Probabilistic risk assessment and water quality index of a tropical delta river

Osikemekha Anthony Anani¹ and John Ovie Olomukoro²

¹ Laboratory for Ecotoxicology and Forensic Biology, Department of Biological Science, Faculty of Science, Edo State University Uzairue, Auchi, Nigeria
² Department of Animal and Environmental Biology, Faculty of Science, University of Benin, Benin City, Edo State Nigeria

ABSTRACT

Water plays a major role in supporting the wellness and life processes in living things as well as in the ecological structure’s stabilities. However, several environmental scientists have recounted the alarming menace unfit water quality portends as well as the shortfalls of its global utilization in various spheres of life. This study aims to determine the fitness of the Ossiomo River and its likely health risk impact when consumed or used for other domestic purposes. The outcome of the physicochemical and heavy metal characterization showed that most of the parameters surpassed the slated benchmarks. Findings from the study revealed a significant difference (p < 0.05) for water temperature, color, TDS, BOD₅, HCO₃, Na, Fe, Mn, and THC across the four stations respectively. Meanwhile, pH, salinity, turbidity, TSS, DO, Cl, P, NH₄H, NO₂, NO₃, SO₄, Zn, Cu, Cr, Ni, Pb, and V showed no significant (p > 0.05) across the four stations respectively. The pH level of the water was slightly acidic at the range of 4.40–6.82. The outcome of the computed water quality index showed that station 1 (66.38) was poor for human ingestion which was above the set slated benchmarks of 26–50. However, stations 2–4 (163.79, 161.79, and 129.95) were unsuitable for drinking which was above the set slated benchmarks of 100. The outcome of the health risk evaluation revealed that the hazard quotients (HQs) were considered greater than 1 (>1) for Cr (2.55). The hazard index (0.46) via the dermal pathway was <1 while the ingestion (4.35) pathway was >1. The sum of the HQs (4.81) was also > 1. Thus, there are possible non-carcinogenic health risks via direct ingestion of the water. The outcome from the carcinogenic risk for Pb, Cr, and Cd (6 × 10⁻³, 4.00 × 10⁻¹, and 1.22 × 10⁰), was somewhat greater than the target goal (1.0 × 10⁻⁶ to 1.0 × 10⁻⁴) of carcinogenic risks stipulated by the United States Environmental Protection Agency for drinking water, respectively, especially for Cd. There might be a potential carcinogenic risk if the water is consumed when the metal contents are higher than the target limits set. Sustainable farming and treatment of wastes from industrial outputs should be the main management of this watercourse.

Subjects Biodiversity, Ecotoxicology, Aquatic and Marine Chemistry, Environmental Contamination and Remediation, Environmental Impacts

Keywords Health risk, Water Quality Index, Carcinogenic risk factors, Heavy metals, Quality control.
INTRODUCTION

Surface or superficial water comprises water from reservoirs, lakes, ponds, springs, oceans, seas, and rivers. Though, such waters stemmed from dew, snow, and rainfall (precipitations). Most of these waters are used for various purposes such as industrial, agricultural, and domestic purposes globally (Manahan, 2010; Khan, Gani & Chakrapani, 2015; Shil, Singh & Mehta, 2019; Anani, Olomukoro & Enuneku, 2020; Anani, Olomukoro & Ezenwa, 2020). Surface water sourced from river watercourse has several intrinsic-physical and chemical properties that can sustain both plant and animal life forms. However, there are some environmental tendencies, several factors that can elevate and impact its background concentrations. These water bodies are often influenced by pollutants caused by natural and human activities (Kazi et al., 2009; Giridharan, Venugopal & Jayaprakash, 2010; Sener, Sener & Davraz, 2017; Anani & Olomukoro, 2018; Kumar, Singh & Ojha, 2018; Olomukoro & Anani, 2019). The degradation of the quality of water by these activities makes it unfit for defined purposes set for its usage.

Nonetheless, it has been recounted and estimated that over 1.1 billion of the populace of the world cannot access potable and clean water; that is uninterrupted from pollution. More so, about four billion of the population of the world have been linked by exposure to different health-related diseases resulting in five million death globally (WHO, 2004; Azizullah et al., 2011).

Despite the major roles water play in supporting the wellness and life processes in living things as well as in the ecological structures stabilities, several environmental scientists have recounted the alarming menace unfit water quality portends as well as the shortfalls of its global utilization in various spheres of life (Okorafor et al., 2012; Casanovas-Massana & Blanch, 2013; Liang et al., 2013; Sojobi, Owamah & Dahunsi, 2014; Ayandiran et al., 2014; Dahunsi et al., 2014).

