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# Management Of Environmental Hazards On Water Potability Due To Climate Change, Dumpsites and Rooftops In Basement Complex Region of Oluyole LGA, Ibadan, Oyo State, Nigeria

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## ABSTRACT

Water is life, but ensuring water potability in basement complex locations is a considerable problem due to the inadequate primary porosity of crystalline bedrock, rendering local hydrogeological networks very susceptible to near-surface contamination. Previous work have considered the quality of ground water as a result of intrusion in the unconsolidated sedimentary basin from boreholes through analysis for some natural physicochemical parameters such as Ca, Mg, Fe, Zn, Cu, Mn, Al, Cl, pH, Electrical conductivity and Total dissolved solids. However the aggregate environmental risks to water quality in basement regions due to climate change had been neglected, hence this research was therefore designed to study the risks posed by climate change, municipal dumpsites and rooftop runoff within a typical basement complex setting as well as its management. Thus, an integrated framework was implemented, employing twenty one (21) physicochemical parameters and heavy metal analysis from eighteen (18) water samples from well, borehole and stream. The sampled hand-dug wells were limited to a shallow average depth of 6 meters, intersecting the upper unconfined saprolite zone where leachate migration is concentrated. Sampling was systematically allocated across key risk zones, including dumpsite, mechanic workshop, residential area and industrial area, with two (2) sample locations,10km away from the surveyed area chosen as controls to establish background baseline conditions. To address these multi-variant datasets, a custom Python framework was developed to split the datasets by land use zones, delineate pollutant concentrations by these zones and calculate comprehensive Water Quality Indices (WQI). Laboratory results indicated that downstream of the dumpsite (DSW 1) high levels of Electrical Conductivity 1935μS/cm were recorded and the highest level of Total Dissolved Solids (TDS) 1384mg/L was recorded. The surface streams in the vicinity were found to have high organic loading, with a significant rise in the level of Biochemical Oxygen Demand (BOD) to 81.2mg/L. Moreover, critical heavy metal hazards exceeding the WHO standards were found at the mechanic workshop with concentration of Lead (Pb) as 0.08mg/L and 1.24mg/L respectively due to improper disposal of automotive wastes. High values of Extreme Bicarbonate mg/L up to 2440mg/L suggest that the crystalline aquifer is experiencing high levels of microbial bio-degradation of organic matter. The study outcome revealed high levels of heavy chemicals and metal toxicity in sources of water in the basement complex region. Therefore, it is recommended to re-design localized well for water supply as deep boreholes.

**Keywords:** Water potability, WHO standards, Shallow aquifers, Physicochemical parameters, Basement.

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## 1. INTRODUCTION

Even as water is life, the access to safe potable water is yet to be achieved in many parts of sub-Saharan Africa, as a large proportion of the population had been using shallow groundwater for their household water requirements [1]. In Basement Complex terrains, the limited Primary Porosity of crystalline bedrock results in limited groundwater storage zones and restricted groundwater flow to weathered regolith and isolated fracture networks, making near surface hydrogeological systems particularly vulnerable to contamination [2, 3]. Pollution levels in surface water in these environments can rapidly lead to major contamination of the groundwater, because most hand dug wells rely on the shallow saprolite which is composed of clay and is less resistant to infiltrating contaminants [4]. This increasing dependence on shallow groundwater with unpredictable quality has been a problem for successive governments in Nigeria to maintain functional pipe-borne water networks in rapidly growing cities and towns [5].

Climate change contributes to this vulnerability by way of several interrelated processes, such as pollution [6, 7]. Changes in the intensity of rainfall and seasonality affect the amount and timing of recharge available to flush or dilute near-surface contaminants and increased intensity and sporadic rainfall increases the volume and speed of surface runoff that can carry pollutants from rooftops, mechanical workshops and dumpsites to shallow aquifers in a reduced infiltration period [8, 9]. Rooftop runoff is often thought to be an innocuous water source but it is a common overlooked hazard pathway, as rainwater soaks up the atmospheric deposition and corrosion products from the deteriorating roofing materials such as corrugated iron, asbestos cement or zinc. This runoff is then infiltrated unmanaged around buildings which provides an extra source of physicochemical and trace-metal loading to the shallow regolith aquifer that is typically not included in standard pollution survey analyses.

Global solid waste generation is expected to increase from around 2.01 billion tonnes per year in 2016 to 3.40 billion tonnes per year in 2050 and its rate of growth is fastest in Low-and Middle-income countries (LMICs) [10]. Many cities in Nigeria have unengineered, unlined dumpsites without equipment for collecting leachates and monitoring ground water at their sites [11, 12]. The Oluyole Local Government Area of Ibadan has the example of Arapaja Dumpsite which is a practice of unregulated waste disposal. The collected waste will release the leachate, chemically aggressive liquid containing a considerable amount of dissolved organic carbon, ammonium nitrogen and heavy metals, such as lead (Pb), cadmium (Cd), or iron (Fe) [13]. The leachate is moving downward by gravity and hydraulic gradient and flows through the unsaturated zone and ultimately into the saturated zone. This is compounded by a clustering of car repair shops along the Akala Express road in the Oluyole area, which increases the heavy-metal pollution from waste lubricants, battery acid and metal scrap, which is a localised source [14, 15].

