Assessment of occurrence and origin of toxic metals in groundwater sources for domestic use in Enugu, Nigeria: Pilot study results

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Front cover

Pictures were taken during the fieldwork showing two handpumps from which water quality samples were collected.

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Assessment of occurrence and origin of toxic metals in groundwater sources for domestic use in Enugu, Nigeria: Pilot study results

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Foreword

This report is the output of a study undertaken by the British Geological Survey (BGS) in partnership with WaterAid Nigeria and the University of Ibadan. It reports results from an assessment of water (groundwater and surface water) quality undertaken in the Enugu area with particular reference to toxic heavy metals (Pb and Cd). Results from this pilot study will be used to inform future water quality assessments in this region by WaterAid and others, and the management of water points for domestic use in Enugu and potentially elsewhere in Nigeria.

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We thank the communities of Enugu for giving permission to undertake this research and allowing us to sample their water sources. We also want to thank the Enugu State authorities who facilitated this research including the Ministry of Water Resources, Ministry of Health, Enugu state Water Corporation and Ministry of Environment.

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Executive summary

In April of 2021, during routine water quality testing on five handpump borehole sources installed by WaterAid in Ugwuaji, Engugu, Nigeria, lead and cadmium were discovered to be above permissible limits in three of the handpump sources. As a result, WaterAid Nigeria commissioned the British Geological Survey and University of Ibadan to conduct further investigation of the occurrence, concentration and origin of lead in handpump boreholes in the Engugu region.

This report describes the findings of a pilot study which focused on identifying the origin and quantifying the concentrations of dissolved and total lead (Pb) and cadmium (Cd) present in boreholes equipped with handpumps. Concentrations of Pb and Cd in handpump boreholes were also compared to concentrations of these elements in other water source types, including shallow hand-dug wells, surface water and boreholes with submersible pumps installed. A total of 32 water samples were collected, including seven shallow hand-dug wells and six surface water samples. Five water samples were also collected from one shallow hand dug well and four handpump boreholes outside Ugwuaji. In addition, a small number handpump component samples were collected (i.e. PV pipe and metal scrapings). Six samples of soil from well cuttings and rocks along the river channels were also collected for Pb isotope analysis to identify potential sources of Pb within groundwater.

The samples were sent to three different laboratories (National water resources institute (NWRI) International Institute of Tropical Agriculture (IITA) and British Geological Survey (BGS)) for analysis of major ions and trace metals (focusing on Pb and Cd). **The results of the elemental analysis found no consistency in concentrations of either Pb or Cd between laboratories.** While some level of variation between results from different laboratories is to be expected, the differences in Pb and Cd concentrations between the laboratories are significant, non-systematic and beyond what might reasonably be expected, raising concerns about the accuracy of results reported from the local labs. Possible sources of uncertainty could be the purity of the acid used, the standards used, and other QA procedures used by the Nigerian labs.

The results from the BGS laboratories indicate that concentrations of Pb and Cd are below WHO guideline values and Nigerian permissible limits in most samples. A single unfiltered sample (i.e. total concentration which includes dissolved and particulate Pb) from the BGS analyses had Pb concentration (10.5 µg/L) exceeding the WHO and Nigerian guideline values for drinking water of 10 µg/L. Median Pb and Cd samples were highest in samples taken early in the morning before the days pumping had begun (5.01 µg/L and 0.036 µg/L respectively) suggesting the handpump materials as a possible source of both elements. There was no systematic increase in heavy metal concentrations for Pb and Cd in unfiltered samples compared to filtered samples, suggesting that for most samples analysed these contaminants are in solution. However, further work on paired dissolved and total samples would help quantify the proportion of dissolved and particulate concentrations and indicate the risk of drinking unfiltered water from the handpump boreholes. No samples analysed by BGS had Cd concentrations exceeding the WHO or Nigerian guideline values for drinking water for Cd of 3 µg/L and 5 mg/l respectively. **Analysis also showed samples from four sites exceeding the guideline value/national standard for fluoride (1.5 µg/L) in drinking water (range 2.39-2.49 µg/L).**

The lead isotope data suggest that the lead found in the water samples analysed (i.e. samples with > 1 µg/l) does not come from the local soil/sediment/cuttings. It appears to be a mixture of lead found in the PVC pipes, scrapings from other handpump components and industrial or lead based petrol (likely in the form of air particulates). **Further analysis would be required to definitively identify the source of the lead found in the water samples but the initial analysis suggests that the handpump components are a likely candidate.** However, it is important to re-emphasize that lead concentrations in the waters analysed were not found at levels that exceed WHO guideline or Nigerian standards, although some studies suggest that there is no safe concentration for lead in potable water supplies.

Recommendations for further work to understand the discrepancies between laboratory results and the origin of lead are as follows:

1. More detailed inter-laboratory comparison. Certified water quality standards and solutions with known element concentrations should be prepared at BGS and analysed independently by all three laboratories. No standard solutions were sent to the Nigerian laboratories in the preliminary study.
2. Further collection and analysis of water quality samples from a larger sample of handpump and other sources to better establish a baseline for total and dissolved Pb and Cd concentrations.
3. More extensive and detailed Pb isotope sampling and analysis including collection of a range of end members from the local area (i.e. air particulate samples).

1 Introduction

This report summarises the results from a pilot study to assess the water quality, focusing particularly on toxic metals, of groundwater sources in Ugwuaji community, which is located in the suburban areas of the city of Enugu, Nigeria. The project aimed to evaluate the presence, origin and concentrations of dissolved and total lead (Pb) and cadmium (Cd) in boreholes equipped with handpumps and compare these with other water source types. Previous water quality assessments, analysed by Nigerian labs from selected WaterAid sources in the outskirts of Enugu have suggested the presence of Pb at elevated concentrations, although results from these sampling rounds are inconsistent providing little clear evidence of the extent of the problem. This study undertook a pilot sampling of 32 water sources, including 25 groundwater sources with one site where elevated Pb and Cd concentrations were reported from previous studies. In addition, total Pb and Cd content was analysed from a set of surface water, soil, rock and handpump scrapings to assess whether these might be potential sources of toxic metals in groundwater. Water and solid samples were also analysed for Pb isotopic compositions with the aim of identifying potential sources of Pb within groundwaters. This pilot study was commissioned by WaterAid and undertaken in partnership with WaterAid Nigeria, the University of Ibadan, Nigeria and the British Geological Study as a follow up to the results of the routine monitoring of water quality from the five handpump wells constructed to meet the groundwater demand of the people of the Ugwuaji community. Understanding the persistence and sources of Pb and Cd in groundwater is necessary to quantify the potential risks to public health that may result from drinking water containing toxic metals.

1.1 BACKGROUND

The human health impacts of elevated Pb concentrations in drinking water supplies are a global challenge (Santucci and Scully 2020). A recent study in Africa pointed to the role of water system components (i.e. pipework and borehole/handpumps components) which may impact on drinking water quality (Fisher et al., 2021). Elevated Pb and Cd contamination in groundwater supplies can also be linked to a range of other anthropogenic sources (Akers et al., 2015; Lapworth et al., 2017). Pb and Cd can also occur in groundwater naturally. Groundwater is commonly accessed through shallow hand-dug wells, and deep and shallow boreholes. In the work described here one of our aims is to determine whether toxic metals could be naturally occurring or a more likely to be from materials used in handpumps.

In July 2019, WaterAid signed a Memorandum of Understanding (MoU) with the Global Environment and Technology Foundation (GETF) and the Replenish Africa Initiative (RAIN). As part of implementation of the MoU WaterAid Nigeria agreed to support the Enugu State government in increasing access to water and sanitation by constructing new water schemes in two communities and rehabilitating dysfunctional water schemes. The MoU responded to the state of emergency in the WASH sector recently declared by the Federal Government of Nigeria and addresses the need for sustainable potable water and sanitation in small towns and rural areas in five Local Government Areas (LGAs) in Enugu state (Nigeria): Nsukka, Ezeagu, Uzo-Uwani, Isiuzo and Enugu South LGAs and two communities in the 9th-mile area of Nsukka LGA. The construction of five handpump boreholes in Ugwuaji community was a key part of the work conducted under the MoU and provided the impetus for the study reported here.

Ugwuaji community lies within Enugu South Local Government Area within the metropolitan city of Enugu and in the southeastern part of Nigeria. It is bounded by Latitudes 6˚20' to 6˚30' North of the equator and Longitudes 3˚20' to 3˚30' East of the Greenwich Meridian (Figure 1). The study area can be accessed through roads off Enugu Port Harcourt road, towards the north-eastern part of Enugu State, while roads and paths linking villages, streams, and farmlands exist within Ugwuaji community. Ugwuaji community has a fast-rising population because it as an affordable location for rent or acquisition of residential properties due to the continuously rising cost of living within the heart of Enugu city. According to the National Population Census and National Bureau of Statistics, Enugu south has a population of about 267,300 with a population density of 2,827/km^2 and an annual population change of 3.0%. The increase in population drives an increase in daily water demand which is constrained by the low groundwater potential of the area and limited investment in public water supply.

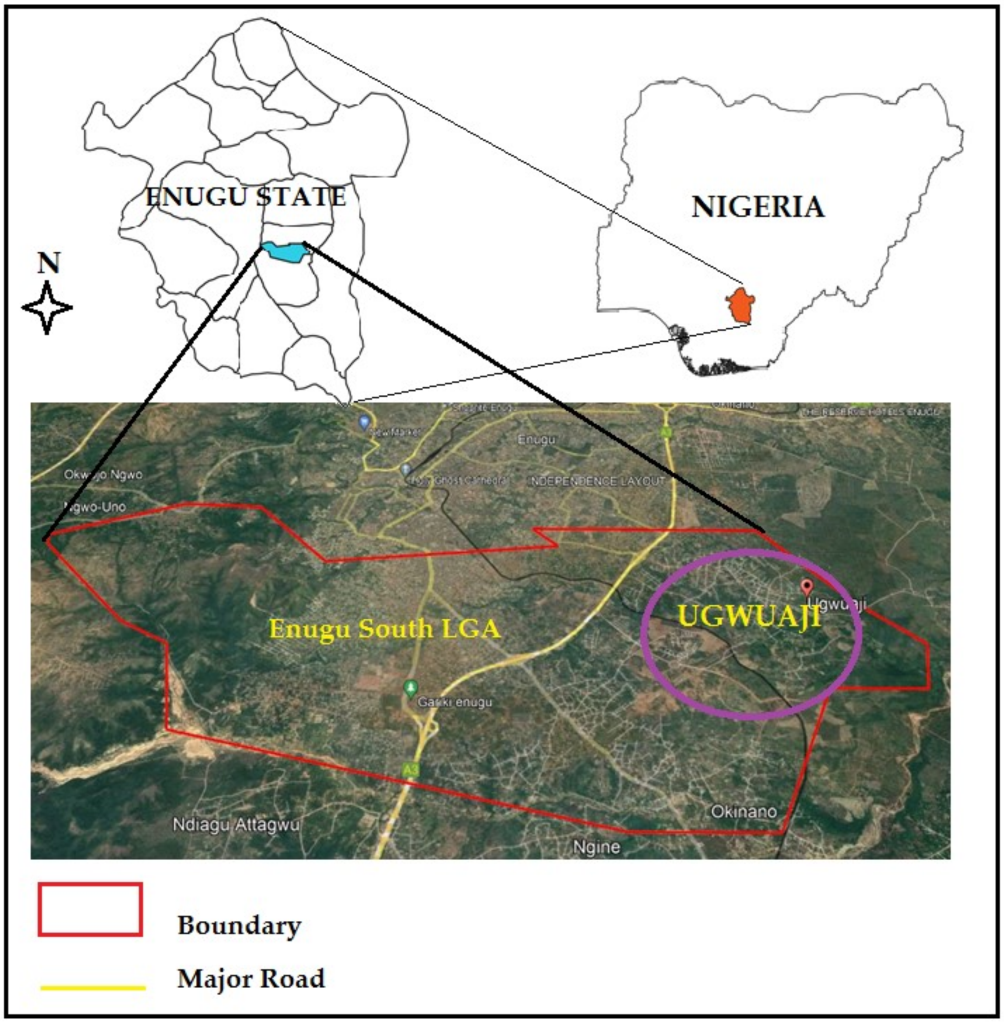

Figure 1. Map showing the location of the study area. Map data ©2022 Google

As part of the commissioning process for the five handpump sources groundwater quality testing was carried out. The samples collected were analysed in three different laboratories in Nigeria and the results indicated that in general metal concentrations were below the Nigerian Standard for Drinking Water Quality (NSDWQ) and WHO maximum permissible limits for drinking water. However, elevated concentrations of iron were observed at two of the five hand pump sources in Ugwuaji. The discoveries necessitated the construction of iron filtration chambers as shown in

Figure 2. However, following commissioning of the handpump sources WaterAid conducted routine water quality monitoring, and the results revealed elevated concentrations of Pb and Cd in some of the handpump sources. As a result, these sources were taken out of use for drinking purposes to ensure public health and safety and until further assessment was conducted.

