstream section of River Kwabrafo per the CCME WQI model could be ascribed to a gamut of factors, which include illegal artisanal mining activities, dumping of domestic waste and dumping domestic grey water via pipes as pertains to most raw water sources in Ghana.

Analysis of water samples from an AKOBEN programme prescribed sampling point downstream River Kwabrafo known as Super Mambo S2 (Fig. 13) revealed a deterioration of all five uses of River Kwabrafo. The upstream water quality of marginal (CCME WQI = 61) for drinking deteriorated to poor for both the pre AKOBEN (CCME WQI = 21) and post AKOBEN (CCME WQI = 29) periods at Super Mambo (Fig. 13). The upstream water quality of good (CCME WQI of 82) for recreation deteriorated to poor for the pre AKOBEN (CCME WQI = 35) and post AKO-BEN (CCME WQI = 39) periods whilst the upstream water quality which was fair for irrigation and livestock (CCME WQI of 72 and 68 respectively) deteriorated to marginal for irrigation (CCME WQI = 46) and poor for livestock (CCME WQI = 28) for the pre AKOBEN period at Super Mambo. The upstream water quality which was fair for irrigation and livestock also deteriorated to marginal for irrigation (CCME WQI = 35) and poor for livestock (CCME WQI = 45) for the post AKOBEN period at Super Mambo. The worsening of the state of the River Kwabrafo per the CCME WQI with reference to drinking could be attributed to gold mining related activities. Though rivers have a self-cleansing ability as they flow over distance (Nesaratnam, 2014), the quality of River Kwabrafo did not see any significant improvement further downstream Super Mambo at

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[15] https://www.goldfields.com/.

[16] Water Resources Commission of Ghana workshop in Ho, Source: GNA, May 13, 2017.

[17] https://www.ccme.ca.

[18] USEPA: Guidance for developing ecological soil screening levels: OSWER-directive 9285.7–55 Available from: https://www.epa.gov/chemical-research/guidance-developingecological-soil-screening-levels [Last accessed 10 October 2018].

[19] Kabata-Pendias A, Pendias H. Trace elements in soils and plants. 3rd ed. Boca Raton, Florida: CRC Press, 2010.

Table 2

Categorization of air quality.

Levels of Concern	Colour	People Affected	Value	Meaning
Good	Green		0–50	• air quality is satisfactory and air pollution presents slight or no risk
Moderate	Yellow	some people who may be unusually sensitive to particle pollution.	51–100	• air quality is acceptable, moderate health concerns however exist for a very small number of individuals who are unusually sensitive to air pollution
Unhealthy for Sensitive Groups	Orange	sensitive groups include people with heart or lung disease, older adults, children and teenagers.	101–150	• sensitive individuals could experience health effects. The public is not likely to be affected.
Unhealthy	Red	everyone	151–200	• everybody may begin to experience health effects; sensitive individuals may experience more severe health effects
Very Unhealthy	Purple	everyone	201–300	• public health warning: all individuals may experience more serious health effects.
Hazardous	Maroon	everyone	301–500	• health warnings of emergency conditions. population in its entirety more likely to be affected

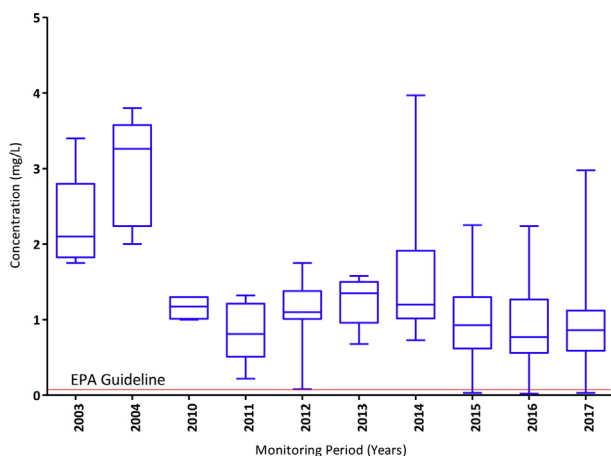Adapted from: USEPA, 2016; https://www.airnow.gov/.

Fig. 5. Box and Whiskers Plots of Arsenic Levels in River Kwabrafo Pre and Post AKOBEN Programme Implementation. Data for arsenic (As) concentration measurements pre and post AKOBEN periods in River Kwabrafo is presented as box and whisker plots in Fig. 5. The median arsenic concentration values are shown by the line that divides the boxes into two parts. The upper and lower whiskers represent the maximum and minimum arsenic concentration while the lower and upper boundaries of the boxes show the lower and upper quartiles arsenic concentrations in River Kwabrafo. All arsenic measurements exceeded the environmental Protection Agency's guideline value 0.05 mg/L.
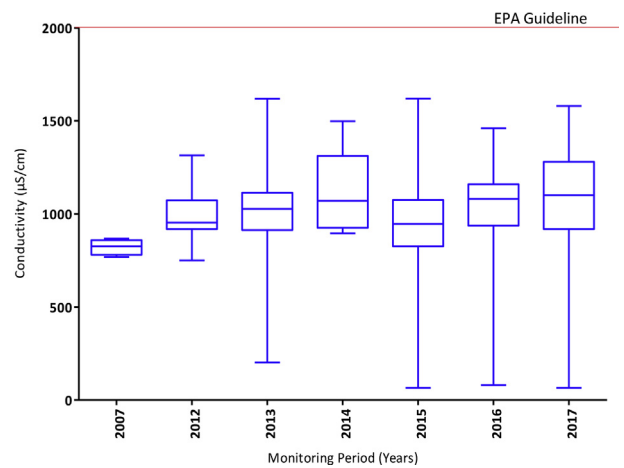

