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Spatial distribution, accumulation and human health risk assessment of heavy metals in soil and groundwater of the Tano Basin, Ghana

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ABSTRACT

Soil serves as a vast matrix for heavy metal accumulation and subsequent redistribution to critical aspects of the environment such as groundwater. Soil pollution study is essential for sustainable human health and ecosystem protection. This study provides vital insight into the fate, accumulation, interactions, and health risk posed by heavy metals in soil and groundwater by employing geochemical accumulation index (Igeo), risk assessment models and multivariate data analysis techniques such as principal component analysis (PCA), preference ranking organisation method for enrichment evaluation (PROMETHEE) and geometrical analysis for interactive aid (GAIA). The median I_{geo} estimates show moderate to strong Pb accumulation levels whilst all the other metals indicate uncontaminated to moderate levels. The PCA output point to anthropogenic origin of Pb and Cd in the Tano Basin and surrounding communities. PROMETHEE-GAIA results indicate that Pb, Cd, Zn and Fe accumulated in the soil matrix may potentially leach into the groundwater resources. The carcinogenic lifetime risks posed by Pb, Cd, and Ni metals to adults are within the tolerable acceptable risk and thus do not present an immediate danger in the study area. Due to the significant toxicity, bioaccumulation and biomagnification properties of Pb and Cd in the environment, areas associated with significant anthropogenic activities require regular monitoring and evaluation in order to ensure that these metals are consistently below the regulatory limits. This study has further elucidated the subject of heavy metal pollution and is therefore expected to enhance sustainable protection of the environment and human health.

1. Introduction

Soil is a critical repository for numerous deleterious pollutants thereby serving as a good matrix for assessing the status quo of environmental pollution. These accumulated pollutants can then be redistributed to other compartments of the environment via the influence of anthropogenic and natural factors such as wind, vehicular movement and gravity (Gbeddy et al., 2018). Organisms especially human beings are subsequently exposed to the pollutants through dermal contact, inhalation and ingestion processes. In this context, heavy metals laden in soil pose significant health challenges due to their high toxicity, bioaccumulation and biomagnification properties (Lin et al., 2012; Wuana and Okieimen, 2011). Heavy metals may percolate into the underlining groundwater resources (Ghosh and Singh, 2005) thereby creating further challenges to water quality and sustainable water supply. Accordingly, Lin et al. (2012) noted that heavy metal pollution is a crucial global problem and therefore, merits continuous investigation in order to provide an up-to-date information required for successful risk mitigation.

Heavy metals emanate from myriad of sources in the environment including industrial waste, spillage of petrochemicals, fertilizer application, atmospheric deposition and mine tailings (Wuana and Okieimen, 2011). Areas associated with significant oil and gas exploration and drilling activities are therefore, most likely to experience challenges with heavy metals due to the generation and release of produced water and solid wastes contaminated with heavy metals (Christie, 2012; Namdari et al., 2017). The Tano Basin in Ghana is one such area with high level of commercial oil and gas industry since 2007

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(Dailly et al., 2012). The main economic activities of the surrounding communities in the Basin are agriculture and fishing with substantial reliance on the groundwater as potable source of clean water. Contamination of the agricultural soil with heavy metals may therefore present significant risks to the food chain and environmental sustainability due to the direct contact of crops with soil. Although there may exist significant environmental challenges in these communities, there has not been any corresponding comprehensive study to evaluate the extent of heavy metal pollution.

This study is therefore, aimed at ascertaining the status and impact of heavy metal pollution in the study area by determining the potential sources, inter-relationship between soil and groundwater heavy metal content, determine the scope of heavy metal accumulation, assess the potential risk posed by these pollutants to human health, and also prioritize study sites for continuous future monitoring and pollution control. In this regard, an accurate source apportionment of heavy metals is vital to minimizing potential human exposure. These objectives will be achieved by the application of the most relevant multivariate analytical tools and risk assessment models. The study is expected to provide further insight into the fate and behaviour of heavy metals thereby promoting greater protection of the ecosystem.

2. Methods

2.1. Study area

The Tano Basin situated south-east of Ghana serves a major offshore area for commercial oil and gas exploration and drilling activities. The underlying kerogen source rock types II and III; schists, phyllite and greywacks rocks form the primary geology of the Basin and thus the field's capability to produce commercial amount of oil and gas in Africa (Atta-Peters, 2014; Dailly et al., 2012; Tetteh, 2016). Communities located approximately 60 km along the coast of the Basin ranging from Axim (4° 52′6″N; 2°14′29″W) to Newtown (5° 6′60″N; 3°4′60″W) constitute the study sites as shown in Fig. 1 in this research. The area experiences wet and dry annual seasons with intense agricultural activities during the rainy periods (Doyi et al., 2017).