Figure 2. (A) One of the hand-pump wells without Iron filtration chamber at Ugwuaji community (B) One of the hand-pump wells with Iron filtration (C) Open Iron filtration/Ion exchange chamber at one of the wells. (D) Water collection point from one of the Hand-pumps.

The work described below represents a detailed evaluation of groundwater quality from the five handpump wells, additional selected hand-dug wells, surface water from rivers around the community and other boreholes which acted as control form other parts of Enugu city. The primary aim of this work was to confirm the presence and concentration of Pb and Cd in the hand pump sources and to investigate the potential origins of any Pb contamination identified.

1.2 REPORTS OF ELEVATED LEAD AND CADMIUM IN GROUDWATER SOURCES

The WASH projects undertaken as part of the GETF MoU were completed in November 2020. At the point of completion and handing over to the communities, all water quality parameters were within the permissible levels of WHO and NSDWQ. In April of 2021 WaterAid, as part of its annual WQ checks on constructed water facilities, analysed paired samples from the five new handpump boreholes in three laboratories (Enugu State Water Corporation, Federal Ministry of Water Resources and Anambra State Water Board Laboratories). Pb was detected in two of the boreholes from one laboratory (Table 1). Cd was found to exceed the WHO drinking water guideline value of 3 µg/L at all five sites by at least one laboratory (Table 1).

The discovery of Pb and Cd prompted WaterAid to stop the people of Ugwuaji from using the water from the affected boreholes as drinking water, which has reduced user access to potable clean and safe water for their domestic water demand. There were inconsistent results from the original sampling rounds and questions about the limitations of some of the methods used to analyse for Pb and Cd. Therefore, it was necessary to re-sample and analyse water from the handpump boreholes to better establish the extent of Pb and Cd contamination in the borehole waters. The study also aimed to investigate the causes and origin of the elevated concentration of these toxic metals in the handpump boreholes.

Table 1.Summary of the hydrochemical results from samples collected in April 2021, prior to the present study but that highlighted potential issues with Pb and Cd concentrations serving as the basis for the present study. Enugu State Water Corporation (Eng. State), Federal Ministry of Water Resources (Fed. Min.) and Anambra State Water Board Laboratories (Ana. State). Number in bold show samples that exceeded the WHO Pb and Cd standards. BDL indicates samples were Pb and Cd concentrations were below detectable limits.

S/N	Name of Well	Cd Status	Cd (µg/L)			Pb Status	Pb (µg/L)		
			Eng. State.	**Fed. Min.**	**Ana. State.**		**Eng. State.**	**Fed. Min.**	**Ana. State.**
1	Nnwige Square	Detected	**50**	BDL	**5**	Detected	BDL	BDL	3
2	Uchefu Hall	Detected	2	BDL	**7**	Detected	BDL	BDL	4
3	Health Centre	Detected	**5**	BDL	BDL	Not Detected	BDL	BDL	BDL
4	Last Bus stop	Detected	**6**	BDL	BDL	Not Detected	BDL	BDL	BDL
5	Egbonwigi	Detected	**15**	BDL	**7**	Not Detected	BDL	BDL	BDL

1.3 STUDY OBJECTIVES AND SCOPE

The main objective of this project was to carry out a hydrogeochemical investigation of groundwater from five existing handpump boreholes, local shallow hand-dug wells, rivers and springs in the Ugwuaji community and its environs to assess Pb and Cd concentrations and to understand their origin and distribution.

The study was carried out in three phases:

1. Measurement of physicochemical parameters and water sampling from the five handpump sources and a range of other water source types.
2. Analysis of a set of the water samples in the field with three other sets transported to three different laboratories for a repeat analysis.

3. Sampling of rock, soil and handpump components at representative points for geochemical analysis of heavy metals with Pb and Cd as the primary target.

The objectives of the study were:

1. Georeference the handpump boreholes, shallow hand-dug wells, surface water from rivers and soil sampling points.
2. Taking measurements of specific physical parameters at each of the locations (Figure 3).
3. Sampling and preservation of three paired sets of water samples from each location.
4. Dismantling of selected handpumps to sample scrapings from components and different materials used in the handpumps.

Figure 3. (A) Cooling boxes for samples preservation and transportation (B) Field measurement of some selected ions using Wagtech Instrument.

2 Methods

2.1 WATER, SOIL/ROCK AND MATERIAL SAMPLING PROCEDURES

A total of 32 water samples (26 groundwater, 6 surface water) were collected from the handpump boreholes and other water points. Three out of the 26 groundwater samples were collected from shallow hand dug wells and a motorised boreholes at locations away from Ugwuaji communities to serve as the control samples. The sampling of the hand-pump wells was carried out as follows:

1. Stage 1: Passive sampling of unfiltered groundwater before the day's pumping commenced, samples were taken early in the morning.
2. Stage 2: Active sampling of filtered water after the mornings pumping had commenced, samples were taken later in the day.
3. Stage 3: Sampling scrapings from the boreholes and pump installations/materials.

Dividing the sampling into three regimes as described above was necessary to assess total metal concentrations and dissolved concentrations (filtered using 0.45-micron filters) and possible leaching from the handpump materials. The sampling bottles were rinsed with sample before filling to avoid cross-contamination. The field study was conducted between the 8th and 18th of March 2022.

2.2 FIELD PHYSICOCHEMICAL MEASUREMENTS

The following measures were carried out and recorded in the field as the first step before sampling water for laboratory analysis.

1. Field physicochemical measurements included pH, electrical conductivity (EC), total dissolved solids (TDS), redox potential (ORP/Eh), dissolved oxygen (DO), total suspended solids (TSS), turbidity and temperature were measured before sampling the water. These were recorded using field multi-parameters pH/EC meter and WAGTECH DO meter.
2. Each sampling point was georeferenced using GPS before sampling.
3. Description of the environment surrounding the sample point.
4. Sampling and preserving the water in three sets for filtered and unfiltered samples.

The process above was repeated at each water point.

2.2.1 Water preservation method

1. The preservation of the samples was carried out by putting the samples collected in HDPE bottles, sent by the BGS, inside an iced cooler. A set of the samples for the metal's analysis were acidified and at the laboratory prior to the analysis with concentrated HNO_3 to a pH < 2. Acid preservation was conducted at the BGS laboratories using 1% HNO_3 high grade acid.
2. Unacidified samples meant for major anions analysis were stored in an iced cooling box below a temperature of 4.0 °C before laboratory analysis.
3. Samples were transported in cool boxes to the various laboratories and refrigerated prior to analysis.

2.2.2 Precipitate collection from the pump and riser pipe components

Three of the five boreholes were dismantled prior to sampling because they were not yielding water. The riser pipes in the boreholes at Ochufu town hall and Nwigwe had been removed because the boreholes had dried up. Thus, it was only possible to collect scrapings from the health centre borehole (Table 1). Approximately 20 to 30 ml of the scrapings was collected after dismantling the hand pump at the health centre. These samples were dissolved in HNO_3 and then stored in the iced cooler box to keep the pH low to preserve the metals before the laboratory analysis. A duplicate sample was collected and stored in an unacidified in air-tight containers for the Pb isotope analysis.

2.2.3 Soil/rock sampling

Soil samples were collected from alluvium materials along the river channels, exposed outcrops along profiles in the river valley or road cuttings which expose rock in the study area. Six samples were collected in total. The samples were pulverized and sieved to obtain the clay portion for digestion and metal analysis using ICP-OES, ICP-MS or AAS for heavy metals analysis with Pb and Cd as the primary target.

2.3 LABORATORY ANALYSIS

Hydrochemical analysis was used to establish the occurrence of Pb and Cd in the environment and isotope analysis was used to investigate three possible Pb sources; 1) natural origins including in the soil, in the water environment and in the rocks that constitute the aquifer. Pb and Cd in these environments are often associated with other metals such as iron (Fe), copper (Cu) and nickel (Ni). Hydrochemical data were compared with WHO and NSDWQ standards for drinking water. Data analysis was conducted using Excel, R and SPSS for statistical interpretation and visualisation.

2.3.1 Cation, anion and trace element analysis

Comprehensive hydrochemical analysis of cations (Ca, Mg, Na and K), anions (HCO_3, SO_4, Cl, PO_4, and NO_3) and trace elements (arsenic (As), cadmium (Cd), cobalt (Co), copper (Cu), chromium (Cr), manganese (Mn), nickel (Ni), iron (Fe), lead (Pb), zinc (Zn)) was conducted.

In the Nigerian laboratories, major cations ions such as Ca, Mg, Na and K were analyzed using ICP-OES and trace elements As, Cd, Co, Cu, Cr, Mn, Ni, Fe, Pb and Zn using AAS. BGS analyses of major ions and trace elements were conducted by ICP-MS (Table 2). Major anions such as HCO_3, SO_4, Cl^- PO_4, and NO_3 were analyzed by ion chromatography (IC) and digital titration. Different instrumentation and/or analytical methods should not materially affect the results of analysis between different laboratories.

Duplicate laboratory analysis was carried out in the following laboratories; the BGS laboratory, the analytical laboratory of the International Institute for Tropical Agriculture (IITA), Ibadan, Nigeria and the water quality laboratory of the National Water Resources Institute (NWRI), Kaduna, Nigeria.

Table 2. Analytical equipment used for water analysis by participating laboratories

S/N	Equipment	NWRI	IITA	BGS
1	ICP-MS	No	No	Yes
2	ICP-OES	No	Yes	No
3	AAS	Yes	Yes	No
4	IC	No	Yes	Yes
5	DO (WAGTECH)	Yes	No	No

2.3.2 Lead isotope analysis

Pb could originate from anthropogenic and geogenic processes. Pb isotope ratio allows investigation of the origin of Pb in the environment. In this study, Pb isotope analysis of selected samples, including the scrapings from the pump and riser pipes and soil/rock samples, were determined to give a broader insight into the origin of Pb in groundwater around Ugwuaji. The Pb isotope ratios ($^{204}Pb/^{206}Pb$, $^{207}Pb/^{206}Pb$, $^{208}Pb/^{206}Pb$) were determined at the BGS isotope laboratory.

2.4 QUALITY CONTROL

BGS analysis by ICP-MS was undertaken using a UKAS ISO 17025 accredited method with scope for surface water and groundwater. A comprehensive Quality Management System is a key part of this accreditation.

For BGS analysis quality control (QC) standards (full compliance and traceability to ISO 17034) are analysed throughout the analytical run. The QCs used cover all elements of interest. Working QC standards are prepared on the day of analysis. A relevant working QC standard is analysed after at most every 30 samples. In the case of the WaterAid analysis this was no more than every 15 samples. QC standard data charting and verification are carried out in accordance with the requirements the BGS quality system. Any part of the analysis run in which bracketing QC samples do not meet specified criteria is repeated for the non-compliant elements. Appropriate explanations are recorded in the quality system.