Fig. 6. Box and Whiskers Plots of Conductivity in River Kwabrafo Pre and Post AKOBEN Programme Implementation. Data for electrical conductivity measurements pre and post AKOBEN periods in River Kwabrafo is presented as box and whisker plots in Fig. 6. The median conductivity values are shown by the line that divides the boxes into two parts. The upper and lower whiskers represent the maximum and minimum conductivity concentration while the lower and upper boundaries of the boxes show the lower and upper quartiles conductivity levels in River Kwabrafo. All conductivity measurements were below the environmental Protection Agency's guideline value 2000 µS/cm.
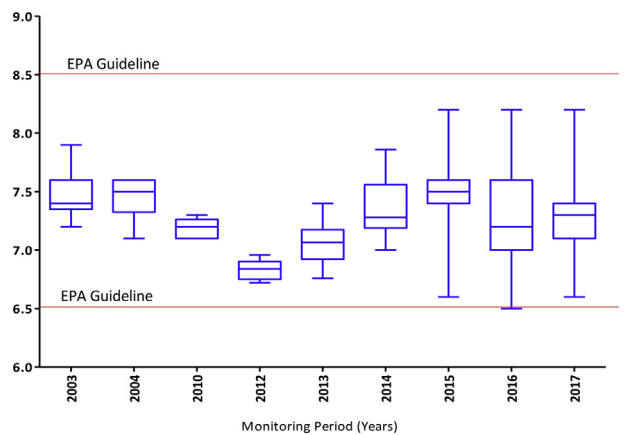

Fig. 7. Box and Whiskers Plots Showing pH levels in River Kwabrafo Pre and Post AKOBEN Programme Implementation. Data for pH measurements pre and post AKOBEN periods in River Kwabrafo is presented as box and whisker plots in Fig. 7. The line that divides the boxes into two parts represent the median values, whilst the upper and lower whiskers represent the maximum and minimum pH values. The lower and upper boundaries of the boxes show the lower and upper quartiles respectively. There was much more variation in pH levels post-AKOBEN Programme period (from 2010) as compared to the pre-AKOBEN Programme period. The acceptable pH range set by the EPA of Ghana is 6.5–8.5.

Amansan (Fig. 14) and Diawuoso (Fig. 15) due to proximity to tailing footprints and communities, which further contaminate River Kwabrafo.

3.3. Trends in sediment metals and metalloid concentration

The concentration of metals and metalloid was in the order As > Pb > Cd > Hg for the AKOBEN site Kwabrafo Super Mambo whilst for the Non-AKOBEN site Kojoba B the order was As > Pb > Hg > Cd. There were significant differences (p < 0.0001) between the mean Cd and Pb concentrations of sediment samples for Kwabrafo Super Mambo and Kojoba B (Table 3). There were also significant differences (p < 0.0001) between mean Hg and As concentrations of sediments at AKOBEN and Non-
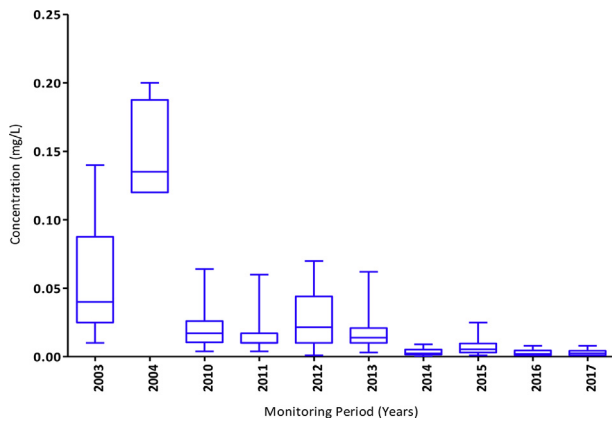
Fig. 8. Box and Whiskers Plots of Copper Levels in River Kwabrafo Pre and Post AKOBEN Programme Implementation. Data for copper measurements pre and post AKOBEN periods in River Kwabrafo is presented as box and whisker plots in Fig. 8. The median copper values are shown by the line that divides the boxes into two parts. The upper and lower whiskers represent the maximum and minimum copper concentration while the lower and upper boundaries of the boxes show the lower and upper quartiles copper concentrations in River Kwabrafo. All measurements were below the environmental Protection Agency's guideline value of 1.0 mg/L.
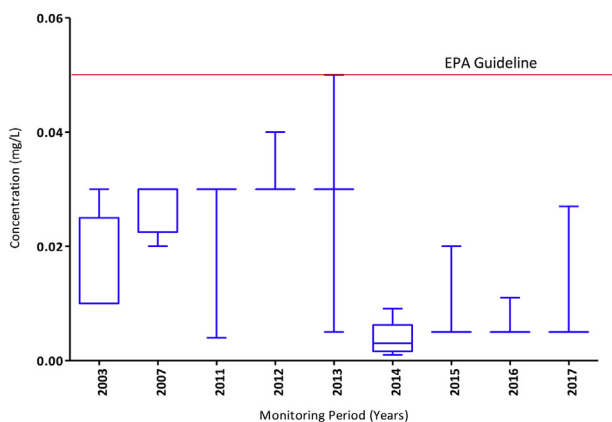

Fig. 9. Box and Whiskers Plots of Cyanide Levels in River Kwabrafo Pre and Post AKOBEN Programme Implementation. Data for free-cyanide measurements pre and post AKOBEN periods in River Kwabrafo is presented as box and whisker plots in Fig. 9. The median free-cyanide values are shown by the line that divides the boxes into two parts. The upper and lower whiskers represent the maximum and minimum free-cyanide concentration while the lower and upper boundaries of the boxes show the lower and upper quartiles free-cyanide concentrations in River Kwabrafo.