2.2. Soil and groundwater sampling

2.2.1. Soil

The sampling area was divided into four sub-areas after the initial survey using a global positioning system (GPS). Twenty seven (27) composite soil samples were collected during the rainy season from a depth of 0 – 2 cm using plastic trowel pre-cleaned with ethanol and deionised water. In order to prevent cross contamination of samples, the trowel was passed through soils adjacent to each sampling site to remove any possible effects associated with the previous site (Doyi et al., 2017, 2018). Samples were oven dried at a temperature of 105 °C for 4 min until the samples were well dried. The samples were homogenized by milling and sieving through a 2 mm pore size mesh for subsequent analysis.

2.2.2. Groundwater

Twenty (20) groundwater samples were taken from community mechanized boreholes and dug wells during the rainy season into 500 mL polyethylene bottle pre-washed with concentrated HNO_3, methylated spirit and deionized water. The bottles were also rinsed with groundwater samples before filling them to the brim to prevent CO_2 trapping (Diedhiou et al., 2014), labelled, placed on ice chest and then transported to the laboratory for further analysis. Physicochemical parameters such as pH, temperature, electrical conductivity, salinity and total dissolved solids (TDS) were measured in situ using calibrated pH meter and conductivity meter (model number WTW pH 3110).

2.3. Heavy metals analysis

2.3.1. Water and soil samples

Water samples were digested by adding 0.25 mL of H_2O_2 (30% v/v), 3 mL of HCl (37% v/v) and 6 mL HNO_3 (65% v/v) to 5 mL of the sample in Teflon digestion tubes. The tubes were firmly closed and placed in an ETHOS 900 microwave digester (Ackah et al., 2014). The digested samples were cooled, poured into clean 25 mL volumetric flask and then diluted to 20 mL with deionized water. On the other hand, 0.25 g of powdered homogenized soil sample in Teflon beaker was digested using 6 mL (65% v/v HNO_3) and 3 mL (37% v/v HCl) based on digestion code 308 (Ackah et al., 2014). The concentrations of cadmium (Cd), manganese (Mn), nickel (Ni), lead (Pb), and arsenic (As) in the digested samples were determined using Varian 240FS atomic absorption spectrometer.

2.3.2. Quality assurance/quality control

High purity analytical grades of chemicals and reagents were used during sample preparation and analysis. Blank solution was analysed after every 10 samples measured. Samples were analysed in triplicates. The recovery of three concentration levels of each analyte spiked samples was determined, and ranged from 90% to 103% with minimal percentage error. The results from the analysis of IAEA-SOIL-7 certified reference material were within 95% confidence level. The regression coefficients for the calibration curves were approximately 1.0.

2.4. Data analysis

The data generated were analysed using various multivariate data analysis techniques such as principal component analysis (PCA), Geometrical Analysis for Interactive Aid (GAIA) and Preference Ranking Organisation Method for Enrichment Evaluation (PROMETHEE) using StatistiXL Version 1.8 and Visual PROMETHEE Academic Edition Version 1.4.0.0 in line with research objectives. The spatial distribution of heavy metals was determined using Minitab version 17.2.1

2.4.1. Multivariate data analysis

The application of multivariate data analysis techniques in environmental pollution investigation has been necessitated by the increasing complexities in environmental data. The application of these techniques in environmental research is still evolving and the potentials are enormous. Multivariate analysis techniques essentially maximize relevant pollutant information whilst reducing inherent complexities in observed data (Miller and Miller, 2010). In this regard, multivariate analysis is indispensable in characterizing pollutant behaviour patterns, source apportionment and ranking (Ayoko et al., 2007).

2.5. Pollution status and health risk assessment

As a result of the direct contact of food crops with soil and the high probability of heavy metals transfer into the food chain, the degree of heavy metal pollution in soil were assessed using the geoaccumulation indexes (I_{geo}) (Gao et al., 2014).

$$I_{geo} = log_2 \frac{C_n}{1.5B_n} \tag{1}$$

Where C_n is the measured concentration of heavy metal (n) in the soil, B_n is the geochemical background value of element n in the soil and 1.5 is the background matrix correction factor due to lithogenic effects. The B_n of elements in this study were assumed to be the natural worldwide distribution of elements in shales (Turekian and Wedopohl, 1961) due to the lack of site specific values. The seven classes of I_{geo} are: < 0 (uncontaminated), 0 – 1 (uncontaminated to moderately contaminated,) 1 – 2 (moderately contaminated), 2 – 3 (moderately to strongly contaminated), 3 – 4 (strongly contaminated), 4 – 5 (strongly