Clean water, waste, ground and saline water samples from the LGC Aquacheck Proficiency Testing scheme (ISO 17043 compliant) are analysed approximately every two months for Ag, Al, As, B, Ba, Be, Ca, Cd, Co, Cr, Cu, Fe, K, La, Li, Mg, Mn, Mo, Na, Ni, P, Pb, S, Sb, Se, Si, Sn, Sr, Ti, V, U and Zn. The timing of WaterAid analytical project did not coincide with Aquacheck analysis. The lab regularly submits results for trace elements, including for Pb and Cd, as part of the UK's Laboratory of the Government Chemist Aquacheck proficiency testing scheme and performs within control limits for these elements. QC data from two BGS internal standards (one high and one low multi element standard) BGS run and report alongside results for the samples were used to QC the analysis of this batch of samples. "LoQC" covers all trace elements which are present at a concentration of either 1 µg/L or 5 µg/L in solution. The concentrations chosen are based upon several years' groundwater and surface water analysis by the Inorganic Geochemistry Facility. BGS results for LoQC for Pb and Cd were all found to be within control limits analysis. These results are summarised in Table 3. Based on BGS analysis, ion balances were within ±10% for all samples except two HDW5 and CHDW1. The majority of samples had ion balances within ±5%.

Table 3. Performance of BGS internal standard 'LoQC' for Pb and Cd by ICP-MS.

Element	QC standard	Target conc. (µg/L)	Mean conc. (µg/L)	Repeat analysis (n)	Recovery (%)	RSD (%)
Pb	LoQC	5.00	4.82	7	96	0.5
Cd	LoQC	1.00	0.999	7	100	2.1

RSD = Relative Standard Deviation

At the IITA laboratory QC samples containing the analytes of interest at known concentrations were prepared and analysed every 20 samples to check instrument performances throughout the sample analysis. Samples whose concentration exceeded the highest standard were adequately diluted to fit in the linear range of the calibration curve. No further information was available on the QC procedures used by the Nigerian laboratories. No standard solutions with known element concentrations were sent to Nigerian laboratories.

3 Results

This section focusses on presenting summary results for the water analysis (total and dissolved Pb and Cd) undertaken at all three laboratories using triplicate samples as well as trace element and Pb isotope analysis of a smaller sub-set of waters, soils and rock samples.

3.1 WATER CHEMISTRY

Pb and Cd results determined by all laboratories for water samples are summarised in Table 4. Overall there was no consistency between the elemental analysis results produced by the three laboratories for Pb or Cd. A single unfiltered sample from the BGS analyses (site UPS4) gave a Pb concentration (10.5 μg/L) that exceeds the WHO guideline value of 10 μg/L. In general, the handpump borehole sources had the highest Pb concentrations, with a median value of 1.73 μg/L compared to the hand-dug well and surface water sources which had a median value of 0.09 μg/L. None of the samples analysed at the BGS laboratories had Cd concentrations that exceeded the WHO drinking water guideline value of 3 μg/L. The highest Cd concentrations were detected at EBH1 and EBH2 at 0.35 and 0.36 μg/L respectively. Samples EBH1-EBH4 were collected from boreholes within Enugu city for comparison. Results from the NWRI and IITA laboratory show exceedance of the WHO and NSDWQ drinking water standards for both Cd and Pb for all samples. However, these results are highly suspect and do not compare with the results from the BGS laboratories. Further investigations are required to understand why the NWRI and IITA results are so different from each other and from the BGS results.

A comparison of results from filtered and unfiltered samples suggests that concentrations are comparable for BGS results for both 'total' and 'dissolved' metals, suggesting that the particulate metal fraction (i.e. the amount of Pb or Cd flocs in suspension in the borehole water column) is not a major component of the overall measured heavy metal concentrations. One exception could be passive (i.e. before pumping) sample UPS 4 which has Pb concentrations of 10.5 μg/L and had a high level of suspended material, some of this Pb appears to be in the particulate (suspended) fraction. Passive samples (in blue text in Table 4) had higher median Pb and Cd levels than active samples (in red text in Table 4) indicating that concentrations of both elements decline after the early morning stagnant water has been flushed out the borehole. The lower concentrations of Pb and Cd in the active samples could indicate that handpump materials as the source of both elements. Median Pb levels for passive samples was 5.01 μg/L but for active samples was 0.35 μg/L. Median Cd levels for passive samples was 0.036 μg/L and for active samples was 0.036 μg/L.

Table A1 (Appendix 1) shows results from BGS analysis of major and trace elements and field parameters. It is noteworthy that three groundwater samples (HDW6, EBH3 and EBH4) have conductivity that exceeds 2000 μS/cm and particularly low pH (<4.5) was recorded in two boreholes (EBH1 and EBH2). Elevated fluoride concentrations (greater than the WHO drinking water guideline value of 1.5 μg/L) were found in four groundwater samples (UPS2, FS2, EBH1 and EBH2, range 2.39-2.49 μg/L). Iron concentrations were typically low (<100 μg/L) in the groundwater samples, higher concentrations were found in some unfiltered samples, with concentrations up to 468 μg/L. All of the results from the three separate laboratory analysis and the field parameters can be found in Appendix 1.

Data from the handpump wells and hand-dug wells were also subjected to statistical analysis using Principal Component Analysis (PCA). This method is commonly used in determining the possible source/origin of metals into soil or water media in environmental pollution studies. The PCA reduces the dimensions of the dataset with a large number of correlated variables (Gvozdic et al, 2012 and Kumar et al, 2018). The results of the PCA analysis indicate that Pb and Cd are derived from anthropogenic, rather than geogenic sources. A more detailed description of the PCA results can be found in Appendix 2.

Table 4. Summary results for Pb and Cd concentrations for waters for all laboratories

Laboratory	BGS Laboratory		NWRI Laboratory		IITA Laboratory	
Parameters	**Pb (µg/L)**	**Cd (µg/L)**	**Pb (µg/L)**	**Cd (µg/L)**	**Pb (µg/L)**	**Cd (µg/L)**
Detection Limit	0.02	0.006	0.04	0.01	0.01	0.003
WHO MPL	10	5	10	5	10	5
NSDWQ	10	3	10	3	10	3
FS 1	0.31	BDL	97	BDL	90	20
FS 2	0.34	BDL	148	BDL	90	20
FS 3	1.95	BDL	331	BDL	90	30
FAS 2	1.73	BDL	465	BDL	170	30
FAS 4	1.41	0.013	795	BDL	90	50
FAS 5	0.35	0.013	BDL	BDL	90	40
FPS 4	4.15	BDL	541	BDL	90	30
FPS 5	5.05	0.089	BDL	9	90	20
UPS 1	0.08	BDL	BDL	BDL	250	40
UPS 2	0.17	BDL	179	BDL	170	20
UPS 3	2.26	0.01	243	7	170	20
UPS 4	**10.5**	**0.024**	**551**	**BDL**	**90**	**40**
UPS 5	5.01	0.048	BDL	BDL	90	20
HDW1	0.5	BDL	118	BDL	250	20
HDW2	0.19	0.018	456	BDL	90	30
HDW3	0.07	0.008	BDL	BDL	250	20
HDW4	BDL	BDL	45	6	90	30
HDW5	0.08	0.008	351	BDL	170	20
HDW6	0.03	BDL	393	1	170	20
HDW7	0.1	BDL	606	BDL	170	20
RW1	BDL	BDL	132	BDL	170	30
RW2	0.6	BDL	236	6	170	20
RW3	0.05	BDL	BDL	BDL	90	40
RW4	BDL	BDL	682	22	170	20
RW5	BDL	BDL	897	25	170	30
RW6	BDL	BDL	182	BDL	170	30
EBH1	2.64	0.349	65	5	90	40
EBH2	2.73	0.357	472	6	90	20
EBH3	0.04	BDL	10	6	170	40
EBH4	0.06	BDL	12	15	250	30
CHDW1	BDL	0.011	BDL	4	90	30

DL=Detection limit, BDL = below detection limit, WHO MPL = World Health Organisation Maximum permissible limits, NSDWQ = Nigeria Standard for Water Quality. Samples with RW ID’s are stream samples. HDW = hand dug well, rest are hand-pump boreholes. Rows highlighted in the colour tan are samples which were not filtered, i.e. these are total metal concentrations rather than dissolved concentrations. Samples in red text are active samples from the handpump boreholes. Samples in blue text are passive samples from handpump boreholes.

3.2 TRACE ELEMENT CONTENT OF SAMPLES FOR LEAD ISOTOPE ANALYSIS

The soil/sediment samples had concentrations in the range 26-33 mg/kg. The handpump scraping sample had a significantly higher Pb concentration of c. 800 mg/kg. The leachable Pb from the PVC pipe was the equivalent of 223 mg/kg. Pb was the only trace heavy metal with an anomalously high concentration in the samples analysed. These results indicate that Pb levels in the materials are significantly higher than those in the surrounding environment, particularly soil and sediments in the surrounding area.

3.3 LEAD ISOTOPE RESULTS

A suite of Pb isotope ratios was determined for the water and solid samples. Here we discuss the ^{207}Pb$^{/206}$Pb and ^{208}Pb$^{/206}$Pb ratios as precision is better than for the less abundant ^{204}Pb isotope. It should be noted that the analysis presented here is based on a small number of samples and without consideration of other potential isotope end members from the local area, so these results are preliminary.

Figure 4 is a bivariate plot of the $^{207/206}$ Pb and $^{208/206}$ Pb ratios for all of the WaterAid (WA) samples plus some other potential end-members from the literature. The handpump scraping and PVC pipe samples cluster together and have compositions similar to the water samples, suggesting that the Pb found in the water samples may be derived from the materials used in the boreholes sampled. The potential end-members shown on the diagram include some of the most extreme Pb isotope ratios found worldwide from major industrial Pb production. Broken Hill Type (BHT) Pb from Australia and Western Canada is often mistakenly referred to as petrol Pb (Ballhöfer and Rosman 2002) because Octel, the maker of tetra-ethyl Pb for Europe and many others across the world used this source. However, this Pb was also used in many other industrial processes. Mississippi Valley Type (MVT) has been commonly used in North America both for petrol and industrial use. Also plotted are Bollhofer's air particulate data from Dakar in Senegal, that might give us a typical air fall-out Pb which would be a mixture of natural geogenic fine dust with anthropogenic industrial and petrol particulates.

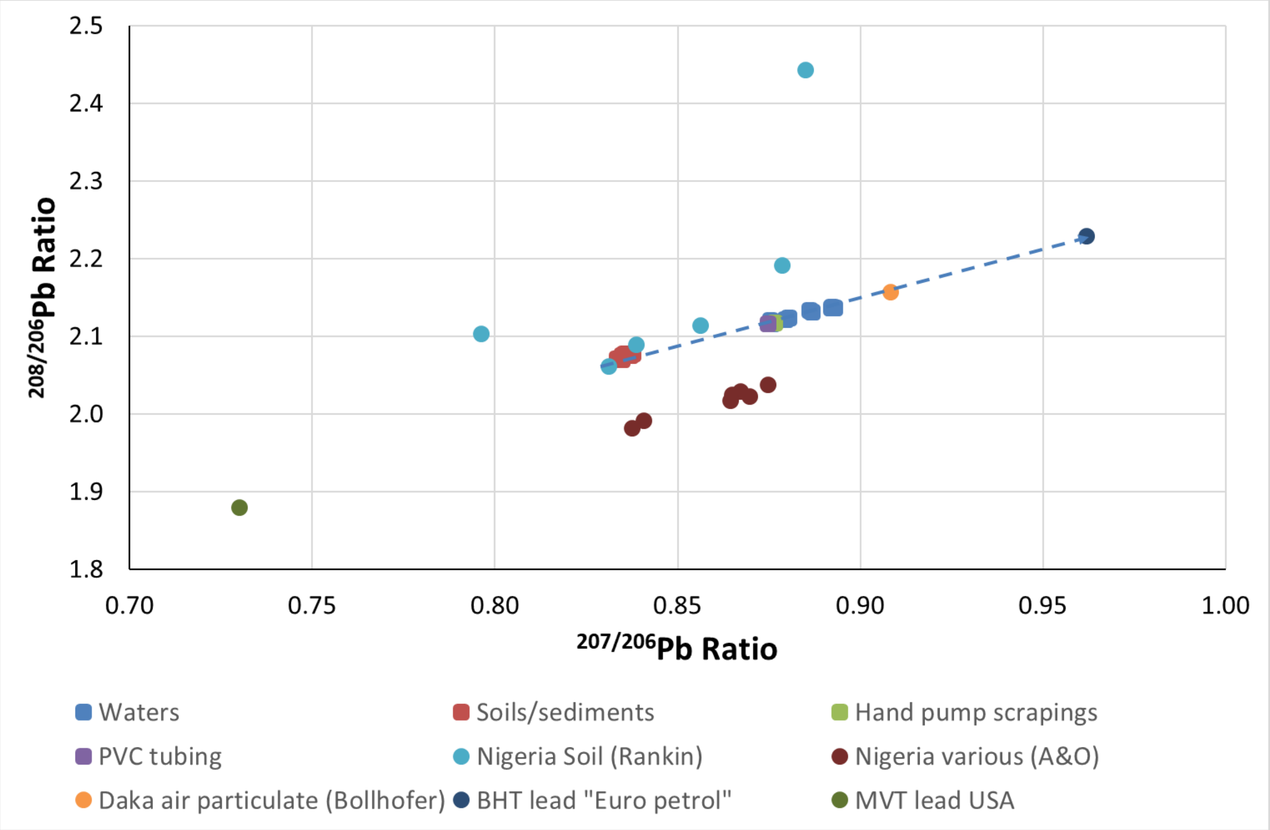

Figure 4. Bivariate plot of the 207/206 Pb and 208/206 Pb ratios for all samples plus some other potential end-members (Daka air particulate, BHT Pb and MVT Pb).

