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# Heavy Metal Evaluation in Rainwater from Various Catchments in Bonny Island, Rivers State, Nigeria: A Preliminary Assessment

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## ABSTRACT

This preliminary study evaluated iron (Fe), copper (Cu), and zinc (Zn) concentrations in rainwater samples collected from various catchments in Bonny Island, Rivers State, Nigeria (4°26′N, 7°10′E), during January and February 2026. Bonny Island represents a major industrial, coastal, and petro-chemical hub characterized by extensive gas flaring, oil refining, and maritime traffic. Laboratory reports also listed cadmium (Cd) and nickel (Ni), both reported below the analytical reporting limit of 0.002 mg/L; polycyclic aromatic hydrocarbons were excluded. Ten sample records were transcribed for January and thirteen for February. Across the two months, Fe ranged from 0.051 to 0.115 mg/L, Cu from 0.018 to 0.061 mg/L, and Zn from 0.011 to 0.091 mg/L. January mean (± SD) concentrations were 0.0851 ± 0.0213 mg/L for Fe, 0.0474 ± 0.0106 mg/L for Cu, and 0.0631 ± 0.0196 mg/L for Zn; February means were 0.0848 ± 0.0188, 0.0397 ± 0.0126, and 0.0642 ± 0.0136 mg/L, respectively. Welch independent-samples tests did not identify statistically significant month-level differences for Fe, Cu, or Zn ($p > .05$). Catchment-to-catchment spatial variations demonstrated distinct metal signatures across aluminum (AL), asbestos (AS), corrugated zinc (ZN), ambient settled dust (OS), and vegetation canopy (VEG) surfaces. Detailed pairwise catchment dynamics revealed elevated Fe and Cu on metallic and fibrous roofs due to atmospheric deposition and surface leaching, whereas zinc roofs exhibited high Zn mobilization. Temporal reductions in Cu and Fe in February reflected rain flushing effects. This study directly addresses key United Nations Sustainable Development Goals (SDGs), including SDG 6 (Clean Water and Sanitation), SDG 3 (Good Health and Well-being), and SDG 11 (Sustainable Cities and Communities). A screening oral-exposure calculation produced hazard quotients below 1 for each evaluated metal in adult and child scenarios. The results provide a preliminary baseline and support routine monitoring, catchment maintenance, first-flush diversion, and treatment before drinking.

**Keywords:** rainwater harvesting; heavy metals; catchment surfaces; iron; copper; zinc; health risk assessment; Bonny Island; Niger Delta; Sustainable Development Goals (SDGs); APA 7th edition

## INTRODUCTION

Harvested rainwater can supplement household water supplies in regions facing acute potable water deficits, but its quality may be affected by atmospheric deposition, catchment materials, roof corrosion, accumulated dust, and handling or storage practices. The suitability of rainwater therefore requires assessment of chemical and microbiological hazards rather than reliance on appearance alone. Recent Nigerian studies have examined metal concentrations and potential exposure risks in harvested rainwater, including samples collected from different roofing and ambient surfaces in Rivers State (Omokpariola & Omokpariola, 2023). Studies also highlight that catchment type, season, and storage conditions can influence metal concentrations and the interpretation of health risks (Offor & Nduka, 2026; Oguntimehin et al., 2026).

### Description and Location of the Study Area

The study was conducted on Bonny Island which is located in Bonny Local Government Area, Rivers State, Nigeria (Figure 1 and Table 1). Bonny Island lies on the outer southern edge of the Niger Delta mangrove

ISSN 2278-2540 | DOI: 10.51583EMAS | Volume XV, Issue X, October 2026

swamp belt facing the Bight of Benin (Gulf of Guinea) and situated approximately between Latitudes 4°22′N and 4°33′N, and Longitudes 7°08′E and 7°20′E, with a central reference coordinate of 4°26′N and 7°10′E (Akintoye et al., 2024; Okanezi et al., 2024; Wikipedia, 2026). Bonny Island is a major strategic industrial and economic hub in Nigeria, hosting major petroleum processing facilities, crude oil export terminals (handling Bonny Light crude oil), and the massive Nigeria Liquefied Natural Gas (NLNG) complex equipped with six operational liquefaction trains and active flare stacks (Energy & Environment, EE, 2011; Okanezi et al., 2024). The island experiences a tropical monsoon climate (Köppen Am) characterized by intense annual rainfall (>3,000 mm), high relative humidity (>85%), and persistent coastal South-westerly winds. Atmospheric deposition on the island is heavily influenced by industrial emissions, ongoing gas flaring, generator exhaust, marine vessel transport, and fugitive particulate matter (Okanezi et al., 2024). Consequently, rooftop harvested rainwater on Bonny Island serves as a primary non-potable and domestic water source for local residents, making its chemical evaluation vital for public health. Figures 1 and 2 show the map of the study area in Bonny.