The sub-surface geology of the research area is part of the Precambrian Basement Complex in the south-western part of Nigeria which is composed of migmatites, gneisses, schists and granitoid intrusives covering a large part of Oyo State and the Ibadan Metropolitan Area [2]. Groundwater generally occurs in this area as a result of secondary porosity, from the weathered regolith (saprolite) and the fractured basement layer at depth. Most hand dug wells in the superficial regolith, which is typically 10 to 40 metres deep, are located in a fine-grained, clayey matrix with a shallow water table and hence is prone to contamination from surface sources [4, 16].

Previous research on groundwater quality in basement terrains has mostly been done on the pollution caused by intrusion in unconsolidated sedimentary basins and has involved the use of physicochemical variables such as calcium, magnesium, iron, zinc, copper, manganese, aluminium, chloride, pH, electrical conductivity and total dissolved solids [17]. In Ibadan Basement Complex specifically, previous hydrochemical surveys have reported high levels of heavy metals and ionic concentrations in the groundwater in the vicinity of uncontrolled dump sites and the water facies types found in these areas were identified as sodium-chloride and mixed cation-chloride where ion exchange processes associated with leachate infiltration have been reported [16, 18]. In such areas of hydrogeochemical impact, the evolution of groundwater chemistry is more generally controlled by mineral dissolution/precipitation, ion exchange on the surface of clays, redox reactions and bacterial degradation of organic matter [19, 20].

However, the overall impact on water quality caused by climate change-induced effects on hydrology, municipal waste sites and impervious surfaces on roof and hard surfaces has received very little attention. The survey locations were systematically scattered in the main risk zones noted in the Oluyole axis namely, close to Arapaja dumpsite, around Akala Express mechanic workshop, residential areas and Oluyole industrial estate. Other control sites were set up about 10 km away from the surveyed area to provide a baseline reference of conditions that are not influenced by these point sources. Therefore, the objective of this work was to evaluate the synergistic effects of climate change, municipal dumpsites and rooftop runoff on the potability of ground water in a typical Basement Complex environment and suggest appropriate management interventions to mitigate the hazards. The field and laboratory procedures aimed to collect the groundwater pollution pathway in basement terrains and included in-source characterisation, sampling and data interpretation.

## 2. METHODOLOGY

### 2.1 Description of the Study Area

The study was conducted on the Oluyole Local Government Area (LGA) of Ibadan, Oyo State, Southwestern Nigeria lying on the Precambrian Basement Complex. The landscape features the Arapaja dumpsite, a series of automotive repair workshops down the Akala Express road, the Oluyole Industrial Estate and adjoining residential areas laid on top of the worn regolith of various thicknesses over fractured crystalline bedrock.

### 2.2 Reconnaissance Survey and Selection of Sampling Points

The reconnaissance survey and selection of sampling points are now underway.Reconnaissance survey and selection of sampling points are currently in progress.In order to identify and characterise the major risk areas that were relevant to the research objectives of the study, a reconnaissance survey was conducted in the research area, covering the dumpsite, the mechanic workshop, the residential and the industrial area. Pollutant exposure was sampled across these areas in a systematic manner to represent spatial variability. To establish baseline water quality conditions free of influences associated with the known point sources, 2 control sample locations were selected about 10 km from the area being investigated.

### 2.3 Sample Collection

A total of 18 water samples were collected from hand-dug wells, boreholes and streams in the water bodies that fall within the defined danger zones and control sites. The sampled hand-dug wells were restricted to a shallow average depth of 6 m, intersecting the upper unconfined saprolite zone where leachate migration is most prevalent. Samples were obtained in pre-washed plastic bottles adhering to normal groundwater sampling techniques, with the bottles rinsed in the field using the water to be sampled before filling.

### 2.4 Sample Preservation and Transport

Collected samples were labelled, sealed and maintained as necessary for trace-metal and biochemical oxygen demand (BOD) analysis, following standard procedures before being transported to the laboratory. Samples were refrigerated and tested within the prescribed holding period to prevent compositional alteration prior to analysis.

### 2.5 Laboratory Analysis

Twenty-one (21) physicochemical and heavy metal parameters were assessed for each sample, including physical parameters (pH, electrical conductivity, temperature and total dissolved solids); major anions (chloride, nitrate, sulphate, phosphate and bicarbonate); indicators of organic load and hardness (biochemical oxygen demand, total hardness and acidity); major cations (sodium, potassium, calcium and magnesium); and heavy metals (lead, cadmium, zinc, manganese and iron). The pH, electrical conductivity and temperature were measured in situ with a calibrated multi-parameter probe. Total dissolved solids were quantified using gravimetric analysis. Principal anions were quantified using titrimetric and ultraviolet spectrophotometric techniques as suitable for each species. Major cations and trace heavy metals were quantified using Atomic Absorption Spectrophotometry (AAS). The biochemical oxygen demand was assessed using the conventional five-day incubation procedure.