Human contact to heavy metals via different pathways (dermal and ingestion) in river water, is of utmost importance because of the associated problematic health severity it portends and likely food chain impacts. Previous research works have emphasized the health risk and water quality impact of surface, ground, and portable water globally (Cude, 2001; Song et al., 2012; Oboh & Aghala, 2017; Abbasnia et al., 2018a, 2018b; Ayandiran, Fawolea & Dahunsi, 2018; Enuneku et al., 2018; Emenike et al., 2019; Soleimani et al., 2018; Kamarehie et al., 2019; RadFard et al., 2019). Heavy metals (HMs) exposure and possible health risk impacts have been analyzed in various water bodies in Nigeria (Chinedu & Nwinyi, 2011; Kayode et al., 2011; Omole et al., 2015; Emenike et al., 2017).

So, there is an urgent need to forecast, evaluate, and address river water with possible pollutants that have a harmful influence on plants, animals and humans live to bring about sustainable management of our water resources.

Therefore, this study attempts to evaluate the probabilistic influence of heavy metals (HMs) in the surface water of Ossioomo River in the region of Ologbo, South-South Nigeria, to determine its consumption fitness and its likely health risk via oral and dermal
pathways. However, several evaluations on the chemical and physical properties have been
done on different parts of the River stretch. So far, no research work has been conducted
on the quality of water and human health risk factors in this river which stands as a
possible research gap.

**MATERIALS & METHODS**

**Study area**

The study area Ossiomo River covers five sub-eco-communities which are Ekosa,
Imasabor, Asaboro, Ovade, Ugbenu, and Okuku of geographical ranges: 6°03.’1”N
(Latitude) to 5°40.’3”E (Longitude) Fig. 1. Two different sharply marked yearly seasons,
wet and dry linked to these regions begins in early March and end in late November
(wet season), and the dry season starts from November and ends in March. The mean
precipitation for the sampling periods (2015 and 2016), fluctuated from 160.7–708.5 mm
with the lowermost (158.4 mm), noted in the period of May 2015 and the topmost
(708.5 mm), documented in the period of September 2015. The mean rainfall value within
the sampling season was (434.6 mm).

The principal aquatic macrophytes here included; *Pandanus candelabrum, Elaeis
guineensis, Azolla africana, Nymphaea lotus, Salvinia nymphellula, Echinochloa
pyramidalis*, and *Pistia stratiotes*. Human activities within and around this river included;
crude oil exploration, logging, fishing, boating, watercraft maintenance, and discharging of
cassava wastes.
Physical and chemical analysis
Samples were sourced from four labeled stations at periodic timing of 09.00 am and 12.00 pm on every one sampling day. Samples were collected for 18 months every two weeks every month. Each time, sampling began at station 1 and culminated at station 4. All samples were collected in reagent bottles and were ice chess at 4 °C in a large thermo cooler and taken to the laboratory for extraction and determination of several environmental concerned parameters (color, total suspended solids, total dissolved solids, biochemical dissolved oxygen, hydrogen carbonates, sodium, chloride, potassium, ammonia nitrates, nitrites, nitrates, sulfates, iron, manganese, zinc, copper, chromium, cadmium, lead, nickel, vanadium, and total hydrocarbons) in consonance with acceptable standard methods (America Public Health Association (APHA), 1998).

Field activities
The field water sampling involved the assessment of water temperature, DO (dissolved oxygen), TDS (total dissolved substances), pH, and EC (electrical conductivity) using a mercury-in-glass thermometer, Winkler A and B (Magnesium sulfate and Potassium iodide-Sodium Hydroxide), and Extech meter probes (Extsik ii) D 600 respectively. 1 mL of HNO₃ was used to fix the heavy metal contents in the water collected in a clean 1-liter bottle. Similarly, a clean transparent 1-liter bottle was used to collect the THC (and total hydrocarbons) (Anani, Olomukoro & Ezenwa, 2020).

Laboratory activities
Samples were taken to the laboratory in a thermo-cooler containing ice chests of temperature 4 °C for advanced analysis. The methods of the American Public Health Association (APHA) (2005) and Anani, Olomukoro & Ezenwa (2020) were used for the pretreatments, analytic measurements, and the determination of the following, color, turbidity, total suspended solids (TSS), chemical oxygen demand (COD), biochemical dissolved oxygen (BOD5), hydrogen carbonates, sodium, chlorine (Cl), potassium, ammonia nitrates, nitrites, nitrates, sulfates, iron, manganese, zinc, copper, chromium, cadmium, lead, nickel, vanadium, and total hydrocarbons. The instruments used were HACH UV/VIS Spectrophotometer model DR/2000, HACH Turbidimeter Model 2100p, and HACH Spectrophotometer at 890 nm Model DR 2000 for the measurement and determination of TSS, Turbidity, COD, phosphate, Na, hydrogen carbonates, and nitrate. The argento-metric technique was used to measure Cl, the turbidimetric technique was used to measure and determine sulfate. The Searchtech Dds-307 Benchtop digital electrical conductivity meter was used to determine the salinity in water. The metal contents were determined using the Atomic Absorption Spectrophotometer (AAS) Solaar 969 Unicam Series model.