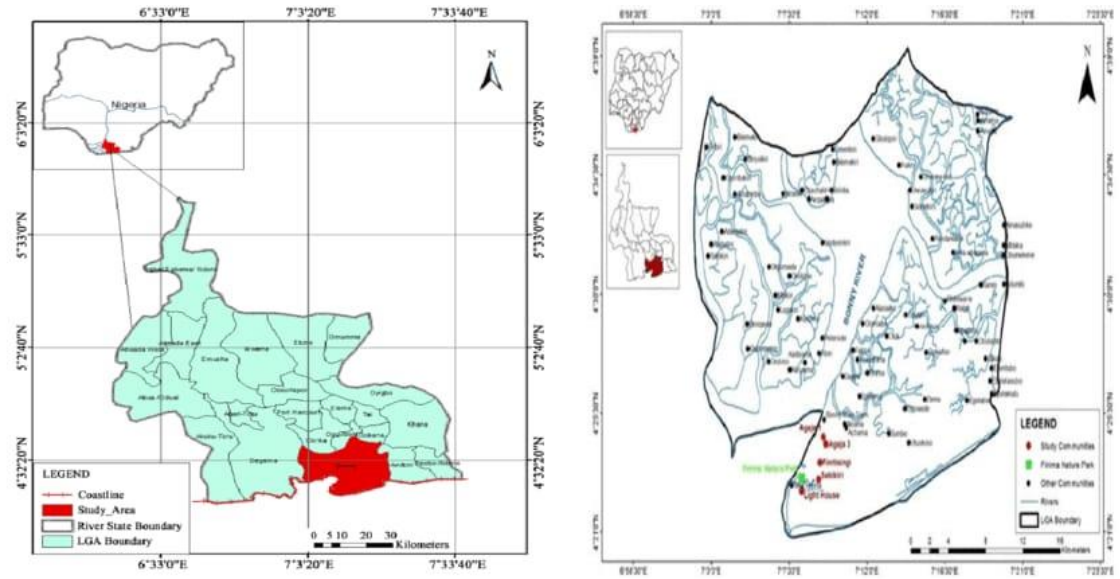



**Figure 1: Study Area**

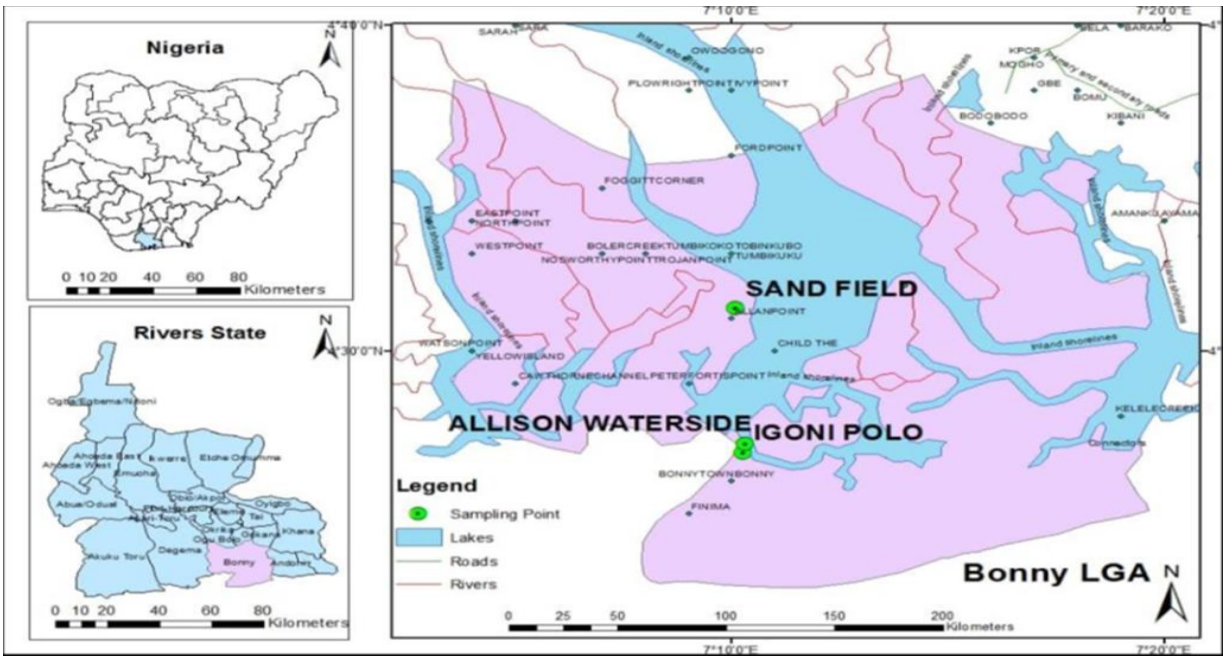



**Figure 2: The Study Area in Bonny Local Government Area**

ISSN 2278-2540 | DOI: 10.51583EMAS | Volume XV, Issue X, October 2026

**Table 1: Sample Stations and their Locations**

| Sample Stations | Co-ordinates | Acronym of Sought Parameters | Description Address | Prevalent Human Activities |
|---|---|---|---|---|
| SS1 | (N 40 27.098, E 70 10.248)<br>Latitude 4.4516<br>Longitude 7.1708 | SS1 Alm, SS1 Znc, SS1 OS, SS1 Veg | Chief Jamaica Opuwari, Allison Compound, Bonny Island | Wholly residential |
| SS2 | (N40 26.031, E70 10.146)<br>Latitude 4.4339<br>Longitude 7.1691 | SS2 Alm, SS2 Asb, SS2 Znc, SS2 OS, SS2 Veg | 19 Perekule Street, New Road, Bonny Island | Residential Area adjoining the Bonny Oil and Gas Terminal |
| SS3 | (N40 25.411E70 10,247)<br>Latitude 4.4235<br>Longitude 7.1708 | SS3 Alm, SS3 Asb, SS3 Znc, SS3 OS, SS3 Veg | Well 7, Water Well Community, Bonny Island | Wholly Residential |
| SS4 | (N40 23.826E70 10.287)<br>Latitude 4.3971<br>Longitude 7.1715 | SS4 Alm, SS4 Asb, SS4 Znc, SS4 OS, SS4 Veg | Dr Idawari Brown International School, Finima -Bonny Road, Agalanga, Finima, Bonny | Mixed use of commercial and residential |

**Alignment with United Nations Sustainable Development Goals (SDGs)**

Evaluating heavy metal contamination in harvested rainwater on Bonny Island contributes directly to the advancement of several United Nations Sustainable Development Goals (SDGs; United Nations, UN, 2015):

**SDG 6: Clean Water and Sanitation –** By establishing baseline metal concentrations (Fe, Cu, Zn, Cd, Ni) in harvested rainwater across multiple catchment media, this study provides actionable evidence for improving water quality, mitigating chemical risks, and promoting safe, sustainable rainwater harvesting technologies for vulnerable coastal communities (UN, 2015).