Fig. 10. Box and Whiskers Plots of Suspended Solids in River Kwabrafo Pre and Post AKOBEN Programme Implementation. Data for total suspended solids (TSS) concentration measurements pre and post AKOBEN periods in River Kwabrafo is presented as box and whisker plots in Fig. 10. The median total suspended solids concentration values are shown by the line that divides the boxes into two parts. The upper and lower whiskers represent the maximum and minimum TSS concentration while the lower and upper boundaries of the boxes show the lower and upper quartiles TSS concentrations in River Kwabrafo. The year 2013 (Post-AKOBEN) period had the widest range of measured TDS with 2014 recording the smallest range.
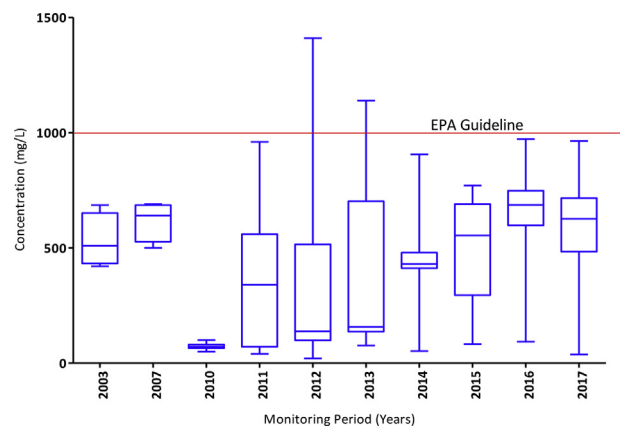
Fig. 11. Box and Whiskers Plots of Dissolved Solids in River Kwabrafo Pre and Post AKOBEN Programme Implementation. Data for total dissolved solids (TDS) concentration measurements pre and post AKOBEN periods in River Kwabrafo is presented as box and whisker plots in Fig. 11. The median total dissolved solids concentration values are shown by the line that divides the boxes into two parts. The upper and lower whiskers represent the maximum and minimum TDS concentration while the lower and upper boundaries of the boxes show the lower and upper quartiles total dissolved solids concentrations in River Kwabrafo. While the pre-AKOBEN TDS concentrations for 2003 and 2007 had very little variations, the post-AKOBEN TDS concentrations measured in 2011–2017 had significant variations.

AKOBEN site. This results differs from the results of (Adjei-Kyereme et al., 2015; Awuah, 2016) in their study on sediments in the Tano and Ankobra Rivers in Ghana. Whilst arsenic concentrations of 73.1 mg/kg, 320 mg/kg were reported in studies on sediments in River Tamar channel and Rio Guadiamar (Hudson-Edwards et al., 2008), concentrations of 58.30 mg/kg and 592 mg/kg were recorded at Kwabrafo Super Mambo (AKOBEN) and Kojoba B (Non-AKOBEN). The significantly higher Hg levels in the sediment of the Non-AKOBEN site could be attributed to the leaching of Hg used during the amalgamation process of gold recovery (Akabzaa and Darimani, 2001; Hilson, 2002). The extremely high arsenic concentration of 592 mg/kg recorded at the Non-AKOBEN site (Table 3) could be attributed to the lack of tailing dam and a treatment plant at the site. Although there were highly significant differences between the sediment arsenic and mercury concentrations from River Kwabrafo (monitored by the AKOBEN Programme) and Kojoba B (not monitored by the AKOBEN Programme) the quality of the sediment in River Kwabrafo
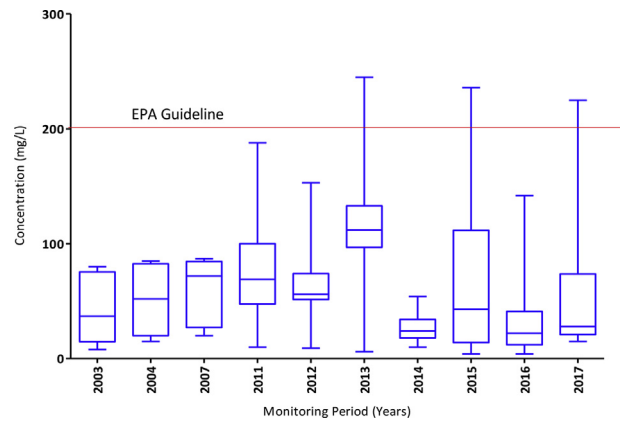
cannot be said to have improved.

3.4. State of air quality at Anyinam (AKOBEN site) and Mampamhwe (background)

More than 76% and 86% of PM10 concentration recorded at Anyinam and Mampamhwe during the monitoring period were below the Environmental Protection Agency of Ghana's guideline value of 70 μg/m³ (Fig. 16). This was largely in agreement with a study in Tarkwa a gold mining hotbed in Ghana by (Bansah and Amegbey, 2012) where 87% of PM10 concentrations were below the Environmental Protection Agency of Ghana's guideline value of 70 μg/m³ for PM10. The findings also
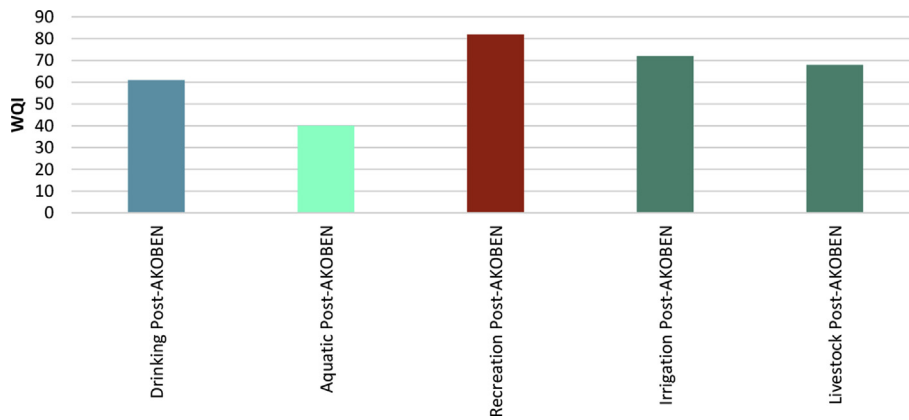
Fig. 12. Classification of Upstream Section of River Kwabrafo. Fig. 12 shows the state of River Kwabrafo upstream with reference to drinking, recreation, irrigation, survival of aquatic organism and livestock. The quality of River Kwabrafo was good fair and bad for recreation, irrigation and the survival of aquatic organisms respectively.
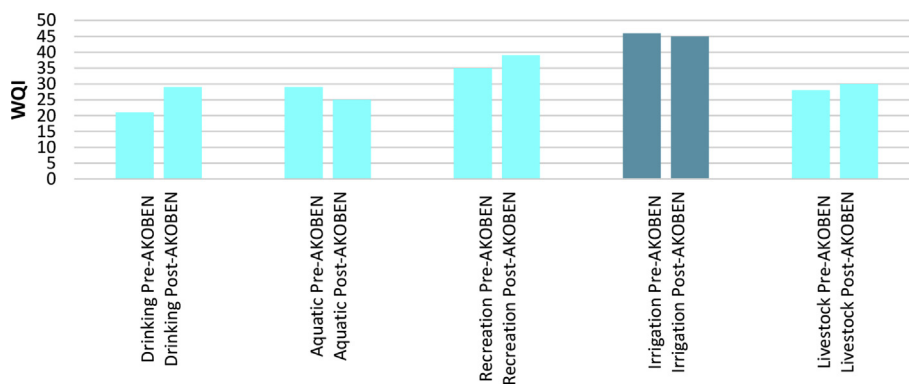