Two sets of relevant Nigerian data were found: Rankin's data (Rankin et al., 2005) were for agricultural soils and the Asowata and Olatunjii (2019) data covered various forms of anthropogenically Pb-contaminated samples. The Olatunji and Afolabi data appear to be displaced negatively on the $^{208/206}$ Pb axis compared to all the other data sources. These may be of suspect data quality and will not be considered further. The project's soils/sediments/cuttings fall in a tight cluster on an array of Rankin's Nigerian soils, approximately midway between the BHT and MVT type end members. The water samples, the WFP-A1 handpump scraping sample and the PVC pipe leach all fall between the BHT and MVT type end members but more towards the BHT type end member than the soils and with a greater spread than the soils.

Figure 5 focusses in on the project's sample data and MVT/BHT end members. The water data fall on an array between the soils/sediments/cuttings and the Dakar air particulate, with a distinct mixing line between the handpump scraping/PVC pipe (both having very similar Pb isotopic ratios) and the anthropogenic Dakar air-particulate.

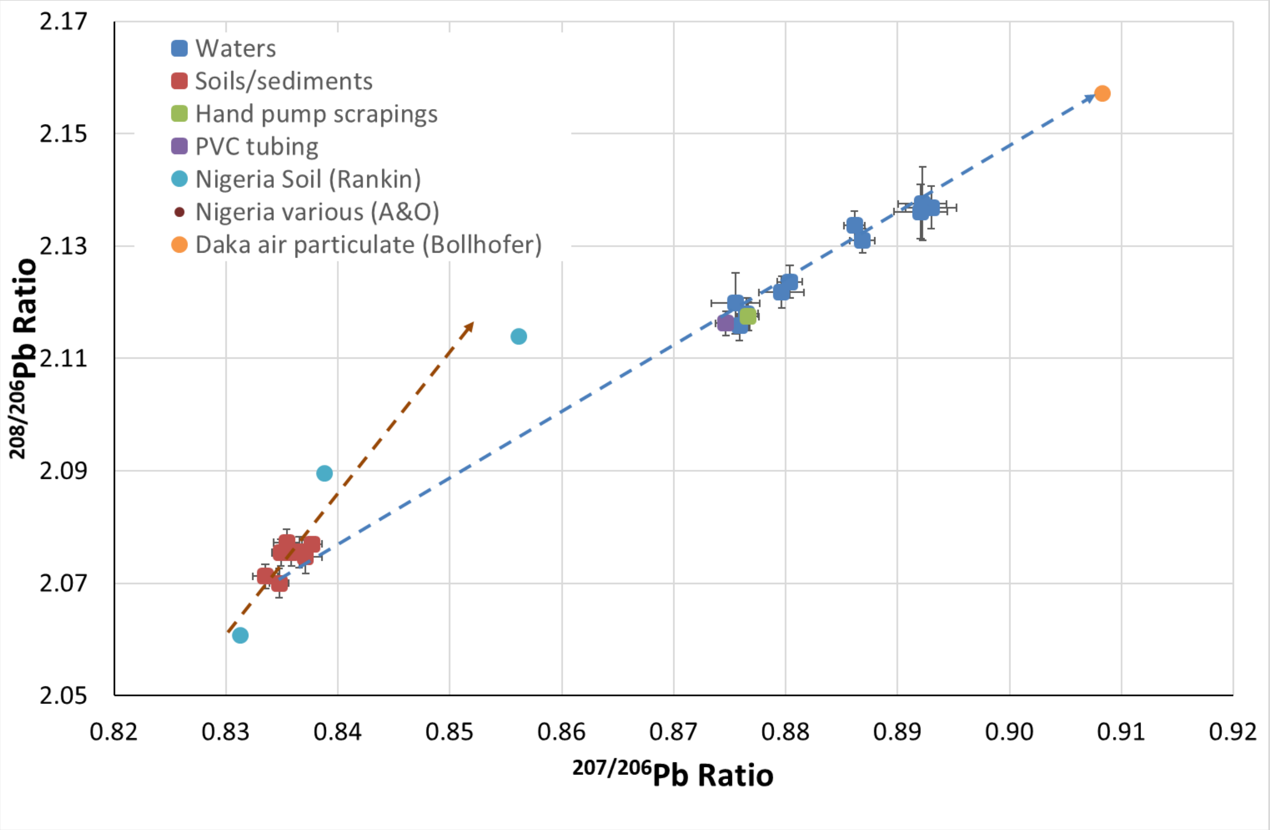

Figure 5. Bivariate plot of the 207/206 Pb and 208/206 Pb ratios for all samples, plus some literature values for comparison.

Figure 6 shows that ^{207}Pb/^{206}Pb ratios appear to be lower at higher concentrations of aqueous Pb and suggest that the higher concentrations have a closer association with the PVC and handpump scraping (metal scrapings) and/or the local rocks/soils than with Dakar ('local') air particulates. It is difficult to distinguish between rocks/soils and borehole components as the isotopically depleted end member. Highest observed Pb concentration in the BGS analyses was from an unfiltered groundwater sample. The particulate matter contributing to the Pb in this water could have been derived from local aquifer materials or borehole PVC/scrapings, though the similarity of isotopic signatures to the borehole components would point tentatively to these as a principal source. More investigation would be needed to verify this inference. Investigations over periods of pumping might be informative if the borehole groundwaters of the area are demonstrated to contain reproducibly uncompliant solute Pb concentrations.

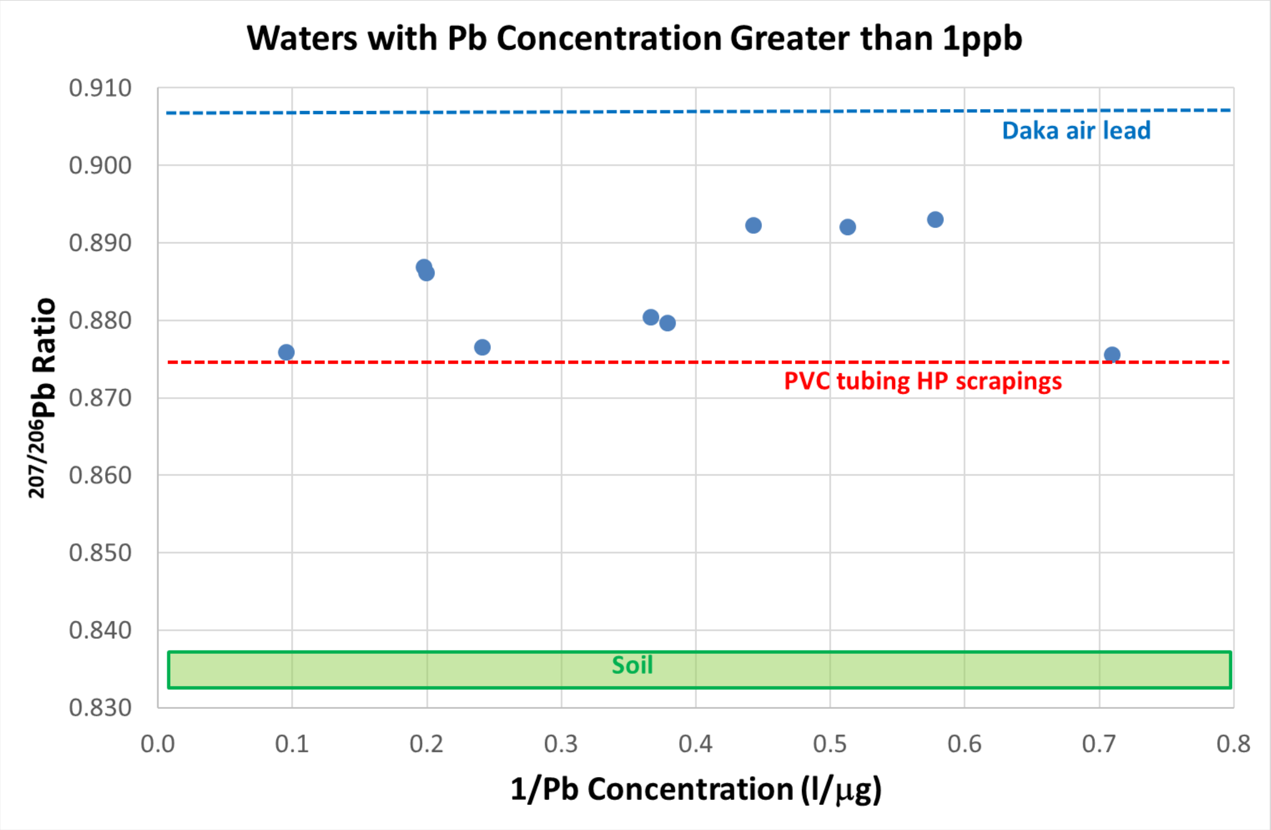

Figure 6. Bivariate plot of the 207/206 Pb and 1/Pb concentration (µg/L) waters from Enugu

4 Discussion

4.1 TOTAL AND DISSOLVED LEAD AND CADMIUM CONCENTRATIONS IN GROUNDWATER

Overall, based on BGS analysis, low Pb and Cd concentrations were found across the surface and groundwater sites in Enugu sampled as part of this pilot study. The median Pb concentration was higher in handpump boreholes than in the other water sources. Only a single sample contained Pb concentrations greater than the WHO and Nigerian standard, although some studies suggest that there is no safe concentration for lead in potable water supplies (WHO, 2022).

There is a clear discrepancy between some of the Pb and Cd results from the initial study undertaken by WaterAid in 2020 using local labs and the results obtained from this study using local labs and BGS labs. This needs to be more thoroughly evaluated through sampling a larger number of groundwater sources and repeated sampling to rule out temporal changes in heavy metal concentrations. There are also clear differences in results obtained for Pb and Cd on a site-by-site basis from the three laboratories used in this study.

The differences in Pb and Cd concentrations found between the different laboratories are significant and raise concerns about the accuracy of results reported from the local laboratories. The fully accredited BGS laboratory consistently found lower concentrations than Nigerian Laboratories. Major sources of uncertainty could include the purity of the acid used, the standards used, and other QA/QC procedures used by the Nigerian laboratories. At the time of writing this report we were not able to obtain any detail from the local labs on QA/QC procedures used by the Nigerian laboratories. To understand this issue fully a more detailed inter-laboratory comparison study needs to be undertaken using a range of triplicate standards and blanks.

Passive samples had higher median Pb and Cd levels than actively pumped samples indicating handpump materials as a potential source for both elements. There was no systematic increase in heavy metal concentrations for Pb and Cd in unfiltered samples compared to filtered samples, suggesting that for the sampled waters, particulate-Pb is not a significant component. However, further work on paired dissolved and total Pb samples would help quantify the proportion of dissolved and particulate Pb in samples more clearly, which would indicate the risk of drinking unfiltered water from the handpump boreholes.