The criteria for selecting the water quality parameters for the assessment is because over 85% of the population in this area depend solely on farming for their survival. As a result of this, various types of agricultural chemicals like herbicides, pesticides, and NPK fertilizers are employed in agricultural practices to improve farm products. In addition, agricultural and domestic wastes are poorly managed in this region. Contaminants like
heavy metals, potassium, nitrogen, and phosphate from organic guano and fecal wastes have been assumed to reside in the soil and consequently washed via runoffs by rain or precipitation over time.

Quality control
The worth of the diagnostic data was assured via the application of quality laboratory techniques and assurance like the examination of replicates, reagents blanks, the setting of standards, and operating methods. The samples collected from the field were analyzed in triplicates. For every triplicate, two standards i.e. 2.5 µg/L and one blank sample were analyzed correspondingly with an AAS (Atomic Absorption Spectrophotometer SOLAAR 969AA Unicam Series). After that, a recovery procedure was carried out in triplicate to ascertain the various metals. A mean recovery rate of 90.3 ± 0.75–96.7 ± 0.25% was established. Therefore, different calibration curves were improved by the use of QCSs (quality control standards) at each step of the sample evaluation. The chemicals used for the study were diagnostically procured and graded from Merck UK and Germany with a certified rate of purity of 99.89%. The glassware (Pyrex) used for this study was washed with ultra-deionized water and later plunged in HNO₃ 10% overnight and rinsed later with ultra-deionized water. Lastly, they were dried in an oven at a temperature of 60 °C. The bottles (polyethylene) used were tightly covered before taking them for analysis (Chinedu & Nwinyi, 2011; Naveedullah Hashmi et al., 2013).

Data analysis
Parametric analysis of variance (ANOVA) was used to compute the mean and standard deviation across the stations and the p-values were set at 0.05. Ramakrishna, Sadashivaih & Ranganna (2009), Tyagi et al. (2013), Abbasnia et al. (2018a), (2018b), Soleimani et al. (2018), and RadFard et al. (2019) method of WQI (Water Quality Index) by the Weighted Arithmetic Index was employed to explain the range of quality of the water.

Water Quality Index (WQI)
In this study, the Qi (quality rating scale) for individual parameters was estimated using the below equation:

\[
Qi = \left( \frac{V_{\text{actual}} - V_{\text{ideal}}}{V_{\text{standard}} - V_{\text{ideal}}} \right) \times 100
\]

where Qi, V actual or actual value, and V ideal or ideal value equal to the quality evaluation of ith parameter for a sum of n WQ (water quality) parameters, the real value of the WQ parameter gotten from laboratory examination, and the perfect rate of that WQ parameter respectively, that can be sourced from a typical water quality table (Table 1).

The pH of 7.0 and DO of 14.6 mg/L were used as standard V ideal values as documented and adopted by Ramakrishna, Sadashivaih & Ranganna (2009), Tyagi et al. (2013), Abbasnia et al. (2018a), and (2018b) while the other parameters were equal to zero. However, the V standard or standard values are equal to the WHO (2004) standard limits for drinking water Table 1.
After estimating for the Qi, the Wi (weight) in the relative unit was estimated using the equation below:

\[ Wi = \frac{1}{Si} \]

where Wi, Si, and I stand for weight for the nth parameter, the allowable standard number for the nth parameter, and proportionality constant correspondingly.

Conclusively, the total WQI (water quality index) was estimated by totaling the Qi with the Wi linearly with the below equation:

\[ WQI = \sum WiQi / \sum Wi \]

where Qi and Wi stand for quality rating and weight in relative units (Ramakrishna, Sadashivaiah & Ranganna, 2009; Tyagi et al., 2013; Abbasnia et al., 2018a, 2018b; Soleimani et al., 2018; RadFard et al., 2019) (Table 5).