Fig. 13. Comparison of the Pre & Post AKOBEN Quality of River Kwabrafo at Sampling Point 2 (S2). Fig. 13 shows the state of River Kwabrafo at the Super Mambo section of River Kwabrafo. The quality of River Kwabrafo is impaired almost at all times (green bars) with reference to drinking, recreation, survival of aquatic organism and livestock rearing.
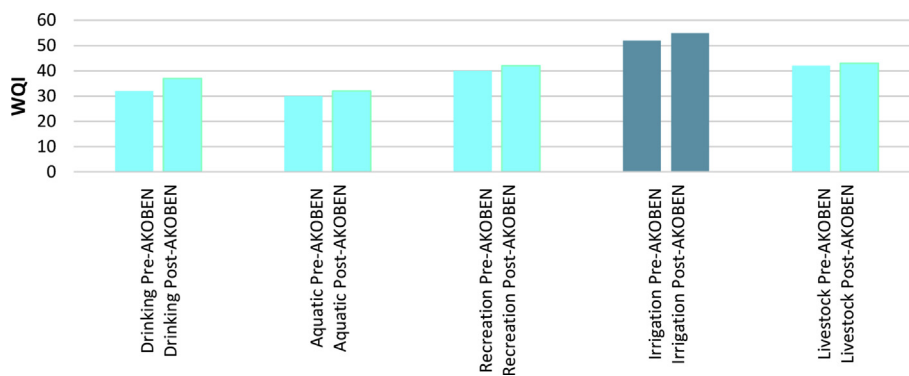

Fig. 14. Comparison of the Pre & Post AKOBEN Quality of River Kwabrafo at Sampling Point 3 (S3). Fig. 14 shows the state of the Amansan section of River Kwabrafo. Green and blue bars are an indication the quality of River Kwabrafo is almost always impaired with conditions usually departing from desirable levels and the quality is frequently threatened respectively.

corroborates the study by Bansah (2016) in the Koninase and Nkran communities which are in close proximity to a waste rock dump for gold mining activities in the Amansie West District of Ghana. A similar trend was observed for total suspended particulate concentrations recorded at Anyinam and Mampamhwe with more than 90% of readings falling below the Ghana EPA's guideline value of 150 μg/m^3 (Fig. 17). This trend could be attributed to increase dust suppression activities by AngloGold Ashanti in their catchment area.

While the air quality with regards to PM10, based on the calculated

air quality index (AQI) for Anyinam (under AKOBEN Programme monitoring) over the monitoring period indicated a majority of number of days had air quality that could be described as moderate, the air quality at Mampamhwe (background) could generally be described as good (Figs. 18 and 19). The quality of air at Anyinam can be categorized acceptable with only a small number of Anyinam residents who may be unusually sensitive to PM10 considered to be at risk. Air quality with reference to total suspended particulates (TSP) pollution however showed a contrasting trend from PM10 (Figs. 20 and 21). Close to 80% of
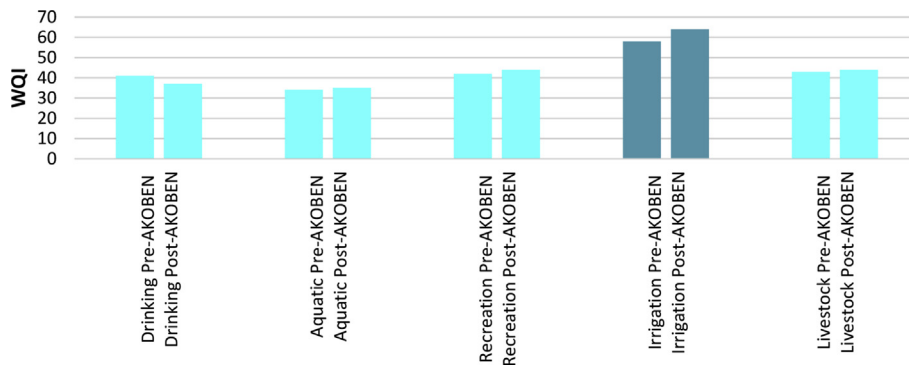
Fig. 15. Comparison of the Pre & Post AKOBEN Quality of River Kwabrafo at Sampling Point 4 (S4). Fig. 15 shows the state of the River Kwabrafo at a sampling location called Diawuso. Green bars are an indication of water quality being almost always threatened or impaired whilst blue bars represent water quality being frequently threatened or impaired.

Table 3
Comparison of heavy metal concentrations in sediments.