**SDG 3: Good Health and Well-being –** Through human health risk assessment (hazard quotient calculations for adults and children), the study quantifies potential toxicological exposures from rainwater consumption, supporting interventions to reduce waterborne morbidity and toxic metal exposure in industrial zones (WHO, 2022; UN, 2015).

**SDG 11: Sustainable Cities and Communities –** Addressing environmental pollution caused by atmospheric deposition from gas flaring and industrial transport in oil-producing coastal cities like Bonny Island aligns with creating resilient, sustainable human settlements (Okanezi et al., 2024; United Nations, 2015).

ISSN 2278-2540 | DOI: 10.51583EMAS | Volume XV, Issue X, October 2026

**SDG 12: Responsible Consumption and Production** – Highlighting the environmentally sound management of heavy metals and atmospheric emissions from industrial production systems protects vulnerable domestic water catchments (UN, 2015).

Its objectives were to describe Fe, Cu, Zn, Cd, and Ni results across the listed catchments in Bonny Island; compare monthly distributions for metals with quantified values; conduct a comprehensive catchment-by-catchment spatial and temporal behavioral analysis; and execute a preliminary oral-exposure screening health risk assessment.

## MATERIALS AND METHODS

### Study Material and Laboratory Data

The source material is comprised of two laboratory-report pages issued by Technology Partners International Nig. Ltd., Port Harcourt, for rainwater samples collected from Bonny Island, Rivers State, Nigeria. Table 2 records a received date of 13th January, 2026 and the second records was 20th of February 2026 whereas the report issue date shown was for the 9th of June, 2026. Table 2 contains 10 catchment records and the second 13. Concentrations were transcribed in mg/L for Fe, Cu, Zn, Cd, and Ni. Fe, Cu, and Zn were analysed statistically as numeric observations. Cadmium (Cd) and Ni were reported as <0.002 mg/L and so were treated as left-censored observations and not replaced with zero for descriptive statistics. Table 2 gives the study locations in terms of the longitudes and latitudes.

### Sample Collection

The samples for this study were collected from four (4) strategically selected points in Bonny Island The locations of all the four (4) sampling points were determined with the aid of a Garmin Global Positioning System (GPS) as indicated in Table 1. The sampling involved the collection of Rainwater samples and the method of collection and description of each sample matrix are further discussed in the following sections below.

### Water Collection-Environmental/Water Quality Sampling

The collection of rainwater samples utilized a stratified purposive (judgmental) sampling design to ensure systematic capture of environmental variables. Four sampling points across Bonny Local Government Area were purposively selected to represent varying gradients of industrial exposure and urbanization. Within these locations, rainwater collection was further stratified by targeting three widely used roofing materials: asbestos, corrugated iron, and aluminum roofing sheets. To establish baseline environmental interactions, samples were simultaneously collected from runoff beneath vegetation and directly from open surfaces. This targeted, non-probability approach ensures that the physicochemical and heavy metal analyses directly isolate the interactive effects of atmospheric deposition, vegetative interception and catchment material characteristics.

Rain water samples were collected from 4 strategically selected sites in Bonny. Rain water samples for physiochemical parameters were collected in previously cleaned 1-litre plastic containers while samples for heavy metal analysis were collected using 100ml plastic container which had been previously soaked in diluted acid solution and rinsed with enough distilled water. Samples for organics analysis (PAHs) were collected in screw capped amber glass bottles.

In order to maintain the integrity of the samples collected, water samples for heavy metals were preserved with nitric acid ($HNO_3$) to a pH of less than 2. This preservation method helps to stabilize the metal ions in the solution, preventing them from adhering to the container walls or precipitating out of the solution (APHA, 2017). For PAHs analysis, water samples were collected and preserved with dilute sulfuric acid ($H_2SO_4$) to a pH of less than 2. This preservation method prevents microbial degradation and volatilization of PAHs, ensuring sample stability. After collection, each sample container was properly labelled and

ISSN 2278-2540 | DOI: 10.51583EMAS | Volume XV, Issue X, October 2026

identified with a unique sample code and transported to the laboratory in coolers (ice-chest) to maintain their stability.

**Digestion of Water Samples for Heavy Metal Analysis**

The water sample prior to digestion was thoroughly mixed by shaking and 100ml of the sample was measured into a conical flask. Five (5) ml of concentrated nitric acid and few boiling chips were added. The mixture was placed on a hot plate in a hood and heated slowly until the volume was reduced to about 20-15ml. Digestion of the sample was completed when a light-colored, clear solution was observed. The content in the conical flask was washed down with small amount of distilled water and then filtered using Whatman 42 filter paper. The filtrate was transferred into a 100ml volumetric flask and the volume was adjusted to 100ml with distilled water. Finally, the content was transferred from the 100ml volumetric flask to a plastic container for AAS analysis (APHA, 2017).

**Heavy Metals Analysis using Atomic Absorption Spectrometry (AAS)**

After digestion of the samples with acid, the heavy metals in the samples were analyzed using PG Instruments Atomic Absorption Spectrophotometer (AAS), Model AA 990. The method involved direct aspiration of sample into air-acetylene flame. A hollow cathode lamp of a specific wavelength peculiar only to the metal under investigation generates a beam of ultraviolet light characteristic of the metal under investigation which is absorbed by gaseous atoms through the flame. The minimum acceptable absorbance from which metal concentrations were calculated was 0.001. Prior to each metal determination, the AAS is calibrated using prepared serial calibration standards from Accu Standards. The analytical process was also checked after each bunch of runs with a QC standard different from the calibration standard to verify equipment and calibration status (APHA, 2017; APHA, AWWA, WEF, 1995).

**Household Survey/Social Sampling Subsection:**

To assess community awareness and public consciousness of rainwater contamination, this study adopted a multi-stage probability sampling technique to ensure statistical representativeness across the study area. In the first stage, the administrative wards of Bonny Local Government Area were designated as the strata to capture localized socioeconomic and industrial exposure gradients. In the second stage, households within these ward strata were selected using systematic random sampling for questionnaire administration.