Results from this small pilot suggest that fluoride and high TDS (Appendix 1) in groundwater may be more of a challenge than Pb and Cd in terms of water quality in this region.

4.2 SOURCES OF LEAD IN WATERS BASED ON LEAD ISOTOPE ANALYSIS

The Pb isotope analysis strongly indicates that the Pb in the water samples results from two types of sources, handpump scrapings/PVC pipe (both having essentially the same Pb ratios) and the anthropogenic air-particulate end members.

Returning to the waters and the question of relative source contributions to the Pb concentration. This is conventionally investigated using a plot of $^{207/206}$ Pb v1/Pb concentration, see Figure 4. The reciprocal of Pb concentration is used as this results in straight mixing lines rather than curved. The random scatter of the data suggests that the end-members (PVC pipe/handpump scraping and air particulate etc) do not contribute a fixed proportion to the Pb concentrations in the water samples. However, perhaps this is to be expected with the diversity of well types and locations.

The Pb isotope data suggest that the Pb in the waters (samples with > 1 μg/l) does not come from the local soil/sediment/cuttings. It appears to be a mixture of the Pb found in both the PVC and handpump component scrapings and Broken Hill type Pb (either industrial or from petrol). It is possible that the scrapings could contain Pb from the PVC. The BHT-like contribution could quite possibly be from air particulates. The similarity between the isotopic signatures of the waters and the handpump materials hint at this being an important source of the Pb concentrations observed in the water samples. However, on the basis of the relatively small sample size used in the analysis, it is difficult at this stage to discriminate between the primary contributing source (i.e. handpump components or Broken Hill type Pb, possibly arising from air particulates). In order to definitely identify the primary source of Pb further sampling and analysis would be required, including collection of local air particulate source samples.

5 Conclusions and Recommendations

5.1 CONCLUSIONS

Analysis of Pb and Cd concentrations from 32 water samples (26 groundwater, 6 surface water) from the hand-pump/boreholes in the Ugwuaji community and three shallow hand dug wells and a motorised borehole at locations away from Ugwuaji was conducted by three laboratories. All three laboratories produced significantly different results for the Pb and Cd concentrations, with the Nigerian laboratories giving much higher concentrations than the BGS laboratory. Further investigations are required to understand the reasons for these discrepancies. Results from the BGS laboratory were considered accurate based on the QA/QC procedures conducted. BGS results indicate that none of the sources had Pb or Cd levels exceeding either the WHO guideline values or Nigerian standards, with the exception of one handpump borehole where an unfiltered passive (i.e. before pumping) sample was taken and total Pb concentration (i.e. sum of dissolved and suspended Pb concentrations) was found to be 10.5 µg/l (WHO and Nigerian standard is 10 µg/l). In general, the median Pb concentration of the handpump boreholes (1.74 mg/l) was higher than the other water sources sampled (0.09 µg/L). Similarly, median Pb and Cd concentrations in the passive (i.e. pre-pumping) samples were both higher than in the active (i.e. post pumping samples), suggesting handpump materials as a possible source. On the basis of concentrations measured by BGS Pb and Cd are not considered to be a significant risk at the sources tested. However, further work is required to rule out the possibility of higher Pb concentrations at other locations, particularly focusing on total Pb concentrations.

Preliminary isotope analysis suggests that the origin of Pb in the handpump sources could be either the materials (i.e. the metal components or PVC pipes) or Pb particulates in the air but the initial analysis cannot distinguish between these sources. Further isotope sampling and analysis would be required to discriminate the primary source for the measured Pb concentrations, although the initial results do indicate the importance of the handpump materials as a source. The results indicate that the handpump components cannot be definitely ruled out as a source of the Pb found in the water samples, particularly because of the relatively high Pb content of the PVC and handpump scraping samples that was found in the solid analysis.

5.2 RECOMMENDATIONS:

1. A detailed inter-laboratory study should be conducted. Certified water quality standards with known elemental concentrations and a range of samples prepared by BGS with known Pb and Cd concentrations should be sent to all three laboratories for independent analysis and comparison of results.

2. Further collection and analysis of water quality samples from a wider sample of handpump and other sources to better establish a baseline for total and dissolved Pb concentrations.

3. More extensive and detailed isotope sampling and analysis including collection of a range of end members from the local area (i.e. air particulate samples). A wider range of materials could also be sampled including components purchased from the local market and more scrapings from handpump components (both metallic and PVC components) installed in-situ.

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Appendix 1

Field parameters, major and trace element chemistry results from BGS analysis of samples.

Information on Water sampling points

Community	Site description	Lat (°m)	Long (°m)	Elev (m)	Date	Scheme type	Sample code
Obeagu Ugwuaji	Last Bus Stop	6.4052	7.5507	165	3/12/2022	Handpump Borehole	UPS-1
Obeagu Ugwuaji	Nwigwe Stream Road	6.4049	7.5465	168	3/12/2022	Handpump Borehole	UPS-2
Obeagu Ugwuaji	Egbo Nwigwe Square	6.4043	7.5422	168	3/13/2022	Handpump Borehole	UPS-3
Obeagu Ugwuaji	Health Centre	6.4097	7.5462	161	3/17/2022	Handpump Borehole	UPS-4
Obeagu Ugwuaji	Ochufu Hall	6.4013	7.5560	164	3/16/2022	Handpump Borehole	UPS-5
WATER SAMPLES FROM ACTIVE HPB							
Obeagu Ugwuaji	Last Bus Stop	6.4053	7.5507	165	3/12/2022	Handpump Boirehole	FS-1
Obeagu Ugwuaji	Nwigwe Stream Road	6.4049	7.5465	168	3/13/2022	Handpump Borehole	FAS-2
Obeagu Ugwuaji	Egbo Nwigwe Square	6.4043	7.5422	168	3/13/2022	Handpump Borehole	FS-3
Obeagu Ugwuaji	Health Centre	6.4097	7.5462	161	3/17/2022	Handpump Borehole	FAS-4
Obeagu Ugwuaji	Ochufu Hall	6.4013	7.5560	164	3/17/2022	Handpump Borehole	FAS-5
WATER SAMPLES FROM HAND-DUG WELLS							
Obeagu Ugwuaji	Opposite St. Michael Catholic Church	6.4091	7.5423	164	3/12/2022	Hand Dug Well	HDW-1
Obeagu Ugwuaji	Ikorogu Layout HDW	6.4013	7.5560	165	3/12/2022	Hand Dug Well	HDW-2
Obeagu Ugwuaji	Opposite Nwigwe Stream Road HDW-1	6.4056	7.5482	108	3/13/2022	Hand Dug Well	HDW-3
Obeagu Ugwuaji	Opposite Nwigwe Stream Road	6.40663	7.5497	167	3/13/2022	Hand Dug Well	HDW-4
Obeagu Ugwuaji	Opposite WASHCOM Chairman House	6.40899	7.5465	173	3/13/2022	Hand Dug Well	HDW-5
Obeagu Ugwuaji	Ikorogu HDW Behind Health Centre	6.4087	7.5418	165	3/15/2022	Hand Dug Well	HDW-6
Obeagu Ugwuaji	Opposite St. Michael Catholic Church HDW-2	6.4066	7.5523	160	3/15/2022	Hand Dug Well	HDW-7

WATER SAMPLES FROM THE RIVER							
Obeagu Ugwuaji	Ine River (Midstream)	6.4097	7.5462	159	3/15/2022	River	RW-1
Obeagu Ugwuaji	Ine River (Downstream)	6.4037	7.5652	138	3/15/2022	River	RW-2
Obeagu Ugwuaji	Ine River (Upstream)	6.4240	7.5395	172	3/16/2022	River	RW-3
Obeagu Ugwuaji	Nwigwe Stream/Afah River (Midstream)	6.4050	7.5486	162	3/16/2022	River	RW-4
Obeagu Ugwuaji	Nwigwe Stream/Afah River (Upstream)	6.4104	7.5466	168	3/16/2022	River	RW-5
Obeagu Ugwuaji	Nwigwe Stream/Afah River (Downstream)	6.4040	7.5493	156	3/16/2022	River	RW-6
CONTROL WATER SAMPLES							
Enugu	Umunnaji Community	6.4579	7.5256	199	3/17/2022	Hand Dug well	CHDW
New haven, Enugu	St. Mulumba Catholic Church	6.4049	7.5465	168	3/18/2022	Motorized Borehole	EBH-1
New haven, Enugu	St. Mulumba Catholic Church	6.4049	7.5465	168	3/18/2022	Motorized Borehole	EBH-2
Ekochin Estate, Enugu	Plot 3, Ekochin Estate, Thinkers Corner	6.4678	7.5457	202	3/18/2022	Motorized Borehole	EBH-3
Ekochin Estate, Enugu	Plot 3, Ekochin Estate, Thinkers Corner	6.4678	7.5457	202	3/18/2022	Motorized Borehole	EBH-4

Statistical summary of the Field measurement results

Param	DO Mg/l	ORP (mV)	EC (µS/cm)	TDS (mg/l)	Turb (NTU)	TSS mg/l	NO3 mg/l	F (mg/l)	PO4 (mg/l)	SO4 (mg/l)
	PASSIVE SAMPLES (N = 5)									
Min	3.58	9.2	198.2	104	1.46	2.1	0.48	0.14	0.6	2
Max	5.74	99.8	1505	785.7	327	772	6.7	1.5	0.88	165
Ave	4.416	46.58	950.8	495.8	96.5	233.2	3.9	1.1	0.75	72.2
Stdev	0.89	33.8	516.7	268.7	142.0	334.0	2.2	0.58	0.12	60.8
	ACTIVE SAMPLES (N = 5)									
Min	1.59	38.7	207.5	110.4	2.18	5	2.22	0.83	0.05	4.5
Max	4.5	74.6	1526	798	505	1088	6.96	1.58	0.54	142
Ave	2.8	52.8	877.0	458.4	184.9	418	4.66	1.14	0.37	58.7
Stdev	1.31	15.6	603.7	314.7	245.2	540.7	1.94	0.32	0.22	51.5
	SHALLOW HAND-DUG WELL (N = 7)									
Min	1.44	4.6	92.85	48.76	3.21	16	8.448	0.14	0.45	1
Max	8.41	109.9	2290	1201	139	419	67.76	1.95	17.5	210
Ave	5.31	36.3	653.5	342.8	29.6	90.9	30.7	1.03	3.48	45.7
Stdev	2.37	35.7	773.7	405.2	48.5	145.2	19.16	0.61	6.87	82.8
	RIVER SAMPLES (N = 6)									
Min	4.51	2.5	147.3	77.27	7.36	26	0.4972	0.03	0.11	1
Max	8.9	65	364	190	155	480	24.86	0.44	0.3	14
Ave	6.865	24.33	249.15	130.51	37.68	116.00	6.52	0.20	0.18	4.83
Stdev	1.82	21.34	98.50	51.52	58.00	179.21	9.06	0.15	0.08	5.04
	CONTROL SAMPLES (N = 5)									
Min	1.8	26.0	201.8	105.9	1.9	4.0	2.8	0.0	0.0	1.0
Max	9.2	431.5	2080.0	1092.0	35.7	71.0	23.5	1.4	2.3	20.0
Ave	5.7	194.60	1045.14	548.72	8.94	17.80	13.19	0.72	0.66	8.80
Stdev	3.73	216.36	963.20	505.68	14.96	29.74	10.38	0.70	0.94	10.23

2a. Filter active samples (NWRI Laboratory results) - Nigerian Standard for Drinking Water Quality (NSDWQ) and WHO guideline values are included.