Location	Kwabrafo Super Mambo		Kojo B		Train Station	
Site Designation	AKOBEN		Non-AKOBEN		Control	
Type of Crop	Sediments		Sediment		Sediments	
Sample Count	3		3		3	
Parameter	Mean	SEM	Mean	SEM	Mean	SEM
Cadmium	10.93 (10–11.9)	±0.549	0.004 (0.004–0.004)	±0.00	9.973 (9.45–10.5)	±0.303
Arsenic	58.3 (57.9–58.9)	±0.305	592 (584–600)	±4.619	21.1 (20.52–21.5)	±0.282
Mercury	0.062 (0.06–0.65)	±0.001	3.1 (3.0–3.2)	±0.057	0.059 (0.057–0.062)	±0.001

All measurements are in mg/kg; Range is in parenthesis: P is significant at $p < 0.05$.
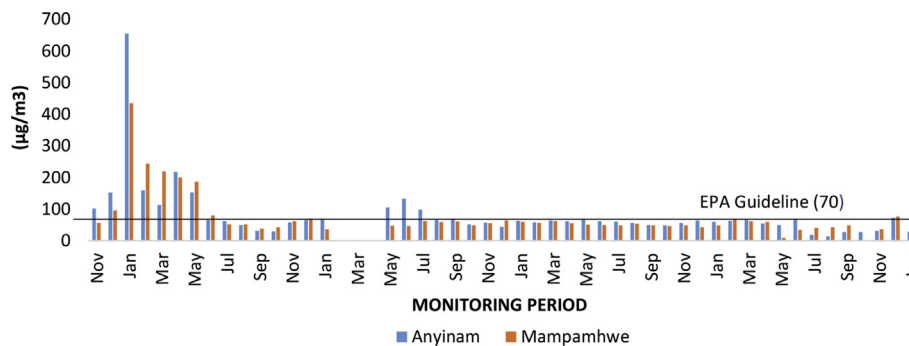

Fig. 16. Time Series Plots for PM10 Concentrations for Anyinam Palace (AKOBEN) and Mampamhwe (Background). Fig. 16 shows the trends in particulate matter 10 (PM10) levels at Anyinam under AKOBEN Programme monitoring and Mampamhwe (background) with reference to the Environmental Protection Agency of Ghana's guideline value of 70 µg/m³.

Fig. 17. Time Series Plot for in TSP Concentrations for Anyinam Palace (AKOBEN) and Mampamhwe (Background). Fig. 17 shows the trends in total suspended particulate (TSP) levels at Anyinam under AKOBEN Programme monitoring and Mampamhwe (background) with reference to the Environmental Protection Agency of Ghana guideline of 150 µg/m³.
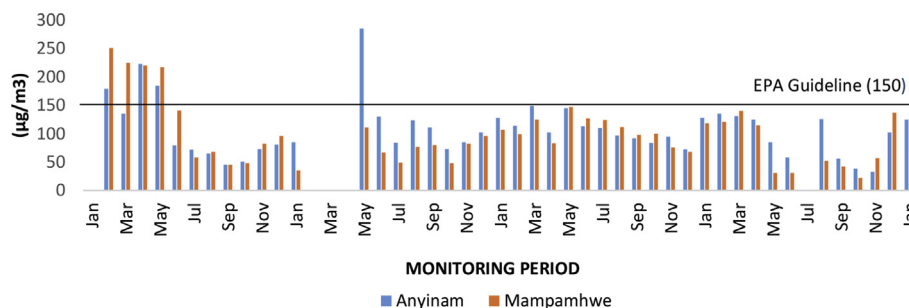
air quality index calculations for Anyinam could be interpreted as unhealthy (AQI 151–200), with 8.8% and 2.2% of readings interpreted as
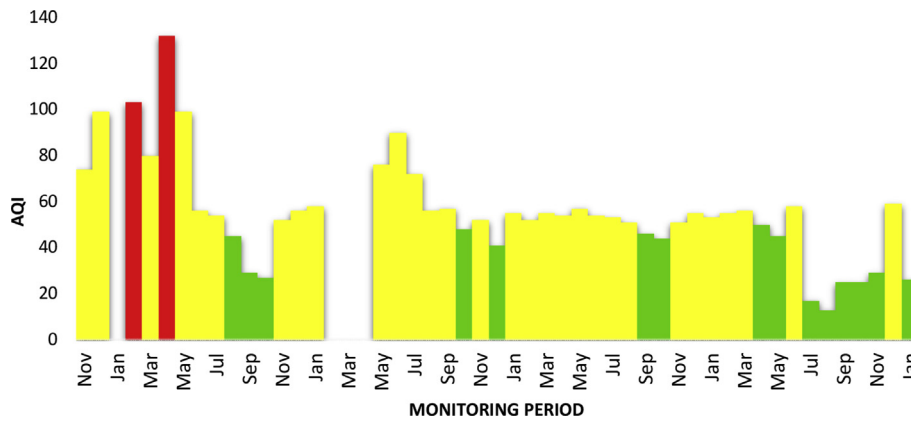
Fig. 18. Time Series Plots for Air Quality (PM10) at Anyinam over Monitoring Months. Fig. 18 shows the trends in air quality with reference to particulate matter (PM10) levels at Anyinam under AKOBEN Programme monitoring. The yellow, green and red bars indicate alerts of moderate, good and unhealthy air quality respectively.
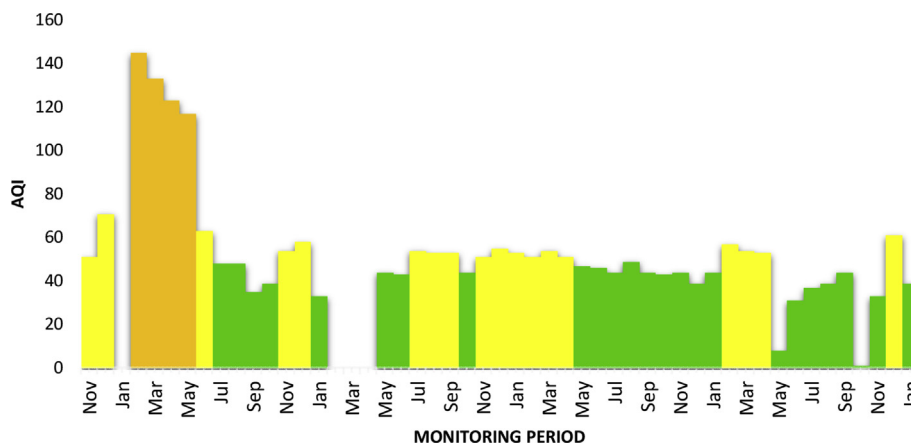