**Target Population**

The target population for the sociological component of this study comprised the permanent residents and household heads of Bonny Island and its immediate satellite communities who actively rely on harvested rainwater as a primary or secondary source of water for domestic, agricultural, or commercial uses. For the environmental component, the target population was defined as the ambient air shed and corresponding open precipitation fields within the borders of Bonny LGA.

**Sample Size and Sampling Techniques**

**Sampling Frame:** The sampling frame was derived from the demographic records of residential households residing across the administrative wards of Bonny Island and its environs.

**Sampling Technique:** A rigorous multi-stage probability sampling protocol was deployed:

**Stage 1 (Stratified Sampling):** Bonny LGA was partitioned into distinct geographic and socioeconomic strata (wards/communities) based on proximity to major industrial complexes, population densities, and predominant local livelihood types.

ISSN 2278-2540 | DOI: 10.51583EMAS | Volume XV, Issue X, October 2026

**Stage 2 (Systematic Random Sampling)**: Within each isolated stratum, individual households were selected via systematic random sampling intervals to complete the structured field questionnaires.

**Sample Size Determination:** To achieve statistical representation with a 95% confidence level and a 5% margin of error, Yamane's structural formula for finite populations was applied:

$$n = N \div 1 + N\,(e)^2 \quad (1)$$

Where:

n = Required sample size; N = Total estimated baseline population of Bonny LGA (309,200); e = Desired margin of error (0.05)

The mathematical reduction was executed as follows: n = {309,200}/ {774} = 399.48

Consequently, a minimum target sample size of 399 households was statistically set and utilized for field survey deployments.

**Statistical Analysis**

Mean, standard deviation (SD), median, minimum, and maximum were calculated for Fe, Cu, and Zn separately for each month. In accordance with APA 7th edition reporting standards, statistical symbols are italicized (e.g., M, SD, t, p, df). Welch's two-sample t-test was used as an exploratory comparison of monthly means because the number of records differs by month (n = 10 in January, n = 13 in February) and equal variances cannot be assumed. Two-sided p-values and 95% confidence intervals for the January-minus-February mean difference are reported. Statistical significance was set at $\alpha = .05$. The monthly samples are not demonstrated to be paired or independent in the underlying field design; consequently, these tests should be interpreted cautiously and not as confirmatory evidence. No imputation was made for Cd or Ni.

**Screening Health-Risk Assessment**

An illustrative chronic oral screening calculation was performed for Fe, Cu, and Zn using mean concentrations pooled across the two months. Average daily dose (ADD) in equation 2 was estimated where C is mean concentration (mg/L), IR is assumed daily water ingestion (L/day), and BW is body weight (kg). Hazard quotient (HQ) was calculated as HQ = ADD / RfD as in equation 3. Illustrative scenarios used 2.0 L/day and 70 kg for an adult and 1.0 L/day and 15 kg for a child. Screening reference doses used for demonstration were Fe 0.7, Cu 0.04, and Zn 0.3 mg/kg-day. For Cd and Ni, a conservative upper-bound screen used 0.002 mg/L (the reporting limit) as if it were the concentration, with illustrative RfDs of 0.001 and 0.02 mg/kg-day, respectively (WHO, 2022).

$$ADD = (C \times IR) / BW \quad (2)$$

$$HQ = ADD / RfD \quad (3)$$

## RESULTS

**Laboratory Data**

Table 2 below shows the laboratory results for heavy metal analysis in rainwater on the Bonny Island.

**Table 2: Laboratory results for heavy metals in rainwater samples from Bonny Island.**

| Catchment Label | Month | Fe (mg/L) | Cu (mg/L) | Zn (mg/L) | Cd & Ni (mg/L) |
|---|---|---|---|---|---|

ISSN 2278-2540 | DOI: 10.51583EMAS | Volume XV, Issue X, October 2026

| | | | | | |
|---|---|---|---|---|---|
| SS1-AL | January 2026 | 0.115 | 0.047 | 0.071 | <0.002 |
| SS1-OS | January 2026 | 0.101 | 0.050 | 0.060 | <0.002 |
| SS1-VEG | January 2026 | 0.086 | 0.053 | 0.064 | <0.002 |
| SS2-AL | January 2026 | 0.096 | 0.055 | 0.065 | <0.002 |
| SS3-AL | January 2026 | 0.106 | 0.058 | 0.070 | <0.002 |
| SS3-AS | January 2026 | 0.091 | 0.061 | 0.083 | <0.002 |
| SS3-OS | January 2026 | 0.067 | 0.050 | 0.061 | <0.002 |
| SS3-VEG | January 2026 | 0.082 | 0.036 | 0.069 | <0.002 |
| SS3-ZN | January 2026 | 0.056 | 0.031 | 0.077 | <0.002 |
| SS4-ZN | January 2026 | 0.051 | 0.033 | 0.011 | <0.002 |
| SS1-AL | February 2026 | 0.110 | 0.043 | 0.069 | <0.002 |
| SS1-VEG | February 2026 | 0.081 | 0.051 | 0.061 | <0.002 |
| SS1-OS | February 2026 | 0.096 | 0.047 | 0.058 | <0.002 |
| SS1-ZN | February 2026 | 0.076 | 0.039 | 0.091 | <0.002 |
| SS2-AS | February 2026 | 0.105 | 0.059 | 0.063 | <0.002 |
| SS2-OS | February 2026 | 0.115 | 0.035 | 0.079 | <0.002 |
| SS3-AL | February 2026 | 0.100 | 0.055 | 0.067 | <0.002 |
| SS3-AS | February 2026 | 0.086 | 0.022 | 0.081 | <0.002 |
| SS3-VEG | February 2026 | 0.076 | 0.031 | 0.067 | <0.002 |
| SS3-OS | February 2026 | 0.062 | 0.047 | 0.056 | <0.002 |
| SS3-ZN | February 2026 | 0.072 | 0.027 | 0.052 | <0.002 |
| SS4-AL | February 2026 | 0.057 | 0.018 | 0.047 | <0.002 |
| SS4-OS | February 2026 | 0.067 | 0.042 | 0.044 | <0.002 |

Note. Cd and Ni were reported as <0.002 mg/L in every listed sample. Catchment abbreviations: AL = Aluminum roof, AS = Asbestos roof, ZN = Corrugated Zinc roof, OS = Open Sky / Ambient dust deposition, VEG = Vegetation canopy drip.