Sample ID	**Unit**	FS- A1	FS-A2	FS-A3	FAS-A2	FAS-A4	FAS-A5	**NSDWQ**	**WHO**
Ca	**ppm**	0.74	0.63	2.81	2.86	0.86	0.20	20.00	
Mg	**ppm**	6.91	6.82	5.62	7.69	4.51	3.40	200.00	
Na	**ppm**	BDL	0.09	BDL	0.36	BDL	0.01	NA	NA
K	**ppm**	115.60	120.60	170.53	165.40	190.45	120.63	250.00	
Cl-	**ppm**	206.25	209.24	154.37	84.85	130.56	60.72	NS	NS
HCO3-	**ppm**	4.09	NA	3.74	6.28	6.96	2.22	50.00	50.00
NO3	**ppm**	1.21	NA	1.24	1.58	0.83	0.83	1.50	1.50
F	**ppm**	0.52	NA	0.50	0.54	0.05	0.22	NS	NS
PO4	**ppm**	41.00	NA	142.00	66.00	4.50	40.00	100.00	
SO4	**ppm**	1.11	1.12	0.43	1.73	0.15	BDL	0.01	
Fe	**ppm**	1.50	0.46	1.85	0.10	0.44	BDL	0.20	
Mn	**ppm**	BDL	BDL	BDL	BDL	BDL	BDL	1.50	2.00
Cu	**ppm**	BDL	0.40	0.23	0.34	0.41	0.17	0.02	0.07
Ni	**ppm**	0.11	0.20	0.36	0.90	0.48	0.95	0.00	
Co	**ppm**	BDL	0.12	0.14	BDL	0.73	0.56	0.05	0.05
Cr	**ppm**	BDL	BDL	BDL	BDL	BDL	BDL	0.003	0.003
Cd	**ppm**	0.10	0.15	0.33	0.47	0.80	BDL	0.01	0.01
Pb	**ppm**	0.74	0.63	2.81	2.86	0.86	0.20	20.00	

2b. Filter passive samples (NWRI Laboratory results)

Sample ID	Unit	FPS-A4	FPS-A5	UPS-A1	UPS- A2	UPS-A3	UPS-A4	UPS-A5	NSDWQ	WHO
Ca	**ppm**	5.136	1.5	3.336	7.871	2.515	0.849	0.867	75	
Mg	**ppm**	0.295	1.858	0.625	0.819	1.936	3.7	1.423	20	
Na	**ppm**	4.371	4.517	6.489	7.393	5.678	5.517	3.961	200	
K	**ppm**	0.03	0.06	2	BDL	0.02	BDL	BDL	NA	NA
Cl-	**ppm**	205.45	225.45	70.7	170.5	95.74	80.8	105.9	250	
HCO3-	**ppm**	126.24	122.5	152.53	186.16	132.4	166.54	117.18	NS	NS
NO3	**ppm**	NA	NA	4.334	3.872	4.026	6.732	0.4796	50	50
F	**ppm**	NA	NA	1.5	1.4	1.43	0.14	0.81	1.5	1.5
PO4	**ppm**	NA	NA	0.60	0.75	0.69	0.85	0.88	NS	NS
SO4	**ppm**	NA	NA	45	90	165	2	59	100	
Fe	**ppm**	0.583	BDL	0.393	0.582	0.06	BDL	BDL	0.01	
Mn	**ppm**	BDL	BDL	0.681	0.851	0.951	0.4	BDL	0.2	
Cu	**ppm**	BDL	BDL	BDL	0.044	BDL	0.367	BDL	1.5	2
Ni	**ppm**	0.174	0.067	0.128	0.281	0.137	0.287	0.047	0.02	0.07
Co	**ppm**	0.556	0.486	0.183	0.664	0.443	0.846	0.638	0.001	
Cr	**ppm**	0.393	0.783	BDL	BDL	0.265	0.109	0.374	0.05	0.05
Cd	**ppm**	BDL	0.009	BDL	BDL	0.007	BDL	BDL	0.003	0.003
Pb	**ppm**	0.541	BDL	BDL	0.179	0.243	0.551	BDL	0.01	0.01

2c. Hand-dug well samples (NWRI Laboratory results)

Sample ID	**Unit**	HDW-A1	HDW-A2	HDW-A3	HDW-A4	HDW-A5	HDW-A6	HDW-A7	**NSDWQ**	**WHO**
Ca	**ppm**	4.013	2.419	1.102	0.504	1.974	2.671	4.233	75	
Mg	**ppm**	0.677	0.216	3.826	2.819	5.284	8.694	0.274	20	
Na	**ppm**	3.806	0.896	3.366	4.895	4.674	6.206	2.057	200	NA
K	**ppm**	0.233	BDL	BDL	0.441	5.06	0.231	BDL	NS	
Cl-	**ppm**	70.96	110.74	160.5	120.65	155.57	185.49	190.74	250	NS
HCO3-	**ppm**	12.8	12.8	39.5	45.85	23.85	115.39	120.27	NS	50.00
NO3	**ppm**	18.008	22.704	28.82	28.38	67.76	40.7	8.448	50	1.50
F	**ppm**	0.94	0.14	0.6	0.95	1.95	1.65	0.98	1.5	NS
PO4	**ppm**	0.87	NA	0.63	0.45	17.5	0.76	0.69	NS	
SO4	**ppm**	6	NA	4	51	2	210	1	100	
Fe	**ppm**	0.165	0.232	BDL	0.142	0.31	0.706	0.972	0.01	
Mn	**ppm**	BDL	BDL	BDL	BDL	BDL	0.7	0	0.2	2.00
Cu	**ppm**	BDL	BDL	BDL	BDL	BDL	BDL	0.018	1.5	0.07
Ni	**ppm**	0.377	0.919	0.289	0.178	0.424	0.537	0.589	0.02	
Co	**ppm**	0.419	0.866	0.376	0.575	0.588	0.159	0.264	0.001	0.05
Cr	**ppm**	0.991	0.338	BDL	BDL	0.776	0.167	0.316	0.05	0.003
Cd	**ppm**	BDL	BDL	BDL	0.006	BDL	0.001	BDL	0.003	0.01
Pb	**ppm**	0.118	0.456	BDL	0.045	0.351	0.393	0.606	0.01	

River water samples (NWRI Laboratory results)

Sample ID	**Unit**	RW-A1	RW-A2	RW-A3	RW-A4	RW-A5	RW-A6	**NSDWQ**	**WHO**
Ca	**ppm**	0.046	0.716	1.495	2.33	3.851	0.576	75	
Mg	**ppm**	0.523	1.133	1.829	3.477	1.09	3.322	20	
Na	**ppm**	1.025	1.537	2.988	3.546	3.542	3.416	200	NA
K	**ppm**	0.01	BDL	0.07	0.307	2.338	BDL	NS	
Cl-	**ppm**	70.8	80.8	55.8	155.5	55.83	85.75	250	NS
HCO3-	**ppm**	45.19	23.81	15.34	12.25	42.72	32.94	NS	50.00
NO3	**ppm**	24.86	0.4972	3.146	3.5112	3.212	3.916	50	1.50
F	**ppm**	0.03	0.10	0.44	0.28	0.11	0.22	1.5	NS
PO4	**ppm**	0.24	0.11	0.124	0.13	0.16	0.30	NS	
SO4	**ppm**	14	2	1	1	7	4	100	
Fe	**ppm**	BDL	0.052	0.035	0.041	0.29	BDL	0.01	
Mn	**ppm**	0.453	0.995	0.775	BDL	2.891	BDL	0.2	2.00
Cu	**ppm**	0.029	0.04	0.061	0.088	0.027	0.03	1.5	0.07
Ni	**ppm**	BDL	0.141	0.196	0.271	0.751	0.049	0.02	
Co	**ppm**	BDL	0.366	0.416	0.791	0.635	BDL	0.001	0.05
Cr	**ppm**	0.672	0.113	0.321	0.606	0.153	0.081	0.05	0.00
Cd	**ppm**	BDL	0.006	BDL	0.022	0.025	BDL	0.003	0.01
Pb	**ppm**	0.132	0.236	BDL	0.682	0.897	0.182	0.01	

Control well water samples (NWRI Laboratory results)

Sample ID	**Unit**	EBH-A1	EBH-A2	EBH-A3	EBH-A4	CHDW-A1	**NSDWQ**	**WHO**
Ca	**ppm**	0.168	2.167	8.122	8.766	1.177	75	
Mg	**ppm**	0.348	0.796	0.414	0.416	2.267	20	
Na	**ppm**	2.056	3.57	6.952	6.99	4.207	200	NA
K	**ppm**	BDL	BDL	0.867	1.406	2.259	NS	
Cl-	**ppm**	84.6	100.7	235.3	240.3	135.63	250	NS
HCO3-	**ppm**	27.95	31.75	428.8	425.6	26.27	NS	50.00
NO3	**ppm**	23.54	23.54	2.77	2.77	13.33	50	1.50
F	**ppm**	BDL	BDL	1.39	1.39	0.84	1.5	NS
PO4	**ppm**	0.03	0.03	0.48	0.48	2.30	NS	
SO4	**ppm**	1	1	20	20	2	100	
Fe	**ppm**	0.879	0.09	0.543	0.542	0.4	0.01	
Mn	**ppm**	0.031	BDL	0.1	0.162	BDL	0.2	2.00
Cu	**ppm**	0.082	0.103	0.17	0.218	0.08	1.5	0.07
Ni	**ppm**	0.335	0.716	1.062	1.21	0.172	0.02	
Co	**ppm**	0.512	1.352	2.061	2.478	0.03	0.001	0.05
Cr	**ppm**	0.714	0.342	0.149	0.177	0.993	0.05	0.00
Cd	**ppm**	0.005	0.006	0.006	0.015	0.004	0.003	0.01
Pb	**ppm**	0.065	0.472	0.01	0.012	BDL	0.01	

Laboratory results (IITA)

Field ID	Unit	FS-A1	FS-A2	FS-A3	FAS-A2	FAS-A4	FAS-A5	NSDWQ	WHO
Ca	ppm	9.28	8.16	13.19	12.63	7.61	3.7	75	
Mg	ppm	1.43	1.28	4.61	3.9	1.8	0.6	20	
Na	ppm	19.13	12.79	20.33	15.55	20.73	29.64	200	NA
K	ppm	8.05	4.11	5.69	2.93	2.53	4.5		
HCO3	ppm	106.75	122	106.75	106.75	38.13	22.88	250	NS
Cl	ppm	19.99	21.99	33.99	32.49	31.19	24.99	NS	50.00
SO4	ppm	4.29	4.186	4.398	4.344	4.058	4.023	50	1.50
NO3	ppm	1.15	0.23	0.38	0.14	2.62	4.56	1.5	NS
F	ppm	1.21	NA	1.24	1.58	0.83	0.83	NS	
PO4	ppm	ND	NA	ND	ND	ND	ND	100	
Fe	ppm	0.05	0.07	0.04	0.12	0.05	0.03	0.01	
Mn	ppm	0.08	0.04	0.06	0.08	0.04	0.06	0.2	2.00
Cu	ppm	0.04	0.06	0.04	0.08	0.06	0.08	1.5	0.07
Ni	ppm	0.02	0.05	0.05	0.02	0.02	0.08	0.02	
Co	ppm	0.02	0.01	0.03	0.02	0.02	0.02	0.001	0.05
Cr	ppm	0.07	0.22	0.07	0.07	0.15	0.07	0.05	0.00
Cd	ppm	0.02	0.02	0.03	0.03	0.05	0.04	0.003	0.01
Pb	ppm	0.09	0.09	0.09	0.17	0.09	0.09	0.01	
Zn	ppm	0.01	0.02	0.01	0.01	0.02	0.01	3	
Se	ppm	0.08	0.06	0.04	0.06	0.04	0.04	NS	

Passive samples from Hand-pump (IITA)