Fig. 19. Time Series Plots for Air Quality (PM10) at Mampamhwe over Monitoring Period. Fig. 19 shows the trends in air quality with reference to particulate matter (PM10) levels at Anyinam under AKOBEN Programme monitoring. The yellow, green and orange bars indicate alerts of moderate, good and unhealthy air quality for sensitive groups respectively.
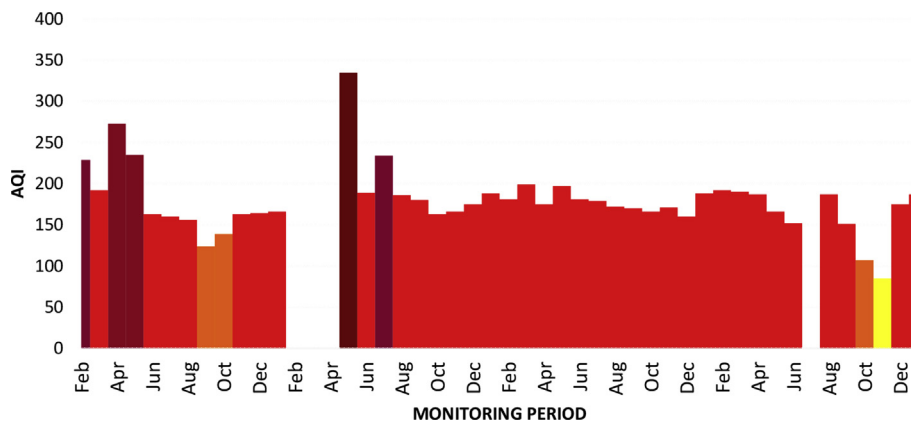

Fig. 20. Time Series Plots of Air Quality (TSP) at Anyinam Covering Monitoring Period. Fig. 20 shows the trends in air quality with reference to total suspended particulate (TSP) levels at Anyinam under AKOBEN Programme monitoring. The yellow, orange, red, purple and maroon bars indicate alerts of moderate air quality, air quality unhealthy for sensitive groups, air quality unhealthy, air quality very unhealthy and air quality hazardous respectively.

very unhealthy and hazardous respectively. The general populace in Anyinam in the Obuasi Municipality could experience health effects such as asthmatic attacks, skin and eye related ailments (Guttikunda and Kopakka, 2014; Arora et al., 2015) with inhabitants considered sensitive experiencing more serious health effects including increased risk for ischaemic heart disease, chronic cardiovascular and respiratory diseases risk associated deaths (Torén et al., 2007; Goldberg, 2008; EPA, 2009). Sensitive groups residing in Anyinam could also suffer from lung cancer related deaths and non-accidental mortality associated with long-term exposure to total suspended particulates (Cao et al., 2011; Crouse
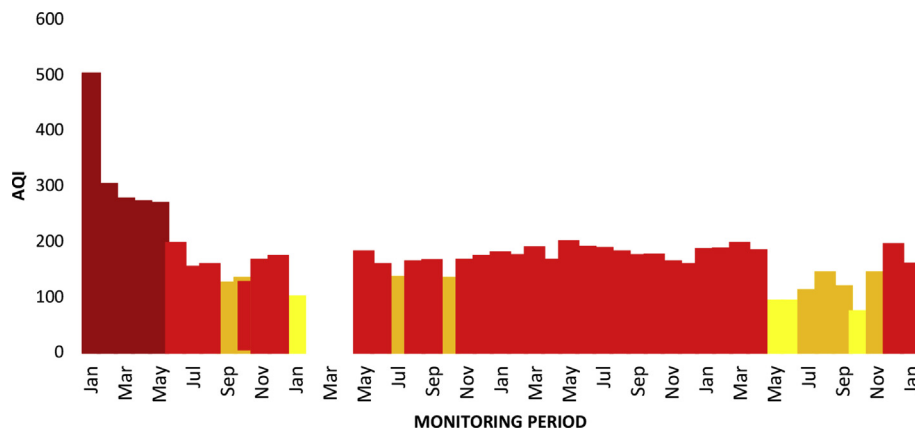
Fig. 21. Time Series Plots of Air Quality (TSP) at Mampamhwe Covering Monitoring Period. Fig. 21 shows the trends in air quality with reference to total suspended particulate (TSP) levels at Mampamhwe over the monitoring period. The yellow, orange, red and maroon bars indicate alerts of moderate air quality, air quality unhealthy for sensitive groups, air quality unhealthy, air quality very unhealthy and air quality hazardous respectively.

et al., 2012).

3.5. Trends in metalloid & metals concentration in agricultural soils

Even though the AKOBEN Programme does not specifically call for soil sampling and monitoring, indicators including legal requirements, hazardous and toxic waste management strategies, best practices in environmental management and consistent environmental monitoring and reporting indirectly ensures soils are monitored for pollution within the catchment area of large scale gold mining firms. Due to the absence of known background soil concentrations for Hg, As and Cd in Ghana, results of a study by (Akoto et al., 2017) in which soil samples were collected from the Botanical Gardens of the Kwame Nkrumah University of Science and Technology (KNUST) with extremely low commuter traffic and no industrial activities on site, located in Kumasi, Ghana was used as reference together with the USEPA reference level values (Table 5) for the evaluation the extent of metals and metalloid pollution at AKOBEN and Non-AKOBEN sites.