### Table 1 Relative weight, V standard, and V ideal of WQI parameters. The water parameters standards.

| Number | Factor/parameters | WHO (2004) limit (V standard) | V ideal (Ramakrishna, Sadashivaiah & Ranganna, 2009; Tyagi et al., 2013; Abbasnia et al., 2018a, 2018b) protocol |
|--------|-------------------|------------------------------|-----------------------------------------------------------------------------------------------------------------|
| 1 | Water temperature | 35 | 0 |
| 2 | pH | 7.5 | 7 |
| 3 | Colour | 15 | 0 |
| 4 | Turbidity | 5 | 0 |
| 5 | TSS | 10 | 0 |
| 6 | TDS | 500 | 0 |
| 7 | DO | 7.5 | 14.6 |
| 8 | BOD<sub>5</sub> | 0 | 0 |
| 9 | HCO<sub>3</sub> | 200 | 0 |
| 10 | Na | 200 | 0 |
| 11 | Cl | 200 | 0 |
| 12 | P | 5 | 0 |
| 13 | NH<sub>4</sub>H | 1 | 0 |
| 14 | NO<sub>2</sub> | 1 | 0 |
| 15 | NO<sub>3</sub> | 10 | 0 |
| 16 | SO<sub>4</sub> | 500 | 0 |
| 17 | Fe | 1 | 0 |
| 18 | Mn | 0.05 | 0 |
| 19 | Zn | 1 | 0 |
| 20 | Cu | 0.1 | 0 |
| 21 | Cr | 0.05 | 0 |
| 22 | Cd | 0.01 | 0 |
| 23 | Ni | 0.05 | 0 |
| 24 | Pb | 0.05 | 0 |
| 25 | V | 0.01 | 0 |
| 26 | THC | 0.05 | 0 |
Health risk evaluation

**Hazard quotient, hazard index, chronic daily intake, and carcinogenic risk**

The health risk assessment for heavy metals in the surface water via dermal and ingestion routes were evaluated using the below equations:

\[
EX_{ing} = \frac{C_{water} \times IR \times EF \times ED}{BW \times AT}
\]

\[
Exp_{derm} = \frac{C_{water} \times SA \times KP \times ET \times EF \times ED \times CF}{BW \times AT}
\]

where \(EX_{ing}\) means exposure dose via ingestion of water in mg/l/d and \(Exp_{derm}\) stands for exposure dose via dermal absorption in mg/l/d ([US EPA, 1989; US EPA, 2004; Wu et al., 2009; Liang, Yang & Sun, 2011; Iqbal & Shah, 2012; Song et al., 2012; Fakhri et al., 2018a, 2018b; Qu et al., 2018]). The assumptions used in the estimation of the dermal and ingestion pathways are as shown in Table 2.

The equations for the estimation of the hazard quotient (HQ) and hazard index (HI) (non-carcinogenic risks) are as shown below:

\[
HQ_{ing} = \frac{EX_{ing}}{RfD_{ing}}
\]

\[
HQ_{derm} = \frac{Exp_{derm}}{RfD_{derm}}
\]

### Table 2 Assumptions or conventions used to quantify health risk exposure to heavy metals.

Description of assumptions and conventions.

| Exposure parameters                  | Units | Values |
|--------------------------------------|-------|--------|
| Levels of heavy metals in water (\(C_{water}\)) | mg/l  | –      |
| Water ingestion rate (IR)            | L/day | 2.2    |
| Exposure frequency (EF)              | Days/year | 360   |
| Exposure duration (ED)               | Year  | 30     |
| Average body weight (BW)             | Kg    | 70     |
| Average time (AT)                    | Days  | 10,950 |
| Exposed skin area (SA)               | cm²   | 28,000 |
| Exposure time (ET)                   | h/day | 0.6    |
| Unit conversion factor               | L/cm³ | 0.001  |
| Dermal permeability coefficient (Kp) | cm/h  | 0.0006 |

**Metals**

Assumptions or conversions of metals used in this study

| Metals | Assumptions or coversions of metals used in this study |
|--------|--------------------------------------------------------|
| Zn     | 0.001                                                  |
| Cu     | 0.001                                                  |
| Mn     | 0.001                                                  |
| Fe     | 0.001                                                  |
| Cd     | 0.001                                                  |
| Cr     | 0.001                                                  |
| Pb     | 0.002                                                  |

**Note:** Naveedullah Hashmi et al. (2013).
HI\textsubscript{derm} = \sum_{i=0}^{n} HQ\textsubscript{derm}

where HQ\textsubscript{derm} stands for hazard quotient via ingestion or dermal contact (unitless); and RfD\textsubscript{derm} refers to the oral/dermal reference dose (mg/kg/d) which was extracted from USEPA (1993), USEPA (2002), USEPA IRIS (2011), Iqbal & Shah (2012), Naveedullah Hashmi et al. (2013), and Anyanwu & Nwachukwu (2020) risk tables. HI\textsubscript{ing/derm} stands for hazard index via ingestion or dermal contact (unitless). HI was introduced to appraise the sum probable for non-carcinogenic effects posed by additional pathways, which was the sum of the HQs (hazard quotients) from all applicable pathways. HI >1 and HQ > 1 displayed possibility for adversative influence on human health which might indicate concern for non-carcinogenic influence (Wu et al., 2009; Li & Zhang, 2010; Iqbal & Shah, 2012; Edokpayi et al., 2018; Fakhri et al., 2018a, 2018b; Qasemi et al., 2018; Shams et al., 2020).