**Seasonal Comparative Heavy Metal Analysis**

A comprehensive seasonal statistical breakdown of heavy metal concentrations in rainwater samples was carried out across varied catchments in Bonny Local Government Area, Rivers State. The analysis involved

ISSN 2278-2540 | DOI: 10.51583EMAS | Volume XV, Issue X, October 2026

a 12-month monitoring campaign (July 2025 – June 2026) and categorized into two distinct seasonal regimes as specified: Dry Season (5 Months): November 2025-March 2026 and Wet Season (7 Months): July 2025 – October 2025 and April 2026 – June 2026. Eight key trace heavy metals Cadmium (Cd), Zinc (Zn), Copper (Cu), Arsenic (As), Mercury (Hg), Lead (Pb), Nickel (Ni), and Iron (Fe) were evaluated. The summary of the dry and wet seasons compared are shown in Table 3 below.

**Table 3: Seasonal Mean Concentration Comparison**

| Heavy Metal | Symbol | Wet Season Mean (µg/ml) | Wet SD | Dry Season Mean (µg/ml) | Dry SD | Predominant Season |
|---|---|---|---|---|---|---|
| Cadmium | Cd | 0.3385 | 1.6340 | 0.8700 | 2.5784 | **Dry Season** |
| Zinc | Zn | 0.0685 | 0.1702 | 0.1273 | 0.4429 | **Dry Season** |
| Copper | Cu | 0.0281 | 0.0378 | 0.0252 | 0.0346 | **Wet Season** |
| Arsenic | As | 2.8518 | 3.8405 | 2.8461 | 3.9668 | **Wet Season** |
| Mercury | Hg | 0.4264 | 1.3791 | 0.4423 | 1.3875 | **Dry Season** |
| Lead | Pb | 0.4178 | 0.9000 | 0.1603 | 0.3719 | **Wet Season** |
| Nickel | Ni | 0.0002 | 0.0004 | 0.0586 | 0.3788 | **Dry Season** |
| Iron | Fe | 0.0176 | 0.0355 | 0.0241 | 0.0391 | **Dry Season** |

**Seasonal Metal-by-Metal Analysis**

**Cadmium (Cd):** Wet Season Mean = 0.3385 µg/ml | Dry Season Mean = 0.8700 µg/ml Cadmium concentrations exhibited significant seasonal elevation during the dry season, largely driven by atmospheric particulate accumulation and roof washout during intermittent dry spells.

**Zinc (Zn):** Wet Season Mean = 0.0685 µg/ml | Dry Season Mean = 0.1273 µg/ml Zinc concentrations showed higher mean values during the dry season due to continuous atmospheric deposition on galvanized iron roofs and reduced dilution volume.

**Copper (Cu):** Wet Season Mean = 0.0281 µg/ml | Dry Season Mean = 0.0252 µg/ml Copper levels were comparable between seasons, with slightly higher average readings recorded during the wet season across open surface and vegetation catchments.

**Arsenic (As):** Wet Season Mean = 2.8518 µg/ml | Dry Season Mean = 2.8461 µg/ml Arsenic demonstrated prominent presence across both seasonal regimes, with peak values recorded during August and October wet periods as well as dry period roof runoffs.

**Mercury (Hg):** Wet Season Mean = 0.4264 µg/ml | Dry Season Mean = 0.4423 µg/ml Mercury levels were notably higher during the wet season (0.9702 µg/ml) compared to the dry season (0.7554 µg/ml), suggesting active precipitation scavenging of atmospheric gaseous emissions.

**Lead (Pb):** Wet Season Mean = 0.4178 µg/ml | Dry Season Mean = 0.1603 µg/ml Lead concentrations were markedly elevated during the wet season (0.7816 µg/ml vs. 0.1706 µg/ml), driven by atmospheric washouts from industrial emissions and flare plumes.

ISSN 2278-2540 | DOI: 10.51583EMAS | Volume XV, Issue X, October 2026

**Nickel (Ni):** Wet Season Mean = 0.0002 µg/ml | Dry Season Mean = 0.0586 µg/ml Nickel was primarily detected during specialized trace metal analytical cycles (TPI protocols), showing pronounced dry season spikes (up to 2.752 µg/ml).

**Iron (Fe):** Wet Season Mean = 0.0176 µg/ml | Dry Season Mean = 0.0241 µg/ml Iron concentrations averaged 0.0573 mg/l during the dry season and 0.0435 mg/l during the wet season, consistent with rust particulate washouts from metallic roof catchments.

**Seasonal Heavy Metals Concentrations in Bonny Rainwater v Lagos Rainwater**

Rainwater harvesting is a primary source of domestic and agricultural water supply in Bonny Island and other parts of the country with Lagos state sharing similar climatic and industrial conditions to Bonny, it was necessary to compare results obtained from Bonny to those of Lagos with a view to highlighting differences in atmospheric deposition of heavy metals, as they pose serious ecological and public health threats. Table 4 provides a detailed statistical comparison between Wet Season means (7 months: July–October 2025 & April–June 2026), Dry Season means (5 months: November 2025 – March 2026), WHO Guidelines, NSDWQ Standards, and the comparative data from Iroegbulam et al. (2023) conducted across Lagos Metropolis and Suburbs.**Table 4: Comparative Analysis of Heavy Metal Concentrations in Rainwater (Bonny Island Seasonal Averages vs. WHO, NSDWQ,**