The concentration of the soil metalloid (As) was in the order AKOBEN > Control > Non-AKOBEN (Table 4). The mean arsenic concentrations for all eight study sites exceeded the arsenic value of 0.03 mg/kg in soils from KNUST used as reference for Ghana (Akoto et al., 2017), the world value of 18 mg/kg (Kabata-Pendias and Pendias, 2001) and the USEPA value of 1.0–15 mg/kg. In the context of study communities and the reference value form KNUST, arsenic concentration was in the order Nhyiaeso > Sansu > Adubriem > Sansu Control > Mmredani > Adubriem Control > Bogum > Komkowu > KNUST (Tables 4 and 5). There were significant differences (p < 0.0001) between the mean soil As concentrations of AKOBEN and Non-AKOBEN sites. The significantly

high mean soil As values of 529 mg/kg, 343 mg/kg and 353 mg/kg recorded at Nhyiaeso, Sansu and Adubriem (Table 4) all AKOBEN sites is consistent with results of a study by (Antwi-Agyei et al., 2009) which reported of mean soil As concentration around the active tailings dams in the Obuasi Municipality to be 581 mg/kg.

The concentration of soil arsenic (74 mg/kg) recorded at a control site at Sansu is also consistent with the value of 84.5 mg/kg recorded by (Antwi-Agyei et al., 2009) for soil samples from an undisturbed location in the Obuasi Municipality. The significantly high soil As values of 529 mg/kg, 343 mg/kg and 353 mg/kg recorded at Nhyiaeso, Sansu and Adubriem could be attributed to As levels in the Obuasi Municipality being among the highest in the world, due to arsenic's association with arsenopyrite rich gold-bearing ores (Amonoo-Neizer et al., 1996; Smedley et al., 1996; Kumi-Boateng, 2007). The high soil As levels recorded at AKOBEN sites including Nhyiaeso, Sansu and Adubriem could also be attributed to the production of arsenic trioxide gas during the processing of gold ore through roasting and the atmospheric deposition of As via dry wet deposition (Haygarth and Jones, 1992; Amonoo-Neizer et al., 1996; Akoto et al., 2017).

The Hg concentrations in soils was in the order Komkowu (Non-AKOBEN) > Sansu (Control) Bogum (Non-AKOBEN) > Adubriem (Control) >Adubriem (AKOBEN) > Nhyiaeso (AKOBEN) = Sansu (AKOBEN) > Mmredani (Non-AKOBEN).> KNUST (Tables 4 and 5). The concentrations of Hg in the soils under AKOBEN Programme monitoring in Obuasi and soils not monitored by the AKOBEN Programme in Tontokrom were higher than Hg concentrations in soils in Tamale in the Northern Region of Ghana which had a range of 0.01mg/kg-0.03 mg/kg reported by (Emmanuel et al., 2014). A study by (Tetteh et al., 2010) reported of mean Hg concentrations of 0.06 mg/kg and 0.8 mg/kg for

Table 4

Soil arsenic, cadmium and mercury concentrations for AKOBEN, Non-AKOBEN and control sites.

AKOBEN				Non-AKOBEN			Control	
Site	Adubriem	Nhyiaeso	Sansu	Mmredani	Bogum	Komkowu	Sansu	Adubriem
Sample Count	3	3	3	3	3	3	3	3
Parameter	Mean (range)	Mean (range)	Mean (range)	Mean (range)	Mean (range)	Mean (range)	Mean (range)	Mean (range)
As	343 (432–344)	529 (520–535)	353 (349–356)	108.5 (106.2–110.2)	41.9 (40.6–42.8)	5.3 (5.1–6)	167 (163–171)	74 (73–75.2)
Cd	0.1 (0.08–0.13)	0.1 (0.09–0.15)	0.03 (0.02–0.04)	61.1 (59.3–63.9)	8.8 (8.6–9.0)	6.7 (5.9–7.3)	0.1 (0.09–0.12)	0.03 (0.03–0.03)
Hg	0.05 (0.05–0.05)	0.04 (0.03–0.05)	0.04 (0.03–0.05)	0.03 (0.03–0.05)	0.12 (0.10–0.14)	0.87 (0.76–1.0)	0.17 (0.14–0.2)	0.06 (0.05–0.07)

Data is presented in means and minimum and maximum values in parenthesis. All parameters are measured in mg/kg.
Table 4 is presented results for arsenic (As), cadmium (Cd) and mercury (Hg) present in soil samples at the concession of a gold mining firm under the AKOBEN Programme (Adubriem, Nhyiaeso, Sansu), small-scale gold mining sites not under AKOBEN monitoring (Bogum, Mmredani, Komkowu) and a control soils (Adubriem control and Sansu control) void of any mining encounter. Nhyiaeso recorded the highest As concentration of 529 mg/kg with Komkowu recording the least As concentration of 5.3 mg/kg. Mmredani and Komkowu (Non-AKOBEN sites) recorded the highest Cd and highest Hg concentrations of 61.1 mg/kg and 0.87 mg/kg respectively. There were significant differences (p < 0.0001) between mean soil As, Cd and Hg concentrations between AKOBEN and Non-AKOBEN sites.

Table 5
Mean concentrations of heavy metals and metalloid in soils in Ghana.