Field ID	Unit	FPS-A4	FPS-A5	UPS-A1	UPS-A2	UPS-A3	UPS-A4	UPS-A5	NSDWQ	WHO
Ca	ppm	10.4	11.51	7.61	8.72	15.42	8.72	11.51	75	
Mg	ppm	1.83	1.35	1.46	1.28	4.57	0.85	1.46	20	
Na	ppm	22.74	39.15	25.98	16.74	19.93	23.95	35.41	200	NA
K	ppm	6.47	3.72	4.11	4.9	5.69	5.29	4.9		
HCO3	ppm	53.38	38.13	137.25	167.72	106.75	35.45	38.13	250	NS
Cl	ppm	26.99	23.99	21.36	36.51	25.89	35.53	21.79	NS	50.00
SO4	ppm	4.254	3.986	4.479	4.222	4.308	4.401	4.019	50	1.50
NO3	ppm	0.63	3.52	0.8	0.34	0.23	0.49	3.44	1.5	NS
F	**ppm**	BDL	BDL	1.5	1.4	1.43	0.14	0.81	NS	
PO4	ppm	ND	ND	ND	ND	ND	1.69	ND	100	
Fe	ppm	0.04	0.07	0.05	0.04	0.03	0.04	0.04	0.01	
Mn	ppm	0.08	0.08	0.08	0.06	0.08	0.08	0.06	0.2	2.00
Cu	ppm	0.14	0.04	0.08	0.04	0.06	0.06	0.04	1.5	0.07
Ni	ppm	0.05	0.08	0.05	0.08	0.08	0.05	0.11	0.02	
Co	ppm	0.01	0.01	0.02	0.01	0.03	0.04	0.02	0.001	0.05
Cr	ppm	0.22	0.3	0.22	0.3	0.22	0.15	0.15	0.05	0.00
Cd	ppm	0.03	0.02	0.04	0.02	0.02	0.04	0.02	0.003	0.01
Pb	ppm	0.09	0.09	0.25	0.17	0.17	0.09	0.09	0.01	
Zn	ppm	0.01	0.15	0.01	0.01	0.02	0.01	0.13	3	
Se	ppm	0.06	0.1	0.1	0.06	0.08	0.14	0.12	NS	

Hand-dug wells (IITA)

Field ID	Unit	HDW-A1	HDW-A2	HDW-A3	HDW-A4	HDW-A5	HDW-A6	HDW-A7	NSDWQ	WHO
Ca	ppm	17.1	4.82	15.98	5.93	31.08	68.71	6.49	75	
Mg	ppm	0.95	1.5	9.16	5.59	11.32	73.17	0.74	20	
Na	ppm	23.15	19.13	39.15	24.36	23.15	23.95	20.33	200	NA
K	ppm	6.87	6.08	5.29	3.72	19.88	7.26	2.14		
HCO3	ppm	38.13	22.88	39.12	38.13	89.5	91.52	22.88	250	NS
Cl	ppm	23.99	25.99	27.99	26.79	38.99	20.99	21.99	NS	50.00
SO4	ppm	4.052	4.059	4.084	4.151	4.04	5.707	4.004	50	1.50
NO3	ppm	3.98	5.74	2.6	11.16	4.6	2.17	3.58	1.5	NS
F	**ppm**	0.94	0.14	0.6	0.95	1.95	1.65	0.98	NS	
PO4	ppm	0.14	ND	ND	ND	1.6	ND	0.12	100	
Fe	ppm	0.03	0.07	0.05	0.08	0.04	0.1	0.11	0.01	
Mn	ppm	0.06	0.08	0.06	0.08	0.18	0.1	0.1	0.2	2.00
Cu	ppm	0.06	0.04	0.06	0.08	0.06	0.12	0.08	1.5	0.07
Ni	ppm	0.08	0.11	0.08	0.05	0.08	0.05	0.02	0.02	
Co	ppm	0.02	0.02	0.03	0.02	0.02	0.03	0.02	0.001	0.05
Cr	ppm	0.15	0.22	0.07	0.15	0.22	0.15	0.15	0.05	0.00
Cd	ppm	0.02	0.03	0.02	0.03	0.02	0.02	0.02	0.003	0.01
Pb	ppm	0.25	0.09	0.25	0.09	0.17	0.17	0.17	0.01	
Zn	ppm	0.01	0.02	0.01	0.01	0.02	0.01	0.02	3	
Se	ppm	0.04	0.06	0.06	0.04	0.1	0.14	0.08	NS	

Rivers Samples (Surface water) (IITA)

Field ID	Unit	RW-A1	RW-A2	RW-A3	RW-A4	RW-A5	RW-A6	NSDWQ	WHO
Ca	ppm	18.22	12.63	12.07	36.12	29.4	36.12	75	
Mg	ppm	2.28	2.43	1.8	3.74	2.66	3.74	20	
Na	ppm	15.95	17.14	16.74	29.23	32.1	28.83	200	NA
K	ppm	6.87	6.47	2.93	6.87	6.08	5.69	NS	
HCO3	ppm	38.13	38.25	22.88	38.13	37.15	38.12	250	NS
Cl	ppm	21.59	29.59	26.32	24.62	28.75	22.21	NS	50.00
SO4	ppm	4.012	4.132	4.229	4.084	4.097	4.174	50	1.50
NO3	ppm	0.65	1.91	0.45	1.21	1.03	0.83	1.5	NS
F	**ppm**	0.03	0.10	0.44	0.28	0.11	0.22	NS	
PO4	ppm	ND	ND	ND	ND	ND	0.12	100	
Fe	ppm	0.05	0.45	0.11	0.05	0.03	0.07	0.01	
Mn	ppm	0.04	0.04	0.06	0.04	0.06	0.04	0.2	2.00
Cu	ppm	0.08	0.04	0.1	0.06	0.08	0.06	1.5	0.07
Ni	ppm	0.05	0.11	0.08	0.02	0.05	0.05	0.02	
Co	ppm	0.01	0.01	0.02	0.01	0.02	0.02	0.001	0.05
Cr	ppm	0.07	0.3	0.15	0.22	0.15	0.15	0.05	0.00
Cd	ppm	0.03	0.02	0.04	0.02	0.03	0.02	0.003	0.01
Pb	ppm	0.17	0.09	0.09	0.17	0.17	0.17	0.01	
Zn	ppm	0.01	0.01	0.01	0.01	0.01	0.01	3	
Se	ppm	0.06	0.04	0.08	0.06	0.1	0.12	NS	

Control Samples (IITA)

Field ID	Unit	EBH-A1	EBH-A2	EBH-A3	EBH-A4	CHDW-A1	NSDWQ	WHO
Ca	ppm	5.93	7.05	3.14	3.7	11.51	75	
Mg	ppm	0.85	0.88	0.45	0.42	4.14	20	
Na	ppm	32.93	33.75	17.54	21.13	16.74	200	NA
K	ppm	4.5	5.29	6.08	4.9	12.39		
HCO3	ppm	22.13	21.88	190.63	194.62	53.38	250	NS
Cl	ppm	19.99	21.99	62.28	64.98	36.59	NS	50.00
SO4	ppm	4.023	4.037	3.96	3.953	4.217	50	1.50
NO3	ppm	8.38	8.27	0.34	0.39	9.52	1.5	NS
F	**ppm**	BDL	BDL	1.39	1.39	0.84	NS	
PO4	ppm	0.1	0.11	0.13	0.17	0.3	100	
Fe	ppm	0.08	0.07	0.04	0.04	0.03	0.01	
Mn	ppm	0.18	0.16	0.06	0.06	0.08	0.2	2.00
Cu	ppm	0.06	0.14	0.08	0.04	0.06	1.5	0.07
Ni	ppm	0.08	0.08	0.05	0.08	0.11	0.02	
Co	ppm	0.03	0.04	0.09	0.02	0.02	0.001	0.05
Cr	ppm	0.15	0.22	0.15	0.22	0.15	0.05	0.00
Cd	ppm	0.04	0.02	0.04	0.03	0.03	0.003	0.01
Pb	ppm	0.09	0.09	0.17	0.25	0.09	0.01	
Zn	ppm	0.04	0.01	0.01	0.02	0.01	3	
Se	ppm	0.1	0.08	0.1	0.1	0.14	NS	

Active samples from the hand pump wells (BGS)

Sample Code	Unit	FS 1	FS 2	FAS 2	FS 3	FAS 4	FAS 5	NSDWQ	WHO
Ca	ppm	5.4	5.5	9.7	12.2	5.4	0.8	75	
Mg	ppm	1.54	1.27	4.37	4.98	1.9	0.51	20	
Na	ppm	307	387	264	263	45.6	21.7	200	NA
K	ppm	1.83	1.42	1.86	2.15	0.68	0.27	NS	
TA (HCO3)	ppm	699.2	940.8	594	611.7	103.4	28.96	250	NS
Cl-	ppm	4.17	44.30783	14.7668	17.1299	11.84404	10.5456	NS	50.00
SO42-	ppm	133.5899	58.21021	133.073	132.213	20.1357	2.7729	50	1.50
NO3-	ppm	1.595504	0.6	0.3	0.3	6.929706	16.6274	1.5	NS
Mn	ppm	0.0152	0.0526	0.0476	0.0563	0.061	0.0194	0.2	
Fe	ppm	0.0025	0.01	0.0113	0.0011	0.0705	0.0356	0.01	
Cu	ppm	0.00161	0.02913	0.00409	0.00098	0.00294	0.0072	1.5	
Zn	ppm	0.0078	0.0166	0.1148	0.0412	0.0819	0.0933	3	2.00
Pb	ppm	0.00031	0.00034	0.00173	0.00195	0.00141	0.00035	0.01	0.07
Cd	ppm	0.000006	0.000006	6E-06	6E-06	0.000013	1.3E-05	0.003	
Cr	ppm	0.0009	0.0009	0.0013	0.0012	0.0009	0.0012	0.05	0.05
Co	ppm	0.000016	0.000022	4.6E-05	0.0001	0.000995	0.0006	0.001	0.00
Ni	ppm	0.0005	0.00139	0.00242	0.0031	0.00492	0.0007	0.02	0.01

Passive samples from the hand pump wells (BGS)

Sample Code	Unit	FPS 4	FPS 5	UPS 1	UPS 2	UPS 3	UPS 4	UPS 5	NSDWQ	WHO
Ca	ppm	9	8.2	5.5	6	12	5.7	8.1	75	
Mg	ppm	2.52	1.37	1.51	1.31	4.89	1.21	1.38	20	
Na	ppm	154	29.8	307	387	262	178	29.9	200	NA
K	ppm	2.06	0.38	1.81	1.54	2.08	1.9	0.38	NS	
TA (HCO3)	ppm	349.7	82.68	698.5	938.7	608.5	363.8	76.09	250	NS
Cl-	ppm	22.99	11.10	3.95	44.07	17.11	21.43	11.17	NS	50.00
SO42-	ppm	89.78712	5.283155	133.16	61.33	132.1735	98.54	5.31	50	1.50
NO3-	ppm	0.35	9.94	0.70	0.6	0.3	0.18	9.94	1.5	NS
Mn	ppm	0.0116	0.033	0.0007	0.0276	0.0455	0.0332	0.0328	0.2	
Fe	ppm	0.1667	0.0291	0.0047	0.0019	0.0026	0.468	0.0256	0.01	
Cu	ppm	0.02418	0.03103	0.00098	0.00409	0.00442	0.03291	0.03263	1.5	
Zn	ppm	0.0129	0.6265	0.0037	0.0281	0.101	0.021	0.6093	3	2.00
Pb	ppm	0.00415	0.00505	0.00008	0.00017	0.00226	0.01046	0.00501	0.01	0.07
Cd	ppm	0.000006	0.000089	6E-06	6E-06	0.00001	2.4E-05	0.000048	0.003	
Cr	ppm	0.0022	0.0019	0.0048	0.0009	0.001	0.007	0.0018	0.05	0.05
Co	ppm	0.000142	0.001037	6E-06	1.6E-05	0.000027	0.00033	0.001065	0.001	0.00
Ni	ppm	0.00111	0.00364	0.00028	0.0012	0.00298	0.00109	0.00389	0.02	0.01

Hand-dug well samples (BGS)