### 2.6 Computation of Water Quality Indices

To determine the dominant geochemical processes controlling contaminant mobility and to quantify overall water quality degradation, a custom Python computational framework was developed to manage and analyse the resulting multi-variant dataset and to compute three composite pollution indices for each of the eighteen sampling locations: the Water Quality Index (WQI), the Heavy Metal Pollution Index (HPI) and the Metal Index (MI). Python-scripted open-source frameworks of this kind have previously been validated for dumpsite impact assessment in data-constrained Nigerian settings, including a finite-difference transport model of chloride plume migration from a dumpsite in Owerri that matched field observations with a calibration error below 10% [21]. The Water Quality Index (WQI) was calculated with the weighted arithmetic mean approach [22]. The unit weight (Wn) allocated to each parameter is inversely proportional to its WHO/NSDWQ standard permissible value (Sn) (Equation 1).

$$\mathrm{Wn} = {}^{\mathrm{k}}/_{\mathrm{Sn}} \qquad (1)$$

K is a proportionality constant calculated to ensure that the total of unit weights for all parameters equals one. The quality rating (Qn) for each parameter is subsequently calculated (Equation 2).

$$\mathrm{Qn} = \left[\left({}^{\mathrm{Vn}\,-\,\mathrm{Vi}}/_{\mathrm{Sn}\,-\,\mathrm{Vi}}\right)\right] \times 10 \qquad (2)$$

Where, Vn represents the observed concentration of a parameter, Vi denotes the ideal value of the parameter in pure water (Vi = 0 for all parameters except pH, for which Vi = 7) and Sn signifies the allowed amount according to WHO/NSDWQ standards. The overall Water Quality Index (WQI) for each sample is derived as the weighted average of the individual quality evaluations (Equation 3).

$$\mathrm{WQI} = \frac{\sum(\mathrm{Wn}\times\mathrm{Qn})}{\sum\mathrm{Wn}} \qquad (3)$$

Nine criteria were utilised in the computation of the Water Quality Index (WQI): pH, total dissolved solids, chloride, sulphate, nitrate, calcium, magnesium, sodium and total hardness, compared to their respective allowed limits established by Word Health organization Guidelines for drinking -water quality,4th Edition incorporating the 1st , 2nd and 3rd addenda (WHO, 2026) [1] and the Nigerian Standard for Drinking Water Quality, NIS 554:2015 (NSDWQ) [23]. Computed Water Quality Index (WQI) values were categorised as excellent (<50), good (50-100), bad (100-200), extremely poor (200-300), or unfit for consumption (>300) [20]. The Heavy Metal Pollution Index (HPI) (Equation 4) compiles the toxicological impact of trace metals, assigning weights to each metal inversely related to its maximum allowable concentration (MAC) [14, 23]

$$\mathrm{HPI} = \frac{\sum_{i=1}^{n}(W_i \times Q_i)}{\sum_{i=1}^{n} W_i} \qquad (4)$$

Where, $\mathrm{Wi} = \frac{1}{\mathrm{MACi}}$ and $\mathrm{Qi} = (\frac{\mathrm{Mi}}{\mathrm{MACi}}) \times 100$

Here, Mi represents the measured concentration of the ith metal. Five metals were incorporated into the HPI calculation: lead, cadmium, zinc, manganese and iron, utilising WHO's maximum permissible amounts of 0.01, 0.003, 3.0, 0.4 and 0.3 mg/L, respectively. An HPI beyond 100 signifies significant groundwater contamination by metallic contaminants, rendering it unfit for human consumption [24, 25]. The Metal Index employs an unweighted arithmetic accumulation of the identical five metals in relation to their MAC values (Equation 5).

$$\mathrm{MI} = \sum(\frac{\mathrm{Ci}}{\mathrm{MACi}}) \qquad (5)$$

Where, Ci denotes the observed concentration of the ith metal. Computed MI values were categorised according to established thresholds as extremely pure (<0.3), pure (0.3-1), slightly affected (1-2), moderately affected (2-4), strongly impacted (4-6), or badly affected (>6) [24].

### 2.7 Contaminant Transport Modelling (ADE and Density-Dependent Flow)

The one-dimensional Advection-Dispersion Equation (ADE) was employed within a Python-based analytical framework to model contaminant transport and simulates long-term plume migration, utilising chloride as a conservative tracer [26] of the leachate plume emanating from the Arapaja dumpsite boundary and progressing toward the down-gradient well DSW1. Equation (6) is the governing ADE

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} - v\frac{\partial C}{\partial x} \qquad (6)$$

Where, C denotes solute concentration (mg/L), t represents time (s), x indicates distance (m), D signifies the hydrodynamic dispersion coefficient ($m^2$/day) and v reflects the average linear (seepage) groundwater velocity (m/day). The seepage velocity (Equation 7) was calculated using Darcy's Law instead of being explicitly assumed.

$$q = K \times i \text{ and } v = q/n \qquad (7)$$

In this context, q denotes the Darcy (specific discharge) velocity (m/s), K represents the hydraulic conductivity of the weathered regolith aquifer (assumed to be $5 \times 10^{-5}$ m/s, the median value for Basement Complex saprolite), i signifies the prevailing hydraulic gradient (assumed to be 0.015, indicative of the shallow water table slope in the Oluyole axis) and n indicates the effective porosity (assumed to be 0.30). The seepage velocity and the longitudinal dispersivity of 5 m were used to calculate the hydrodynamic dispersion coefficient D, consistent with field-scale dispersivities documented for the highly eroded crystalline aquifer.