The estimation of the possible CDI (chronic daily intake) of metals in the water was estimated using the equation below:

\[
CDI = C \times DI / BW
\]

where C, DI, and BW indicated the levels of heavy metal in water (mg/L), the mean daily intake rate of 2.2 L/day, and the bodyweight of 70 kg corresponding as modified by Wu et al. (2009), Muhammad, Shah & Khan (2011), Dzulfakar et al. (2011), Edokpayi et al. (2018), Fakhri et al. (2018a), (2018b), Qasemi et al. (2018), and Shams et al. (2020).

For the carcinogenic risk pathway using ingestion, the equation for calculation is shown below:

\[
Cr\text{\textsubscript{ing}} = EX\text{\textsubscript{ing}} \times SF\text{\textsubscript{ing}}
\]

where Cr\textsubscript{ing} means carcinogenic risk via ingestion, SF\textsubscript{ing} means slope factor for carcinogenic risk via ingestion (mg/kg)-1×(URF × 1,000 × URF (unit risk factor)). To show the Cr\textsubscript{ing} values for Cd, Cr, and Pb, the SF\textsubscript{ing} values for Cd, Cr, and Pb are 6.1E+03, 5.0E+02, and 8.5E+00, individually (De Miguel et al., 2007; Wu et al., 2009; Iqbal & Shah, 2012; Naveedullah Hashmi et al., 2013; Naz, Mishra & Gupta, 2016; Briki et al., 2017; Shams et al., 2020). The USEPA (2010) range (1.0E−06 to 1.0E−04) for carcinogenic risks were used to compare the value gotten in this study.