Sample Code	Unit	HDW1	HDW2	HDW3	HDW4	HDW5	HDW6	HDW7	NSDWQ	WHO
Ca	ppm	16.9	4	13.5	4.8	30.2	68	2.4	75	
Mg	ppm	0.72	1.58	9.44	5.75	11.58	66.49	0.79	20	
Na	ppm	14.5	11.5	30.2	113	63.8	361	12	200	NA
K	ppm	12.76	0.78	5.16	5.14	31.35	4.74	0.46	NS	
TA (HCO3)	ppm	86.45	<5	77.6	170.9	376.6	478.8	<5	250	NS
Cl-	ppm	8.82	12.68	32.95	41.74	63.59	3.12	14.65	NS	50.00
SO42-	ppm	6.00	1.79	32.68	73.14	3.79	853.45	1.33	50	1.50
NO3-	ppm	13.43	19.85	7.59	38.92	8.45	4.18	11.39	1.5	NS
Mn	ppm	0.00	0.03	0.01		0.13	0.00	0.02	0.2	
Fe	ppm	0.0009	0.0067	0.0351	0.0009	0.0777	0.0008	0.021	0.01	
Cu	ppm	0.00118	0.00212	0.00158	0.00117	0.00245	0.00042	0.00076	1.5	
Zn	ppm	0.0072	0.0222	0.005	0.002	0.0123	0.0031	0.0078	3	2.00
Pb	ppm	0.00005	0.00019	0.00007	0.00002	0.00008	0.00003	0.0001	0.01	0.07
Cd	ppm	0.000006	0.000018	8E-06	6E-06	0.000008	6E-06	0.000006	0.003	
Cr	ppm	0.0413	0.0009	0.0013	0.0009	0.0084	0.0009	0.0009	0.05	0.05
Co	ppm	0.000966	0.003219	0.00029	0.00027	0.005057	6.5E-05	0.001858	0.001	0.00
Ni	ppm	0.00091	0.00275	0.00174	0.00209	0.01494	0.00062	0.0011	0.02	0.01

Surface water samples from the rivers (BGS)

Sample Code	Unit	RW1	RW2	RW3	RW4	RW5	RW6	NSDWQ	WHO
Ca	ppm	14.3	10.9	11.4	32.7	26.6	32	75	
Mg	ppm	2.57	2.79	1.94	4.3	2.88	4.14	20	
Na	ppm	9	9.4	9.1	20.9	22.1	20.2	200	NA
K	ppm	4.38	6.75	2.17	8.33	5.82	8.63	NS	
TA (HCO3)	ppm	73.4	76.48	45.28	158.6	118.9	143.6	250	NS
Cl-	ppm	10.007	6.831	11.535	22.758	23.620	21.966	NS	50.00
SO42-	ppm	2.445	2.076	9.258	11.938	13.167	18.205	50	1.50
NO3-	ppm	0.049359	0.03936	0.04583	0.03188	1.374295	0.08903988	1.5	NS
Mn	ppm	0.0013	0.002	0.0051	0.0003	0.0002	0.0002	0.2	
Fe	ppm	0.002	0.7311	0.1789	0.0261	0.0151	0.006	0.01	
Cu	ppm	0.0004	0.00069	0.00075	0.00045	0.00092	0.00075	1.5	
Zn	ppm	0.0008	0.0008	0.0008	0.0005	0.0008	0.001	3	2.00
Pb	ppm	0.00002	0.00006	0.00005	0.00002	0.00002	0.00002	0.01	0.07
Cd	ppm	0.000006	0.000006	6E-06	6E-06	0.000006	0.000006	0.003	
Cr	ppm	0.0009	0.0009	0.0009	0.0011	0.0009	0.0009	0.05	0.05
Co	ppm	0.000175	0.000234	6.2E-05	0.0002	0.00011	0.000181	0.001	0.00
Ni	ppm	0.00046	0.00073	0.00034	0.00087	0.00081	0.00119	0.02	0.01

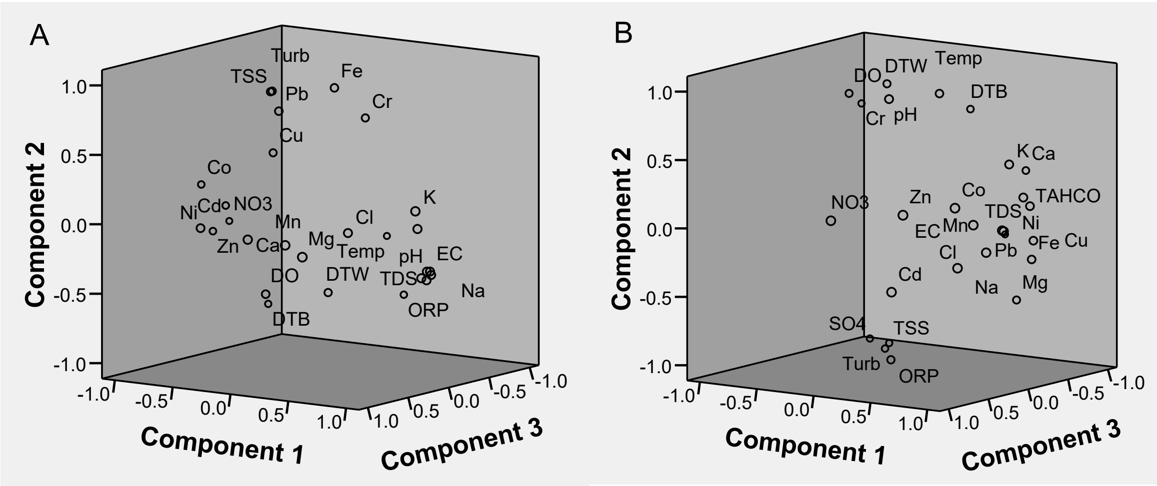
Control water samples from motorized boreholes and a hand-dug well (BGS)

Sample Code	Unit	EBH1	EBH2	EBH3	EBH4	CHDW1	NSDWQ	WHO
Ca	ppm	2.9	2.9	1.6	1.8	7.5	75	
Mg	ppm	0.92	0.91	0.43	0.43	4.52	20	
Na	ppm	23.4	23.2	496	499	58.4	200	NA
K	ppm	2.37	2.35	1.57	1.62	17.41	NS	
TA (HCO3)	ppm	<5	<5	1127	1120	185.4	250	NS
Cl-	ppm	31.939	32.533	151.686	156.480	74.474	NS	50.00
SO42-	ppm	4.68456	4.69828	2.50000	2.50000	8.84759	50	1.50
NO3-	ppm	30.32310	30.81824	1.50000	1.50000	33.46488	1.5	NS
Mn	ppm	0.23080	0.23000	0.00060	0.00190	0.12890	0.2	
Fe	ppm	0.01790	0.01810	0.00170	0.00190	0.03000	0.01	
Cu	ppm	0.00459	0.00451	0.00017	0.00016	0.00163	1.5	
Zn	ppm	0.02730	0.02640	0.00060	0.00060	0.01970	3	2.00
Pb	ppm	0.00264	0.00273	0.00004	0.00006	0.00002	0.01	0.07
Cd	ppm	0.00035	0.00036	0.00001	0.00001	0.00001	0.003	
Cr	ppm	0.00200	0.00190	0.00090	0.00090	0.00090	0.05	0.05
Co	ppm	0.00484	0.00480	0.00002	0.00001	0.00571	0.001	0.00
Ni	ppm	0.00466	0.00464	0.00003	0.00010	0.00502	0.02	0.01

Appendix 2

The principal component analysis (PCA) data are presented in table 5 and 6 below. BGS laboratory results were used for this analysis. Results from Hand pump wells were treated separately from the hand-dug wells to see the possible influence of the installation materials on the water quality. Three-component factors were extracted in both cases (Table 6). For the groundwater sources, the first three components of PCA explain 74% of the total variance (Table 5 and Figure 8). PC1 can explain 40.4% of the total variance and shows maximum loadings on pH, ORP, EC, TDS, Na, K. Alk HCO_3 and SO_4, PC2 explains the total variance of 18.9%, and it has maximum loadings on Turb, Fe, TSS, Pb, K and Cr. PC3 has a variance of 14.67% with maximum loading on DO, Ca, Mg, Mn and Ni. The contribution of ions and metals in components 1 and 3 suggest geogenic origins (i.e. from the rocks that constitute the aquifer or the soils and sediments in the surrounding areas), while component 2 suggests an anthropogenic origin for the Pb, Fe and Cr in the hand pump wells.

For the hand-dug wells, the total variance of 100% is explained by PC1 with a maximum loading of EC, TDS, Ca, K, and HCO_3. Cl, Mn, Fe, Cu Zn and Ni with a variance of 44.5% PC2 has a maximum loading of ORP, Turbidity, TSS, Mg, SO_4 and Cd with 34.6% variance. Finally, 20.919 % variance in PC3 with a maximum loading of well depth, Ca, Mg, Fe and Pb. In this case, PC1 and PC2 suggest geogenic influence from weathering and leaching, while PC3 may be due to the anthropogenic sources.



Component Plot in Rotated Space for Hand Pump wells (A) and Hand dug wells (B) using BGS data.

Results from the component matrix analysis for Handpump and Hand-dug wells

Parameters	**Handpump Wells Component**			**Hand-dug Wells Component**		
	1	**2**	**3**	**1**	**2**	**3**
Depth to groundwater	0.268	-0.446	0.123	0.042	**-0.999**	0.014
Well depth	-0.257	**-0.855**	-0.017	0.23	**-0.737**	**0.636**
DO	0.004	-0.446	**0.534**	-0.174	**-0.971**	-0.166
Temp	0.151	-0.344	**-0.747**	0.494	**-0.867**	0.07
pH	**0.953**	0.043	0.031	0.361	**-0.876**	-0.318
ORP	**0.515**	**-0.57**	**-0.523**	-0.116	**0.972**	-0.204
EC	**0.972**	0.048	0.021	**0.981**	0.193	0.014
TDS	**0.956**	0.009	0.092	**0.983**	0.185	-0.002
Turb	**-0.665**	**0.684**	-0.095	-0.469	**0.875**	0.117
TSS	**-0.675**	**0.676**	-0.089	**-0.506**	**0.838**	0.206
Ca	0.209	0.159	**0.797**	0.497	-0.24	**0.834**
Mg	0.362	0.135	**0.79**	0.484	**0.677**	**0.554**
Na	**0.965**	0.001	-0.021	**0.933**	0.327	-0.149
K	**0.804**	**0.504**	0.129	**0.933**	-0.283	0.222
T. Alk (HCO_3)	**0.955**	-0.039	0.008	**0.956**	-0.033	0.293
Cl	0.37	0.14	0.228	**0.836**	0.409	-0.365
SO_4	**0.803**	0.323	0.037	**-0.608**	**0.784**	0.121
NO_3	**-0.797**	-0.49	-0.164	0.235	-0.063	**-0.97**
Mn	-0.1	0.048	**0.789**	**0.957**	0.12	-0.263
Fe	-0.249	**0.879**	-0.215	**0.791**	0.411	**0.454**
Cu	**-0.5**	0.282	-0.015	**0.857**	0.281	0.431
Zn	**-0.706**	-0.396	0.205	**0.705**	-0.022	**-0.708**
Pb	**-0.486**	**0.667**	0.07	0.053	0.183	**0.982**
Cd	**-0.709**	-0.221	0.102	0.482	**0.51**	**-0.713**
Cr	**-0.071**	**0.639**	-0.437	-0.404	**-0.896**	0.183
Co	**-0.945**	-0.167	0.094	**0.922**	-0.019	-0.388
Ni	**-0.529**	-0.097	**0.721**	**0.924**	0.033	0.381
% Variance	40.4	18.9	14.7	44.5	34.6	20.9
Cumulative %	40.4	59.3	74	44.5	79.1	100

Loading Parameters for Hand pump and Hand-dug wells

	Hand pump Wells		Hand-dug Wells	
Component	**Loading Parameters**	**% Variance**	**Loading Parameters**	**% Variance**
C1	pH, ORP, EC, TDS, Na, K. Alk HCO_3 and SO_4,	40.4	EC, TDS, Ca, K, HCO_3. Cl, Mn, Fe, Cu Zn and Ni	44.5
C2	Turb, Fe, TSS, Pb, K and Cr	18.9	ORP, Turb, TSS, Mg, SO_4 and Cd	34.6
C3	DO, Ca, Mg, Mn and Ni	14.7	DTB, Ca, Mg, Fe and Pb	20.9