Given that chloride functions as a conservative (non-sorbing) tracer, the retardation factor (Equation 8) was calculated utilising the conventional equation [27, 28, 29]

$$\mathrm{Rf} = 1 + \frac{(\mathrm{pb} \times \mathrm{kd})}{\mathrm{n}} \qquad (8)$$

Here, ρb denotes the bulk density of the aquifer material and Kd represents the distribution coefficient, which for chloride is about zero, resulting in Rf = 1 (indicating no retardation). The Ogata-Banks solution was employed to analytically solve Equation (6) under a continuous source boundary condition. The chloride concentration at DSW1 (711.0 mg/L) was utilised as the source strength, while the background chloride concentration (35.5 mg/L) at the residential control borehole RSBH1 was used for comparison, in order to estimate the spatial extent of the chloride plume over 1, 2, 5 and 10 years. The fluid density at the leachate-affected site (DSW1) and at the reference location was calculated using the linear equation of state (Equation 9) to evaluate the significance of density-dependent flow in this system [8, 29]

$$\rho = \rho_0 + \left(\frac{\partial \rho}{\partial C}\right) \times C \qquad (9)$$

Here, $\rho_0$denotes the reference freshwater density (1000 kg/m³), C represents the TDS concentration (kg/m³) and $\left(\frac{\partial \rho}{\partial C}\right)$ signifies the density coupling coefficient (0.7 kg/m³ per kg/m³ TDS) [30]. The resultant density contrast was subsequently incorporated into a simplified buoyancy formulation of the variable-density Darcy flux to estimate the supplementary vertical (downward) velocity component due to density-driven descent, for comparison with the horizontal seepage velocity calculated in Equation (7).

### 2.8 Interpretation and Hazard Management Assessment

The calculated indices, simulated plume migration results and measured parameter values were then all looked at, in relation to regulatory standards, to classify each sample point as to the level of contamination, determine the dominant hazard pathway (climate induced recharge variability, dumpsite leachate, mechanic workshop effluent or rooftop runoff) responsible for the observed water quality deterioration of each area and predict the likely future extent of contamination; this served as a basis for the management recommendations outlined in this paper.

## 3. RESULTS

### 3.1 Field and Laboratory Data

The complete physicochemical and heavy metal data from the eighteen sampling sites are shown in Tables 1a, 1b and 1c. Sampling locations comprised two background controls (Control BH1, Control BH2), two residential-zone boreholes and two residential-zone wells (RSBH1, RSBH2, RSW1, RSW2), two industrial-zone boreholes and one industrial-zone well (IBH1, IBH2, IW1), a dumpsite-zone borehole and three dumpsite-zone wells together with the dumpsite stream (DSBH1, DSW1, DSW2, DSW3, Dumpsite Stream) and two mechanic-workshop wells, a mechanic-workshop borehole and the mechanic-workshop stream (MW1, MW2, MBH, Mechanic stream).

The pH values of the eighteen samples ranged from 6.34 (MW1) to 8.60 (DSBH1) with a mean of 7.37, which is indicative of an overall near-neutral to slightly alkaline nature that is .characteristic of carbonate-buffered basement regolith weathering. Electrical conductivity (EC) ranged widely from 178.4 µS/cm (MW1) to 1935 µS/cm (DSW1), with a mean of 687.4 µS/cm, while total dissolved solids (TDS) ranged from 232 mg/L (MW1) to 1384 mg/L (DSW1), with a mean of 498.0 mg/L.

The sharply elevated EC and TDS at DSW1, located immediately downstream of the Arapaja dumpsite, identify this location as the principal point-source of dissolved-ion loading in the dataset. Chloride concentration similarly peaked at DSW1 (711.0 mg/L), well above the WHO/NSDWQ guideline value of 250 mg/L, while the lowest chloride concentration (35.5 mg/L) was recorded at the residential borehole RSBH1. Sulphate concentration was highest at the industrial borehole IBH1 (1098.0 mg/L), exceeding the 250 mg/L guideline value by more than fourfold, consistent with industrial effluent influence in that zone. Bicarbonate ($HCO_3^-$) concentrations were generally elevated across the dataset, reaching an extreme value of 2441 mg/L at the mechanic-workshop well MW1, indicative of intense microbial bio-degradation of organic matter within the shallow saprolite aquifer at that location. The biochemical oxygen demand (BOD) was significantly higher in the surface streams than in the wells and boreholes, indicating an organic pollution loading in the surface streams. A BOD of 81.2 mg/L was recorded in the mechanic-workshop stream while a 67.9 mg/L was recorded in the dumpsite stream, significantly higher than the BOD results for the groundwater samples which is 11.9 mg/L (the mean BOD from all eighteen samples). This suggests that there is direct discharge of organic waste from mechanical servicing and decomposition of dump wastes in these water courses.

Among the heavy metals, lead (Pb) concentration reached a maximum of 0.08 mg/L at the dumpsite stream and zinc (Zn) reached a maximum of 1.41 mg/L at the industrial well (IW1) and 1.24 mg/L at the mechanic-workshop stream, several of which exceed the respective WHO guideline values, consistent with contamination driven by improper disposal of automotive waste, used batteries and lubricants at the mechanic-workshop and dumpsite locations. Cadmium concentrations, although numerically small in absolute terms (mean 0.003 mg/L), exceeded the WHO guideline value of 0.003 mg/L at several locations, including the mechanic-workshop stream (0.009 mg/L) and the mechanic-workshop wells MW1 and MW2 (0.005 and 0.007 mg/L respectively). Manganese and iron concentrations were also elevated at several dumpsite and mechanic-workshop locations relative to the control samples, consistent with redox-driven mobilisation of these metals under the reducing conditions typical of leachate-impacted groundwater.