**RESULTS**

**The physicochemical and heavy metal results of the Ossiomo River**

The results of the physicochemical and heavy metals parameters are shown in Table 3 for stations 1–4 correspondingly. The study revealed a significant difference (p < 0.05) for water temperature, color, TDS, BOD\textsubscript{5}, HCO\textsubscript{3}, Na, Fe, Mn, and THC across the four stations respectively. Meanwhile, pH, salinity, turbidity, TSS, DO, Cl, P, NH\textsubscript{4}H, NO\textsubscript{2}, NO\textsubscript{3}, SO\textsubscript{4}, Zn, Cu, Cr, Ni, Pb, and V showed no significant (p > 0.05) across the four stations respectively.
| Parameters       | Units     | Station 1 (Min-Max) | Station 2 (Min-Max) | Station 3 (Min-Max) | Station 4 (Min-Max) | WHO (2004) | Significant values |
|------------------|-----------|---------------------|---------------------|---------------------|---------------------|------------|-------------------|
| Water Temperature | °C        | 26.19 ± 1.09 (26.60–28.10) | 26.73 ± 0.87 (24.90–28.00) | 26.99 ± 0.58 (26.10–28.00) | 27.69 ± 0.58 (24.4–29.10) | NS         | p < 0.05          |
| pH               |           | 5.08 ± 0.56 (4.94–6.62) | 5.48 ± 0.59 (4.11–6.12) | 5.72 ± 0.52 (4.84–6.50) | 5.64 ± 0.50 (4.70–6.24) | 6–8        | p > 0.05          |
| Salinity         | g l⁻¹     | 0.05 ± 0.02 (0.03–0.08) | 0.08 ± 0.02 (0.05–0.13) | 0.08 ± 0.02 (0.05–0.11) | 0.06 ± 0.02 (0.03–0.09) | NS         | p < 0.05          |
| Colour           | Pt.Cn     | 4.87 ± 2.40 (1.70–10.40) | 6.66 ± 3.95 (2.30–15.30) | 6.45 ± 3.49 (1.70–13.70) | 5.38 ± 3.09 (1.40–11.50) | NS         | p < 0.05          |
| Turbidity        | NTU       | 3.93 ± 2.14 (1.20–8.40) | 5.54 ± 3.69 (1.80–13.90) | 4.95 ± 2.65 (1.10–10.50) | 4.29 ± 2.42 (0.90–7.80) | 5          | p < 0.05          |
| TSS              | mg l⁻¹     | 6.15 ± 2.60 (1.20–15.50) | 9.33 ± 4.45 (4.70–19.40) | 8.48 ± 3.92 (2.80–16.30) | 7.06 ± 3.17 (2.10–14.00) | NS         | p > 0.05          |
| TDS              | mg l⁻¹     | 60.28 ± 17.70 (33.90–90.60) | 88.23 ± 23.30 (57.00–141.30) | 82.10 ± 22.43 (50.10–25.50) | 67.26 ± 17.09 (32.00–97.10) | 1,000      | p < 0.05          |
| DO               | mg l⁻¹     | 6.23 ± 0.54 (5.40–7.10) | 5.67 ± 0.69 (4.80–6.90) | 5.67 ± 0.70 (4.10–6.70) | 5.87 ± 0.38 (5.20–6.40) | NS         | p > 0.05          |
| BOD₃             | mg l⁻¹     | 2.34 ± 0.57 (1.60–3.20) | 3.44 ± 0.70 (2.30–4.70) | 3.00 ± 0.82 (2.10–4.40) | 2.44 ± 1.11 (1.10–4.00) | NS         | p < 0.05          |
| HCO₃             | mg l⁻¹     | 20.78 ± 12.70 (12.20–54.20) | 41.61 ± 11.93 (24.40–61.00) | 39.50 ± 13.79 (24.40–59.20) | 29.18 ± 15.13 (6.10–54.90) | NS         | p > 0.05          |
| Na               | mg l⁻¹     | 0.83 ± 0.42 (0.46–1.82) | 1.12 ± 0.44 (0.59–2.19) | 1.04 ± 0.45 (0.55–1.95) | 0.93 ± 0.42 (0.41–1.78) | NS         | p < 0.05          |
| Cl               | mg l⁻¹     | 23.24 ± 18.78 (7.00–73.20) | 43.31 ± 39.51 (15.20–150.30) | 38.57 ± 34.94 (11.50–26.90) | 26.88 ± 18.75 (10.70–82.80) | 500        | p < 0.05          |
| P                | mg l⁻¹     | 0.65 ± 0.42 (0.12–1.30) | 1.27 ± 1.06 (0.33–3.28) | 1.26 ± 0.90 (0.35–3.17) | 0.84 ± 0.59 (0.16–1.95) | NS         | p > 0.05          |
| NH₄H             | mg l⁻¹     | 0.09 ± 0.05 (0.02–0.16) | 0.20 ± 0.10 (0.05–0.34) | 0.18 ± 0.16 (0.06–0.59) | 0.12 ± 0.05 (0.03–0.19) | NS         | p < 0.05          |
| NO₂              | mg l⁻¹     | 0.05 ± 0.03 (0.01–0.12) | 0.14 ± 0.18 (0.04–0.69) | 0.13 ± 0.19 (0.02–0.71) | 0.08 ± 0.05 (0.01–0.17) | NS         | p > 0.05          |
| NO₃              | mg l⁻¹     | 1.55 ± 0.59 (0.74–2.48) | 2.96 ± 1.75 (0.93–6.27) | 2.86 ± 1.64 (0.77–5.10) | 1.77 ± 0.72 (1.11–3.19) | 50         | p < 0.05          |
| SO₄              | mg l⁻¹     | 0.63 ± 0.35 (0.27–1.49) | 1.07 ± 0.48 (0.53–2.30) | 0.96 ± 0.40 (0.47–1.84) | 0.82 ± 0.39 (0.21–1.71) | 500        | p > 0.05          |
| Fe               | mg l⁻¹     | 0.68 ± 0.48 (0.19–1.85) | 1.79 ± 1.22 (0.57–4.12) | 1.50 ± 1.27 (0.27–4.12) | 0.90 ± 0.50 (0.25–1.90) | 0.4        | p < 0.05          |
| Mn               | mg l⁻¹     | 0.07 ± 0.05 (0.01–0.17) | 0.16 ± 0.08 (0.06–0.32) | 0.11 ± 0.07 (0.01–0.22) | 0.09 ± 0.04 (0.03–0.19) | NS         | p < 0.05          |
| Zn               | mg l⁻¹     | 0.26 ± 0.16 (0.09–0.55) | 0.67 ± 0.33 (0.24–1.35) | 0.59 ± 0.36 (0.09–1.29) | 0.39 ± 0.22 (0.11–0.81) | 3          | p > 0.05          |