Sampling Site	District/ Municipality	Land Use	Mercury	Cadmium	Arsenic
Tamale	Tamale	Fuel Station	0.02	**2.29**	0.33
Kaasi	Kumasi	Industrial	0.02	0.09	2.68
Takoradi	Takoradi	Residential	BDL	BDL	0.08
Twumwaa	Amansie West	Mining	0.014	**3.5**	12.4
Oforikrom	Kumasi	Residential	0.04	0.03	0.94
Korle Area	Accra	Agriculture	BDL	**3.55**	0.08
Danyme	Kumasi	Residential	0.04	0.03	1.92
Adubriem	Obuasi (SA)	Agricultural (Reclaimed)	0.05	0.1	**343**
Nhyiaeso	Obuasi (SA)	Agricultural (Reclaimed)	0.04	0.1	**529**
Sansu	Obuasi (SA)	Agricultural (Reclaimed)	0.04	0.03	**353**
Mmredani	Amansie West (SA)	Mining	0.03	**61.1**	**108.5**
Bogum	Amansie West (SA)	Mining	0.12	**8.8**	**41**
Komkowu	Amansie West (SA)	Mining	5.3	**6.7**	0.87
Huniso	Tarkwa	Agricultural	0.13	0.052	1.5
Wangarakrom	Tarkwa	Agricultural	1.9	0.021	5.4
Suame	Kumasi	Industrial	8.4	**10.1**	**18.6**
KNUST[#]	Kumasi	Botanical Garden	0.005	0.01	0.03
USEPA[a]			32	0.7–1.1	1.0–15
World range[18]				1.6	18

Adapted from: Tetteh et al. (2010); Kodom et al., 2012; Emmanuel et al. (2014); Bortey-Sam et al., 2015; Minerals Commission, 2016; Akoto et al. (2017); Fosu-Mensah et al., 2017. All parameters are measured in mg/kg. SA: Study area; BDL: Below detection limit; #: reference values (KNUST); Bold values: concentrations higher than, USEPA and World range; USEPA[a]: United States Environmental Protection Agency Ecological-Soil Screening Levels, World range[19]: world range of metals in unpolluted soils.

Table 5 shows the concentrations of As, Cd and Hg in selected communities with varying land uses in Ghana. The Kwame Nkrumah University of Science and Technology's (KNUST) botanical garden had the least measured concentrations for As, Cd and Hg. Adubriem, Nhyiaeso, Sansu, Mmredani, Bogum and Suame recorded As concentration greater than the world range and the levels set by the United States Environmental Protection Agency.

university of Cape Coast in the Central Region of Ghana and Takoradi in the Western Region of Ghana all higher than the Hg concentrations recorded at sites monitored by the AKOBEN Programme but lower than mean soil Hg concentration of 0.87 mg/kg and 0.12 mg/kg for Komkowu and Bogum respectively.

The highly significant difference ($p < 0.0001$) between mean Hg concentration recorded at AKOBEN sites (Adubriem, Nhyiaeso, Sansu) and Non-AKOBEN sites (Komkowu and Bogum) could be attributed to the two Non-AKOBEN sites being a hub for artisanal and small-scale mining operations where Hg leached into soil during amalgamation of gold is subsequently alkylated, oxidized or deposited as the metal (Schlüter et al., 1996; Akabzaa and Darimani, 2001; Hilson, 2002). Agricultural soils from Agona Nkwanta, Takoradi and Shama junction all in Ghana with Hg levels of 0.21 mg/kg, 0.19 mg/kg and 0.12 mg/kg respectively were relatively high in comparison to all soil Hg levels at AKOBEN sites and Non-AKOBEN sites including Mmredani and Bogum (Tables 4 and 5). The higher levels of Hg in agricultural soils from Agona Nkwanta, Takoradi and Shama junction which host no mining activity could be attributed to the aerial dispersion of Hg from the mining areas due to the high vapour pressure of mercury (Golow and Adzei, 2002).

The mean soil Cd concentration for the study sites was in the order Non-AKOBEN sites (Mmredani, 61.1 mg/kg, Bogum 8.8 mg/kg, Komkowu, 6.7 mg/kg) > AKOBEN sites (Adubriem = Nhyiaeso, 0.1 mg/kg) = Control Site (Sansu 0.1 mg/kg) > AKOBEN site (Sansu, 0.03 mg/kg) = Adubriem Control, 0.03 mg/kg > KNUST (Tables 4 and 5). There were significant differences ($p < 0.0001$) between mean soil Cd levels of

AKOBEN, Non-Akoben sites and Control sites. The reported Cd concentration of 2.29 mg/kg in the soils in Tamale in the Northern Region of Ghana by (Emmanuel et al., 2014) was significantly higher ($p < 0.05$) than the Cd levels in soils at AKOBEN sites including Nhyiaeso, Sansu and Adubriem but significantly lower than Cd levels in soils at Non-AKOBEN sites including Mmredani, Bogum and Komkowu. The mean soil Cd concentration of 0.03 mg/kg recorded at Sansu an AKOBEN site is in agreement with the result of (Akoto et al., 2017) study on soil Cd at Oforikrom in Kumasi, Ghana.

4. Conclusions

The AKOBEN Programme has had little impact on the quality of River Kwabrafo vis-à-vis agricultural use, recreational use, as a habitat for aquatic organisms and as a source of drinking water for downstream communities due to the fact that the quality of River Kwabrafo remained unchanged in quality post the AKOBEN Programme implementation.

The variable-by-variable water quality parameters prescribed for monitoring under the AKOBEN Programme, which shows the concentrations of effluent parameters using the EPA'S permissible discharge levels as a reference underestimates the impacts of gold mining activities on River Kwabrafo.

The mean soil arsenic concentrations for all eight study sites exceeded the arsenic reference for Ghana with significant differences existing between mean soil Cd and Hg levels of AKOBEN, Non-Akoben sites and Control sites.

The quality of air at Anyinam can be categorized acceptable with reference to PM10 with only a small number of Anyinam residents being sensitive to PM10. The AKOBEN Programme failed to delineate total suspended particulate (TSP) into oxides of nitrogen, carbon dioxide, methyl mercury and oxides of sulfur for which reason the impacts of greenhouse gases and methyl mercury on the Obuasi Municipality environment cannot be investigated under the AKOBEN Programme.

Declarations

Author contribution statement

Kenneth Bedu-Addo: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed analysis tools or data; Wrote the paper.

Abeiku Arthur: Conceived and designed the experiments; Performed the experiments; Contributed analysis tools and data.

Martha Ofori-Kuragu: Analyzed and interpreted the data.

Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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