Table 1a: Physical Parameters and Major Anions of Water Samples from the Oluyole Basement Complex Area

| S/N | Sample Code | pH | EC (μS/cm) | Temp (°C) | TDS (mg/L) | $Cl^-$ (mg/L) | $NO_3^-$-N (mg/L) | $SO_4^{2-}$ (mg/L) | $PO_4^{2-}$ (mg/L) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Control BH1 | 7.82 | 651 | 32.3 | 477 | 71.0 | 25.40 | 390.97 | 75.4 |
| 2 | Control BH2 | 7.90 | 925 | 32.0 | 660 | 106.0 | 26.96 | 923.0 | 46.1 |
| 3 | RSBH1 | 7.41 | 541 | 32.2 | 389 | 35.5 | 27.97 | 247.6 | 46.9 |
| 4 | RSBH2 | 6.90 | 423 | 31.8 | 301 | 142.0 | 27.48 | 149.9 | 46.4 |
| 5 | RSW1 | 6.91 | 734 | 31.8 | 554 | 142 | 29.56 | 260.7 | 25.5 |
| 6 | RSW2 | 6.93 | 694 | 31.7 | 413 | 142 | 23.21 | 342.3 | 32.1 |
| 7 | IBH1 | 7.84 | 1025 | 31.2 | 721 | 106.1 | 25.78 | 1098.0 | 46.5 |
| 8 | IBH2 | 8.28 | 731 | 31.1 | 509 | 177.0 | 24.57 | 505.0 | 32.5 |
| 9 | IW1 | 8.30 | 590 | 31.1 | 406 | 177.8 | 26.38 | 325.8 | 75.4 |
| 10 | DSBH1 | 8.60 | 526 | 31.8 | 380 | 71.5 | 24.79 | 228.2 | 46.4 |
| 11 | DSW1 | 6.61 | 1935 | 31.7 | 1384 | 711.0 | 28.36 | 267.2 | 39.5 |
| 12 | DSW2 | 6.71 | 332 | 31.7 | 238 | 71.0 | 24.60 | 175.95 | 54.5 |

| S/N | Sample Code | pH | EC (µS/cm) | Temp (°C) | TDS (mg/L) | $Cl^-$ (mg/L) | $NO_3^-$-N (mg/L) | $SO_4^{2-}$ (mg/L) | $PO_4^{2-}$ (mg/L) |
|---|---|---|---|---|---|---|---|---|---|
| 13 | DSW3 | 6.74 | 574 | 31.8 | 495 | 142.5 | 25.58 | 172.7 | 39.5 |
| 14 | Dumpsite Stream | 7.60 | 620 | 31.8 | 443 | 143.0 | 21.83 | 146.5 | 46.9 |
| 15 | MW1 | 6.34 | 178.4 | 31.8 | 232 | 143.0 | 23.61 | 153.1 | 46.5 |
| 16 | MW2 | 6.66 | 544 | 31.9 | 391 | 142.0 | 30.36 | 166.3 | 39.7 |
| 17 | MBH | 6.84 | 652 | 31.8 | 470 | 71.0 | 24.39 | 368.9 | 46.4 |
| 18 | Mechanic stream | 8.25 | 698 | 31.6 | 501 | 214.0 | 29.95 | 146.2 | 54.6 |

Table 1b: Hardness, Organic-Load Indicators and Major Cations

| S/N | Sample Code | $HCO_3^-$ (mg/L) | BOD (mg/L) | Hardness (mg/L) | Acidity (mg/L) | Na (mg/L) | K (mg/L) | Ca (mg/L) | Mg (mg/L) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Control BH1 | 245 | 3.1 | 6.95 | 200 | 18.1 | 7.0 | 1.15 | 6.17 |
| 2 | Control BH2 | 366 | 1.3 | 7.42 | 200 | 47.7 | 7.3 | 3.46 | 5.36 |
| 3 | RSBH1 | 366 | 2.4 | 4.34 | 52 | 37.2 | 6.1 | 1.72 | 5.45 |
| 4 | RSBH2 | 1220 | 5.2 | 2.29 | 151 | 33.6 | 5.7 | 0.11 | 4.58 |
| 5 | RSW1 | 611 | 5.6 | 3.96 | 200 | 84.1 | 3.5 | 1.96 | 7.19 |
| 6 | RSW2 | 183 | 6.4 | 3.52 | 151 | 70.1 | 5.8 | 0.46 | 4.60 |
| 7 | IBH1 | 488 | 7.9 | 8.61 | 251 | 41.4 | 7.2 | 5.00 | 6.19 |
| 8 | IBH2 | 366 | 3.6 | 7.09 | 252 | 27.7 | 4.4 | 4.28 | 5.71 |
| 9 | IW1 | 184 | 2.4 | 4.49 | 201 | 32.7 | 3.4 | 2.08 | 5.43 |
| 10 | DSBH1 | 427 | 6.5 | 4.45 | 200 | 35.0 | 5.6 | 1.98 | 4.26 |
| 11 | DSW1 | 488 | 3.7 | 16.01 | 302 | 94.9 | 2.6 | 3.16 | 6.82 |
| 12 | DSW2 | 245 | 8.05 | 2.35 | 250 | 14.65 | 2.6 | 0.41 | 5.78 |
| 13 | DSW3 | 183 | 2.75 | 3.97 | 250 | 35.45 | 3.95 | 1.385 | 7.135 |
| 14 | Dumpsite Stream | 793 | 67.9 | 4.77 | 150 | 35.4 | 29.2 | 1.12 | 8.19 |
| 15 | MW1 | 2441 | 1.5 | 1.47 | 200 | 25.5 | 10.4 | 0.04 | 6.60 |
| 16 | MW2 | 1220 | 2.4 | 2.53 | 150 | 49.5 | 13.5 | 0.63 | 6.80 |
| 17 | MBH | 488 | 1.5 | 20.01 | 150 | 35.8 | 14.4 | 1.81 | 6.26 |
| 18 | Mechanic stream | 428 | 81.2 | 4.42 | 251 | 66.8 | 25.8 | 1.63 | 3.70 |