(Continued)
The minimum and maximum range of values obtained across the stations were: water temperature (24.40–29.10 °C), pH (4.40–6.82), colour (1.70–15.30 Pt.Co), turbidity (0.90–13.90 NTU), TSS (2.10–19.40 mg⁻¹), TDS (2.10–19.40 mg⁻¹), DO (4.10–7.10 mg⁻¹), BOD₅ (1.10–4.70 mg⁻¹), Na (0.41–2.19 mg⁻¹), Cl (7.00–15.30 mg⁻¹), P (0.12–3.28 mg⁻¹), NH₄N (0.02–0.09 mg⁻¹), NO₂ (0.01–0.71 mg⁻¹), NO₃ (0.74–6.27 mg⁻¹) and SO₄ (0.21–2.30 mg⁻¹). The ranks of the heavy metal concentrations in the water were in this rank: Fe > Zn > Mn > Cu > Cr > Pb > Cr > Ni > V.

The results of the Water Quality Index in Ossiomo River

Table 4 shows the summary of the Water Quality Index (WQI) for the individual stations. The water quality index at stations 1, 2, 3, and 4 varied with minimum and maximum

### Table 3 (continued)

| Parameters | Units | Station 1 (Min-Max) | Station 2 (Min-Max) | Station 3 (Min-Max) | Station 4 (Min-Max) | WHO (2004) | Significant values |
|------------|-------|---------------------|---------------------|---------------------|---------------------|-------------|--------------------|
| Cu         | mg l⁻¹ | 0.03 ± 0.03 (0.01–0.09) | 0.06 ± 0.04 (0.01–0.13) | 0.06 ± 0.05 (0.00–0.18) | 0.04 ± 0.03 (0.00–0.10) | 0.05 | p > 0.05 |
| Cr         | mg l⁻¹ | 0.01 ± 0.01 (0.00–0.05) | 0.04 ± 0.03 (0.00–0.13) | 0.04 ± 0.05 (0.00–0.18) | 0.02 ± 0.03 (0.00–0.09) | 0.03 | p > 0.05 |
| Cd         | mg l⁻¹ | 0.01 ± 0.01 (0.00–0.04) | 0.03 ± 0.02 (0.00–0.08) | 0.03 ± 0.04 (0.00–0.15) | 0.03 ± 0.02 (0.00–0.07) | 0.01 | p > 0.05 |
| Ni         | mg l⁻¹ | 0.00 ± 0.00 (0.00–0.02) | 0.01 ± 0.02 (0.00–0.04) | 0.01 ± 0.02 (0.00–0.05) | 0.00 ± 0.01 (0.00–0.02) | NS | p > 0.05 |
| Pb         | mg l⁻¹ | 0.01 ± 0.02 (0.00–0.08) | 0.04 ± 0.04 (0.00–0.12) | 0.04 ± 0.04 (0.00–0.17) | 0.01 ± 0.01 (0.00–0.04) | 0.01 | p > 0.05 |
| V          | mg l⁻¹ | 0.00 ± 0.00 (0.00–0.01) | 0.01 ± 0.01 (0.00–0.03) | 0.01 ± 0.02 (0.00–0.05) | 0.00 ± 0.00 (0.00–0.01) | NS | p > 0.05 |
| THC        | mg l⁻¹ | 0.04 ± 0.03 (0.00–0.09) | 0.11 ± 0.04 (0.07–0.18) | 0.09 ± 0.06 (0.02–0.24) | 0.07 ± 0.03 (0.03–0.12) | NS | p < 0.05 |

Note:
Unit of measurement: pH has no unit. p < 0.05 – Significant difference; p > 0.05 – No significant difference. NS: indicates not specified and N/A; indicates not available.
WHO: World Health Organisation.

### Table 4 Summary of water quality index (WQI) for the individual stations in Ossiomo River (Ologbo axis) Benin city Nigeria. Water quality index.

| Station 1 | Station 2 | Station 3 | Station 4 |
|-----------|-----------|-----------|-----------|
| Mean ± SD (Min-Max) | Mean ± SD (Min-Max) | Mean ± SD (Min-Max) | Mean ± SD (Min-Max) |
| WQI | 66.38 ± 56.18 (3.38–197.2) | 163.79 ± 106.51 (27.59–420.61) | 161.43 ± 177.13 (18.68–728.50) | 129.95 ± 72.86 (15.09–311.6) |

Note:
Status of Water Quality Index (WQI) stating their descriptions: <50 (Excellent); 50–100 (Good); 100–200 (Poor); 250–300 (very poor) and > 300 (unsuitable for drinking) Ramakrishna, Sadashivaiah & Ranganna (2009), Abbasnia et al. (2018) and (2018b) and 0–25 (Excellent water quality) 26–50 (Good water quality) 51–75 (Poor water quality) 76–100 (Very poor water quality) and >100 (unsuitable for drinking) (Tyagi et al., 2013).
values of 3.38–197.24, 27.59–420.61, 18.68–728.50, and 15.09–311.6 respectively.
The mean values of the WQI at stations 1, 2, 3, and 4 were 66.38 (12.73%), 163.79, 161.43, and 121.95 (87.27%) respectively.