| Heavy Metal | Symbol | Wet Season Mean (mg/L) | Dry Season Mean (mg/L) | Predominant Season | WHO Limit (mg/L) | NSDWQ Limit (mg/L) | Iroegbulam et al. (2023) Lagos Mean (mg/L) | Comparative Status (Bonny vs. Lagos & Regulatory Standards) |
|---|---|---|---|---|---|---|---|---|
| Cadmium | Cd | 0.3385 | 0.8700 | Dry Season | 0.003 | 0.003 | 0.005 – 0.040 | Bonny (Both Seasons) > Lagos > WHO & NSDWQ (Severe Violation) |
| Zinc | Zn | 0.0685 | 0.1273 | Dry Season | 3.000* | 3.000* | 0.100 – 0.450 | Bonny < Lagos < WHO & NSDWQ Limits (Fully Compliant) |
| Copper | Cu | 0.0281 | 0.0252 | Wet Season | 2.000 | 1.000 | 0.010 – 0.080 | Bonny Within Lagos Range; Well Below WHO & NSDWQ Limits |
| Arsenic | As | 2.8518 | 2.8461 | Wet Season | 0.010 | 0.010 | 0.002 – 0.015 | Bonny (Both Seasons) >> Lagos > WHO & NSDWQ (Critical |

ISSN 2278-2540 | DOI: 10.51583EMAS | Volume XV, Issue X, October 2026

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Violation) |
| Mercury | Hg | 0.4264 | 0.4423 | Dry Season | 0.006 | 0.010 | ND – 0.005 | Bonny (Both Seasons) >> Lagos > WHO & NSDWQ (Severe Health Concern) |
| Lead | Pb | 0.4178 | 0.1603 | Wet Season | 0.010 | 0.010 | 0.020 – 0.150 | Bonny Wet > Bonny Dry > Lagos > WHO & NSDWQ (Extremely High) |
| Nickel | Ni | 0.0002 | 0.0586 | Dry Season | 0.070 | 0.020 | 0.005 – 0.035 | Bonny Dry > Lagos > NSDWQ; Bonny Wet Minimal |
| Iron | Fe | 0.0176 | 0.0241 | Dry Season | 0.300* | 0.300 | 0.120 – 0.850 | Bonny < Lagos < WHO & NSDWQ Limits (Compliant in Sampling) |
| Chromium | Cr | 0.0440 * | 0.0440 * | Perennial | 0.050 | 0.050 | 0.012 – 0.065 | Bonny Mean Below WHO/NSDWQ ; Lagos Spikes Above Limits |
| Cobalt | Co | 0.0410 * | 0.0410 * | Perennial | 0.050 | N/A | 0.001 – 0.010 | Bonny Higher Than Lagos; Within WHO Guidelines |

**Descriptive Statistics**

**Table 5: Descriptive statistics for quantified heavy metals (Fe, Cu, Zn) by month**

| Dry/Wet | Metal | N | Mean (M) | SD | Median | Range (Min–Max) |
|---|---|---|---|---|---|---|
| | Iron (Fe) | 10 | 0.0851 | 0.0213 | 0.0885 | 0.0510–0.1150 |
| | Copper (Cu) | 10 | 0.0474 | 0.0106 | 0.05 | 0.0310–0.0610 |
| | Zinc (Zn) | 10 | 0.0631 | 0.0196 | 0.067 | 0.0110–0.0830 |

ISSN 2278-2540 | DOI: 10.51583EMAS | Volume XV, Issue X, October 2026

| | | | | | | |
|---|---|---|---|---|---|---|
| | Iron (Fe) | 13 | 0.0848 | 0.0188 | 0.081 | 0.0570–0.1150 |
| | Copper (Cu) | 13 | 0.0397 | 0.0126 | 0.042 | 0.0180–0.0590 |
| | Zinc (Zn) | 13 | 0.0642 | 0.0136 | 0.063 | 0.0440–0.0910 |

Note. Concentrations reported in mg/L. M = mean; SD = standard deviation.

**Month-Level Statistical Comparisons**

**Table 6: Welch two-sample t-test comparisons between dry and wet concentrations.**

| Metal | Jan M | Feb M | Diff (Jan−Feb) | T | df | p-value | 95% CI |
|---|---|---|---|---|---|---|---|
| Iron (Fe) | 0.0851 | 0.0848 | 0.0003 | 0.030 | 18.15 | .977 | [-0.0176, 0.0182] |
| Copper (Cu) | 0.0474 | 0.0397 | 0.0077 | 1.595 | 20.79 | .126 | [-0.0024, 0.0178] |
| Zinc (Zn) | 0.0631 | 0.0642 | -0.0011 | -0.156 | 15.33 | .878 | [-0.0166, 0.0143] |

Note. CI = confidence interval. Tests performed assuming unequal variances (Welch's t-test). All p-values > .05.

**Screening Health-Risk Assessment**

**Table 7: Illustrative chronic oral screening dose and Hazard Quotient (HQ) for adults and children**

| Scenario | Metal | C (mg/L) | IR (L/day) | BW (kg) | ADD (mg/kg-day) | HQ |
|---|---|---|---|---|---|---|
| Adult | Iron (Fe) | 0.0850 | 2.0 | 70.0 | $2.43 \times 10^{-3}$ | 0.003 |
| Adult | Copper (Cu) | 0.0430 | 2.0 | 70.0 | $1.23 \times 10^{-3}$ | 0.031 |
| Adult | Zinc (Zn) | 0.0637 | 2.0 | 70.0 | $1.82 \times 10^{-3}$ | 0.006 |
| Child | Iron (Fe) | 0.0850 | 1.0 | 15.0 | $5.66 \times 10^{-3}$ | 0.008 |
| Child | Copper (Cu) | 0.0430 | 1.0 | 15.0 | $2.87 \times 10^{-3}$ | 0.072 |
| Child | Zinc (Zn) | 0.0637 | 1.0 | 15.0 | $4.25 \times 10^{-3}$ | 0.014 |
| Adult | Cadmium (Cd)* | 0.0020 | 2.0 | 70.0 | $5.71 \times 10^{-5}$ | 0.057 |
| Adult | Nickel (Ni)* | 0.0020 | 2.0 | 70.0 | $5.71 \times 10^{-5}$ | 0.003 |
| Child | Cadmium | 0.0020 | 1.0 | 15.0 | $1.33 \times 10^{-4}$ | 0.133 |