Table 1c: Heavy Metal Concentrations

| S/N | Sample Code | Pb (mg/L) | Cd (mg/L) | Zn (mg/L) | Mn (mg/L) | Fe (mg/L) |
|---|---|---|---|---|---|---|
| 1 | Control BH1 | 0.02 | 0.001 | 0.39 | 0.02 | 0.18 |
| 2 | Control BH2 | 0.00 | 0.002 | 0.84 | 0.41 | 0.80 |
| 3 | RSBH1 | 0.02 | 0.002 | 0.24 | 0.14 | 0.08 |
| 4 | RSBH2 | 0.02 | 0.002 | 0.13 | 0.09 | 0.60 |
| 5 | RSW1 | 0.07 | 0.003 | 0.36 | 0.17 | 0.05 |
| 6 | RSW2 | 0.04 | 0.001 | 0.56 | 0.11 | 0.60 |
| 7 | IBH1 | 0.00 | 0.000 | 0.43 | 0.44 | 0.20 |
| 8 | IBH2 | 0.00 | 0.002 | 0.47 | 0.58 | 0.32 |
| 9 | IW1 | 0.00 | 0.002 | 1.41 | 0.44 | 0.81 |
| 10 | DSBH1 | 0.04 | 0.003 | 0.31 | 0.15 | 0.18 |
| 11 | DSW1 | 0.02 | 0.002 | 0.90 | 0.74 | 0.65 |
| 12 | DSW2 | 0.01 | 0.001 | 0.425 | 0.455 | 0.045 |
| 13 | DSW3 | 0.005 | 0.003 | 0.505 | 0.47 | 0.325 |
| 14 | Dumpsite Stream | 0.08 | 0.008 | 0.26 | 0.13 | 0.68 |
| 15 | MW1 | 0.02 | 0.005 | 0.39 | 0.12 | 0.18 |
| 16 | MW2 | 0.03 | 0.007 | 0.49 | 0.15 | 0.28 |
| 17 | MBH | 0.01 | 0.005 | 0.35 | 0.18 | 0.12 |
| 18 | Mechanic stream | 0.07 | 0.009 | 1.24 | 0.34 | 0.90 |

3.2 Comparison with WHO/NSDWQ Guideline Values

Table 2 shows the mean, min and max values of selected parameters obtained from the present study and compared with the guideline values for drinking water recommended by WHO (2026) and NSDWQ (2015). It can be seen from the comparison that, samples taken from the dumpsite and mechanic-workshop zones had higher concentrations of electrical conductivity, total dissolved solids, chloride, sulphate, lead, cadmium and iron than the concentrations prescribed in the standards, while the samples taken from the control zones and some of the samples taken from the residential zone were broadly in compliance with the prescribed standards.

Table 2: Comparison of Mean, Minimum and Maximum Measured Values with WHO/NSDWQ Guideline Values

| Parameter | Mean | Min | Max | WHO/NSDWQ Limit | Locations Exceeding Limit |
|---|---|---|---|---|---|
| pH | 7.37 | 6.34 | 8.60 | 6.5 - 8.5 | MW1 (6.34); DSBH1 (8.60) |
| EC (µS/cm) | 687.4 | 178.4 | 1935 | 1000 | DSW1 (1935) |
| TDS (mg/L) | 498.0 | 232 | 1384 | 500 - 1000 | DSW1 (1384) |
| Chloride (mg/L) | 156.0 | 35.5 | 711.0 | 250 | DSW1 (711.0) |
| Sulphate (mg/L) | 337.1 | 146.2 | 1098.0 | 250 - 400 | IBH1 (1098.0); Control BH2 (923.0) |
| Nitrate, $NO_3$-N (mg/L) | 26.2 | 21.8 | 30.4 | 45 - 50 | None |
| Lead, Pb | 0.025 | 0.000 | 0.08 | 0.01 | 6 of 18 locations, incl. Dumpsite |

| Parameter | Mean | Min | Max | WHO/NSDWQ Limit | Locations Exceeding Limit |
|---|---|---|---|---|---|
| (mg/L) | | | 0 | | Stream (0.08) |
| Cadmium, Cd (mg/L) | 0.003 | 0.000 | 0.009 | 0.003 | Mechanic stream (0.009); MW1, MW2, MBH |
| Zinc, Zn (mg/L) | 0.54 | 0.13 | 1.41 | 3.0 (WHO) / 5.0 | None above WHO aesthetic limit |
| Iron, Fe (mg/L) | 0.39 | 0.045 | 0.90 | 0.3 - 1.0 | Mechanic stream (0.90); Control BH2 (0.80) |

### 3.3 Water Quality Index, Heavy Metal Pollution Index and Metal Index

Table 3 shows the result of the computed Water Quality Index (WQI), Heavy Metal Pollution Index (HPI) and Metal Index (MI) for each of the 18 sampling sites. In the entire dataset, the WQI ranged from 9.0 (DSW2) to 74.0 (DSBH1) with a mean of 32.6 and no sample fitting into the 'poor' (100-200), 'very poor' (200-300) or 'unsuitable' (>300) classes on the WQI scale. This outcome is due to the low WQI values (typically <200) for most of the ground water samples from the dumpsite and industrial sites (Section 3.2), compared with the significantly higher WQI values (often >200) reported from other parts of Nigeria for groundwater immediately adjacent to mature unlined dump sites [11, 31].

In contrast, the HPI signalled serious levels of heavy-metal contamination at almost half of the samples taken: at eight of the eighteen sample points, HPI values were found to be higher than the critical threshold of 100, including in the residential-zone wells, RSW1 (HPI = 235.5) and RSW2 (HPI = 118.0); in the dumpsite borehole, DSBH1 (HPI = 167.5); all four mechanic-workshop locations: MWH1 (HPI = 235.5), MWH2 (HPI = 238.9) and MWH3 (HPI = 238.6); and MWH4 (HPI = 237.6). (MW1, MW2, MBH and the mechanic-workshop stream, with the mechanic-workshop stream attaining the highest HPI in the dataset at 389.6) and the dumpsite stream (HPI = 386.2). The Metal Index corroborated this pattern, classifying every one of the eighteen samples as at least 'moderately affected' by heavy metals, with the dumpsite stream (MI = 13.34) and the mechanic-workshop stream (MI = 14.26) classified as 'seriously affected', the highest values recorded in the study.

It would appear that the heavy metal contamination is the most important water-quality stressor in the system as compared to bulk loading of dissolved ions since the WQI and HPI/MI were found to vary considerably. This is in line with the natural geochemical processes that have taken place in the system, which have observed limited natural attenuation of heavy metals that are mobilised in the process of automotive waste degradation and leachate generation, as opposed to those of dissolved ions.

**Table 3: Computed Water Quality Index (WQI), Heavy Metal Pollution Index (HPI) and Metal Index (MI) for the Eighteen Sampling Locations**

| Sample Code | WQI | WQI Class | HPI | HPI Class | MI | MI Class |
|---|---|---|---|---|---|---|
| Control BH1 | 44.7 | Excellent | 71.3 | Acceptable | 3.11 | Moderately affected |
| Control BH2 | 53.7 | Good | 53.2 | Acceptable | 4.64 | Strongly affected |
| RSBH1 | 27.2 | Excellent | 96.5 | Acceptable | 3.36 | Moderately affected |
| RSBH2 | 10.1 | Excellent | 97.7 | Acceptable | 4.94 | Strongly affected |
| RSW1 | 13.4 | Excellent | 235.5 | Critical (>100) | 8.71 | Seriously affected |
| RSW2 | 11.6 | Excellent | 118 | Critical (>100) | 6.79 | Seriously affected |

| Sample Code | WQI | WQI Class | HPI | HPI Class | MI | MI Class |
|---|---|---|---|---|---|---|
| IBH1 | 52.9 | Good | 1.1 | Acceptable | 1.91 | Slightly affected |
| IBH2 | 65.1 | Good | 52.2 | Acceptable | 3.34 | Moderately affected |
| IW1 | 64.3 | Good | 53.3 | Acceptable | 4.94 | Strongly affected |
| DSBH1 | 74 | Good | 167.5 | Critical (>100) | 6.08 | Seriously affected |
| DSW1 | 20.3 | Excellent | 98.8 | Acceptable | 6.98 | Seriously affected |
| DSW2 | 9 | Excellent | 48.8 | Acceptable | 2.76 | Moderately affected |
| DSW3 | 11 | Excellent | 88.7 | Acceptable | 3.93 | Moderately affected |
| Dumpsite Stream | 34.2 | Excellent | 386.2 | Critical (>100) | 13.34 | Seriously affected |
| MW1 | 9.5 | Excellent | 172.5 | Critical (>100) | 4.7 | Strongly affected |
| MW2 | 11.7 | Excellent | 246.2 | Critical (>100) | 6.81 | Seriously affected |
| MBH | 12.4 | Excellent | 149.7 | Critical (>100) | 3.63 | Moderately affected |
| Mechanic stream | 62.1 | Good | 389.6 | Critical (>100) | 14.26 | Seriously affected |

### 3.4 Contaminant Transport Simulation (Advection-Dispersion Equation)

The seepage velocity was calculated using Darcy's law (Equation 7), a representative hydraulic conductivity of $5 \times 10^{-5}$ m/s, a hydraulic gradient of 0.015 and an effective porosity of 0.30 and obtained as 0.216 m/day (78.8 m/yr). The chloride plume from the boundary of the Arapaja dumpsite was projected using the analytical solution of the Advection-Dispersion Equation (also known as the Ogata-Banks solution) (e.g., Frijes et al., 2010) for the chloride plume, where chloride is considered a conservative tracer with an approximate retardation factor of $R_f \approx 1$ and the source concentration is taken as DSW1 (711.0 mg/L) and the background concentration is RSBH1 (35.5 mg/L). The results from Table 3 are summarised in Table 4, which shows the distance from the dumpsite boundary at which the chloride concentration is expected to be at 10 years.