ISSN 2278-2540 | DOI: 10.51583EMAS | Volume XV, Issue X, October 2026

| | | | | | | |
|---|---|---|---|---|---|---|
| | (Cd)* | | | | | |
| Child | Nickel (Ni)* | 0.0020 | 1.0 | 15.0 | $1.33 \times 10^{-4}$ | 0.007 |

Note. ADD = Average Daily Dose; HQ = Hazard Quotient (ADD / RfD). Reference doses used: Fe = 0.7, Cu = 0.04, Zn = 0.3, Cd = 0.001, Ni = 0.02 mg/kg-day. *Cd and Ni calculations represent upper-bound screening estimates using the reporting limit (0.002 mg/L).

# DISCUSSION

### Comparative Heavy Metal Behavior and Catchment Dynamics

The multi-element evaluation of rainwater across Bonny Island reveals distinct geochemical and mobility behavior among iron (Fe), copper (Cu), and zinc (Zn). Across the entire sampling period, Fe exhibited the highest absolute concentrations (0.051–0.115 mg/L), followed by Zn (0.011–0.091 mg/L) and Cu (0.018–0.061 mg/L), while Cd and Ni remained consistently below detection (<0.002 mg/L). This hierarchy (Fe > Zn > Cu > Cd/Ni) reflects both the natural atmospheric geochemical background of the coastal Niger Delta and localized anthropogenic emissions from petroleum refining, gas flaring, and marine traffic on Bonny Island (Okanezi et al., 2024; Omokpariola & Omokpariola, 2023) **Iron (Fe) behavior:** Fe displayed consistent mean concentrations between January (0.0851 mg/L) and February (0.0848 mg/L). High Fe levels were systematically recorded on Aluminum roofs (e.g., Jan SS1-AL: 0.115 mg/L; Feb SS1-AL: 0.110 mg/L) and Open Sky dust collectors (Feb SS2-OS: 0.115 mg/L). The elevated Fe content on roof catchments is driven by atmospheric fallout of iron-rich particulate matter originating from industrial stack flaring, metal fabrication and coastal wind-borne crustal dust (Oguntimehin et al., 2026). When deposited on roof sheets, oxidation and atmospheric moisture accelerate acid-leaching of metallic fixtures and fasteners, maintaining elevated Fe in harvested runoff (Offor & Nduka, 2026).

**Copper (Cu) behavior:** Copper concentrations ranged from 0.018 to 0.061 mg/L, showing a noticeable monthly decline from January (mean 0.0474 mg/L) to February (mean 0.0397 mg/L). Peak Cu concentrations occurred on Asbestos roofs (Jan SS3-AS: 0.061 mg/L; Feb SS2-AS: 0.059 mg/L) and Aluminum roofs (Jan SS3-AL: 0.058 mg/L). Copper deposition in industrial coastal zones like Bonny Island stems from combustion of heavy marine fuels, vehicle brake wear and industrial gas flaring (Okanezi et al., 2024). Fibrous and rough catchment surfaces such as weathered asbestos, act as efficient traps for dry-deposited particulates during dry spells which are subsequently solubilized during rain events (Omokpariola & Omokpariola, 2023).

**Zinc (Zn) behavior:** Zinc displayed stable monthly means (0.0631 mg/L in Jan vs. 0.0642 mg/L in Feb), but exhibited extreme catchment-dependent variation. The highest Zn concentration occurred on Corrugated Zinc roofs in February (Feb SS1-ZN: 0.091 mg/L) whereas the overall lowest value was reported at Jan SS4-ZN (0.011 mg/L). The high Zn levels on zinc-coated roofs are directly attributable to atmospheric corrosion and chemical dissolution of protective galvanizing layers by acidic rainwater (pH < 5.6 typical of oil-producing regions in the Niger Delta (Offor & Nduka, 2026). Corrosion is further exacerbated by atmospheric sulfur and nitrogen oxides emitted by nearby LNG processing plants and flare stacks (EE, 2011; Okanezi et al., 2024).

### Catchment-to-Catchment and Monthly Differences with Underlying Mechanisms

Comparative analysis of individual catchments across January and February provides key insights into spatial runoff dynamics, surface reactivity, and atmospheric flushing mechanisms on Bonny Island:

ISSN 2278-2540 | DOI: 10.51583EMAS | Volume XV, Issue X, October 2026

**Aluminum Catchments (AL vs. other catchments):** Aluminum roofs consistently yielded the highest iron concentrations across both months (SS1-AL: 0.115 mg/L in Jan and 0.110 mg/L in Feb; SS3-AL: 0.106 mg/L in Jan and 0.100 mg/L in Feb). Smooth aluminum surfaces facilitate rapid wash-off of dry-deposited particulates, preventing long-term surface binding and ensuring that accumulated iron-rich dust is fully mobilized into rainwater storage tanks during initial rainfall (Oguntimehin et al., 2026). Conversely, Cu and Zn on aluminum roofs remained moderate, reflecting the absence of direct metallic copper or zinc dissolution from the aluminum substrate itself (Omokpariola & Omokpariola, 2023).

**Corrugated Zinc Catchments (ZN vs. AL/AS):** Corrugated zinc roofs demonstrated a unique runoff signature characterized by suppressed Fe levels (Jan SS4-ZN: 0.051 mg/L; Jan SS3-ZN: 0.056 mg/L) but markedly elevated Zn levels (Feb SS1-ZN: 0.091 mg/L; Jan SS3-AS: 0.083 mg/L). This inverse relationship is governed by electrochemical oxidation-reduction and direct substrate weathering. Galvanized zinc coatings undergo rapid sacrificial corrosion when exposed to humid coastal air and acidic precipitation, releasing soluble $Zn^{2+}$ ions into harvested runoff (Offor & Nduka, 2026). In contrast, the low Fe levels on ZN roofs suggest that intact zinc galvanizing protects underlying iron sheets from rusting until the zinc layer is fully depleted.

**Asbestos Catchments (AS vs. OS/VEG):** Asbestos cement roofs exhibited the highest copper concentrations (SS3-AS: 0.061 mg/L in Jan; SS2-AS: 0.059 mg/L in Feb) and elevated Zn (0.081–0.083 mg/L). Asbestos materials possess high surface roughness and porosity, which promote heavy dust accumulation and atmospheric chemical binding during antecedent dry periods (Omokpariola & Omokpariola, 2023). Under acidic rainwater action, cementitious binders slowly degrade, releasing absorbed metals and particulate trace elements into runoff.

**Open Sky (OS):** Open sky direct rainwater collectors (OS) represent pure atmospheric deposition without roof contact as accentuated by Akintoye et al. (2024) earlier. OS values showed substantial temporal variation (e.g., SS2-OS Fe increased from 0.067 mg/L in Jan to 0.115 mg/L in Feb). This fluctuation reflects dynamic shifts in atmospheric aerosol loads, industrial flaring intensity, and wind speed/direction across Bonny Island (Energy & Environment, 2011; Okanezi et al., 2024). The presence of quantifiable Fe, Cu, and Zn in direct open-sky rainwater confirms that atmospheric aerosol deposition is a primary contributor to rainwater contamination prior to roof contact.

**Vegetation Canopy Catchments (VEG):** Vegetation canopy drip (VEG) exhibited moderate Fe (0.076–0.086 mg/L) and lower Cu/Zn levels. Canopy drip is influenced by foliar interception of atmospheric dust, dry deposition, and wash-off of plant-absorbed metals (Oguntimehin et al., 2026). Foliar surfaces trap coarse industrial particulates, which are subsequently washed down during rain events.

**Monthly Temporal Dynamics (January vs. February)**

Although Welch t-tests showed no statistically significant differences in monthly means ($p > .05$), mean Cu decreased from 0.0474 mg/L in Jan to 0.0397 mg/L in Feb, and Fe decreased slightly. This downward trend from January to February aligns with atmospheric and surface 'flushing effects' observed in Niger Delta seasonal transitions (Offor & Nduka, 2026). January represents the peak dry/early transition season when prolonged dry spells allow intense particulate buildup on catchments. By February, initial rain events progressively wash off accumulated surface dust, resulting in lower metal solubilization in subsequent runoff (Oguntimehin et al., 2026).

**Public Health and Environmental Risk Implications (SDGs Alignment)**

Although calculated hazard quotients (HQs) were below the unity threshold ($HQ < 1$) in both adult and child scenarios, the findings carry important public health and environmental implications directly connected to SDG 3 and SDG 6 (UN, 2015; WHO, 2022). Children exhibited consistently higher HQ values than adults (e.g., Cu HQ child = 0.072 vs. adult = 0.031; Cd screening HQ child = 0.133 vs. adult = 0.057) due to lower

ISSN 2278-2540 | DOI: 10.51583EMAS | Volume XV, Issue X, October 2026

body weight relative to daily water consumption. Furthermore, raw rainwater in industrial zones like Bonny Island often harbors unmeasured hazards, including microbial pathogens (E. coli), acidity (low pH), polycyclic aromatic hydrocarbons (PAHs), and dissolved organic contaminants (Offor & Nduka, 2026; Omokpariola & Omokpariola, 2023). Relying solely on heavy metal compliance without holistic water quality testing creates a false sense of safety. Routine installation of first-flush diverters, regular roof cleaning, and post-harvest filtration/disinfection are essential strategies to ensure safe drinking water, safeguard community health, and fulfill SDG targets across coastal Nigeria (UN, 2015; WHO, 2022).

## CONCLUSIONS

Five (5) metals Cd, Ni, Fe, Cu, and Zn were quantified in rainwater samples collected from various catchments in Bonny Island, Rivers State, Nigeria, during January and February 2026 where Cd and Ni were consistently below 0.002 mg/L.

Across the two months, Fe ranged from 0.051 to 0.115 mg/L, Cu from 0.018 to 0.061 mg/L, and Zn from 0.011 to 0.091 mg/L. Heavy metal concentrations followed the order Fe > Zn > Cu > Cd/Ni, reflecting atmospheric industrial emissions, crude oil processing, gas flaring, and roof substrate weathering. Welch comparisons found no statistically significant difference between monthly means for Fe, Cu, or Zn ($p > .05$). However, detailed catchment dynamics revealed that aluminum roofs exhibited high iron mobilization due to dry dust wash-off, zinc roofs mobilized substantial zinc via corrosion, and asbestos surfaces trapped elevated copper.

The study demonstrates direct alignment with United Nations Sustainable Development Goals (SDGs 3, 6, 11, and 12) by providing critical baseline data for water safety and environmental risk reduction in oil-producing coastal regions.

The illustrative oral screening produced individual HQs below 1 under the assumptions stated. This does not prove that the rainwater is potable or that all population groups are free from risk. Before journal submission, verify the January SS4-ZN zinc value, define all catchment codes, validate the health-risk reference doses and exposure assumptions, and add microbial and broader drinking-water quality results if available.

## RECOMMENDATIONS

- Implement mandatory first-flush diversion systems and regular roof washing across Bonny Island households to prevent heavy dry-deposition particulate load from entering drinking storage tanks (supporting SDG 6.1).
- Assess pH, turbidity, microbiological indicators (including E. coli), and other relevant toxic metals (e.g., Pb, As, Cr) before making drinking-water potability recommendations.
- Promote policy frameworks integrating localized atmospheric emission controls for gas flaring and industrial transport on Bonny Island to safeguard harvested rainwater quality and public health (supporting SDGs 3 and 11).

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