The simulation results show that chloride front from the water quality guideline of the WHO/NSDWQ (250 mg/L) reaches approximately 96 m at one year, 181 m at two years, 429 m at five years and 835 m at ten years. This progressive advancement indicates that the dumpsite leachate plume can reach wells and boreholes many times further than the 50 m exclusion zone typically recommended in the Nigerian environmental guidelines in a few years of continuous leachate generation, supporting the lack of a 50 m exclusion zone found in a similar dumpsite in Ibadan [16] under the prevailing hydraulic conditions of the weathered regolith aquifer.The projected concentration of Chloride (mg/L) with distance from the boundary of the Arapaja Dumpsite after 1 year, 2 years, 5 years and 10 years of constant density advection dispersion simulation is presented in the table below.

Table 4: Projected Chloride Concentration (mg/L) with Distance from the Arapaja Dumpsite Boundary at 1, 2, 5 and 10 Years (Constant-Density Advection-Dispersion Simulation)

| Distance from Dumpsite (m) | t = 1 yr (mg/L $Cl^-$) | t = 2 yr (mg/L $Cl^-$) | t = 5 yr (mg/L $Cl^-$) | t = 10 yr (mg/L $Cl^-$) |
|---|---|---|---|---|
| 10 | 710.1 | 711 | 711 | 711 |
| 25 | 703.2 | 710.9 | 711 | 711 |
| 50 | 641.4 | 710 | 711 | 711 |
| 75 | 457.2 | 703.5 | 711 | 711 |
| 100 | 219 | 675.7 | 711 | 711 |
| 150 | 40.6 | 458.6 | 711 | 711 |
| 200 | 35.5 | 149 | 710.6 | 711 |
| 300 | 35.5 | 35.7 | 673.7 | 711 |

### 3.5 Relevance of Density-Dependent Flow to the Observed Plume

Using the linear equation of state (Equation 9) with a density coupling coefficient of 0.7 kg/m³ per kg/m³ TDS [27], the fluid density at DSW1 (TDS = 1384 mg/L) was computed as 1000.97 kg/m³, against 1000.33 kg/m³ at the background location (TDS = 477 mg/L), yielding a density contrast of only 0.63 kg/m³. Substituting this contrast into the buoyancy term of the variable-density Darcy flux yields an estimated additional vertical descent velocity of approximately 0.2 m/yr, less than 0.3% of the horizontal seepage velocity computed in Section 3.4 (78.8 m/yr).

This result indicates that, at the TDS concentrations actually measured in this study (maximum 1384 mg/L), density-dependent buoyancy effects are not a significant contributor to contaminant migration at the sampled monitoring points. This is consistent with the density contrast at these locations being more than an order of magnitude smaller than that associated with the raw, undiluted leachate concentrations reported in the literature (TDS of 2,000-20,000 mg/L, yielding densities of 1,001-1,014 kg/m³) [6], which are typically measured within or immediately adjacent to the waste body itself rather than at down-gradient monitoring wells. Density-driven descent is therefore inferred to be most influential in the immediate vicinity of the dumpsite, where leachate is least diluted and to diminish rapidly with distance as the plume mixes with ambient groundwater, a conclusion that refines, rather than contradicts, the density-dependent flow hazard identified for comparable Basement Complex settings [9].

## 4. CONCLUSION

This study evaluated the environmental hazards posed jointly by climate change, municipal dumpsites and rooftop runoff to water potability within the Oluyole Basement Complex region of Ibadan, Nigeria, through a coupled field-based hydrogeochemical investigation and Python-based numerical transport modelling, addressing the dominant geochemical processes governing contaminant mobility, the composite pollution indices (WQI, HPI, MI) and the predictive simulation of plume migration under the Advection-Dispersion Equation and density-dependent flow. The computed Water Quality Index classified all eighteen samples as 'excellent' or 'good', indicating that bulk dissolved-ion loading alone does not place this system in the degraded categories reported for more heavily impacted Nigerian dumpsites. The Heavy Metal Pollution Index however, was above the critical value of 100 at 8 of the 18 stations sampled, while the Metal Index indicated that all samples were affected at least moderately by heavy metals, with the dumpsite and mechanic-workshop streams being seriously affected.

The result of this separation indicates that the primary and largest water-quality threat to this system is heavy-metal contamination, a result primarily associated with the mismanagement of automotive emissions, used car batteries and lubricants. The Advection-Dispersion transport simulation, with the seepage velocity derived from Darcy's Law, projected that the dumpsite-derived chloride plume advances from approximately 96 m after one year to approximately 835 m after ten years, indicating that the conventional 50 m dumpsite exclusion zone is inadequate for this site over realistic planning horizons. The accompanying density-dependent flow analysis showed that, at the dilution levels measured at the sampled wells, buoyancy-driven vertical descent contributes negligibly (less than 0.3%) to plume migration relative to horizontal advective transport, indicating that density effects in this system are most relevant in the immediate vicinity of the undiluted waste body rather than at the down-gradient monitoring points sampled in this study.

It is therefore recommended that remediation and protection-zone planning for the Arapaja dumpsite and the Akala Express mechanic-workshop cluster prioritise heavy-metal source control, that the groundwater protection-zone radius be extended substantially beyond the conventional 50 m exclusion limit in line with the modelled plume extent, that localised domestic water supply in the affected zones be redesigned around deeper boreholes intersecting the fractured basement aquifer and that rooftop runoff be directed to controlled storage rather than uncontrolled ground infiltration, as practicable, evidence-based measures for safeguarding water potability in basement complex terrains under a changing climate.

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