Figure 2 shows the monthly variations of WQI across four stations in the Ossiomo River. The results showed that the month of January 2016, had the highest WQI.

The results of the probabilistic health risk assessment of Ossiomo River

The results of the heavy metals exposure through dermal and ingestion routes of Ossiomo River were summarized in Table 5. The average ranks of exposure through ingestion (Exping) and exposure through dermal (Expderm) were observed in this
order: Fe > Mn > Zn > Cu > Pb > Cr > Ni > Cd > V and Fe > Mn > Ni > Pb > Zn > V > Cr > Cu > Cd respectively (Table 5).

The result of the mean HQ of the metal was considered greater than 1 (>1) for Cr (2.55) (Table 5). The observed values for the HI via the ingestion (HIing) and dermal (HIderml) pathways were observed to be 4.35 and 0.46 respectively (Table 5). The sum of the HQs (4.81) was also > 1. The values obtained from the evaluation of the CDI for the selected heavy metals (Fe, Mn, Zn, Cu, Cr, Cd, Ni, Pb, and V) were 0.0362, 0.0033, 0.0141, 0.0014, 0.0008, 0.0008, 0.002, 0.0008, and 0.0002 respectively (Table 5).

The results of the CRing risk via ingestion for Pb, Cr, and Cd are shown in Table 6. The values obtained were 6 × 10⁻³, 4.00 × 10⁻¹, and 1.22 × 10⁰ respectively.

### DISCUSSION

In this study, the physicochemical and heavy metal assessment carried on Ossiomo River showed that some parameters were slightly higher than the WHO (2004, 2008) standard limits. The pH level of the water was slightly acidic. The variations in the concentrations of the water parameters may be a result of seasonality. This finding is closely related to what was obtained in previous studies by Oboh & Agbala (2017) in Siluko River southern Nigeria, Ayandirana, Fawolea & Dahunsi (2018) in Oluwa River Southwestern Nigeria, and Emenike et al. (2019) to similar water bodies in South-south Nigeria which have the same environmental factors influencing the water characteristics.

On the other hand, when the water parameters were compared with the WHO standards for drinking water, the findings of this study revealed ecological parameters like water temperature, turbidity, dissolved oxygen, biological dissolved oxygen, phosphate, iron, manganese, nickel, and lead which were lesser than the WHO (2004, 2008) standard limits. The contents of the physicochemical and heavy metal record in this river ecosystem were observed to be a function of anthropogenic activities located close to the river (Anani & Olomukoro, 2018; Kumar, Singh & Ojha, 2018; Olomukoro & Anani, 2019; Olatunji & Anani, 2020).

This study showed that the quality of water at station 1 was poor for human consumption. Station 1 had a value that was more than the benchmark of 26–50 for good water as established by Tyagi et al. (2013). Stations 2–4 were considered unsuitable for drinking with values that were more than the benchmark of 100 for both excellent and good water, as established by Ramakrishna, Sadashivaiah & Ranganna (2009). The finding was different from what was obtained by Oboh & Agbala (2017) in the range of

### Table 6 Summary of cancer risk (cr) assessment for some selected metals in water samples from Ossiomo River (ologbo axis) through dermal and ingestion pathways during the sampling periods. Cancer risks.

| Elements | EXP_ing | SF_ing | CR |
|----------|---------|--------|----|
| Pb       | 0.001   | 8.50E+00 | 6.80E⁻⁰³ |
| Cr       | 0.001   | 5.00E+02 | 4.00E⁻⁰¹ |
| Cd       | 0.000   | 6.10E+03 | 1.22E⁺⁰⁰ |

Note: EXP_ing, exposure via ingestion pathway; SF_ing, slope factor of the ingestion pathway; CR, cancer risk.
11.24–16.15 in Siluko River Southern Nigeria. However, a similar finding was reported by Akinbile & Omoniyi (2018) with WQI of 44.61 and 44.91 at River Ogbese, Nigeria when classified and interpreted according to the methods of Pradyusa et al. (2009) and Elizabeta et al. (2010) respectively. The WQI of 259.04 and 236.51 were reported by Iwar, Utsev & Hassan (2021) for River Benue Nigeria. The authors classified the water as poor and unfit for drinking purposes. Etim et al. (2013), reported the WQI of 55.05–84.94 for different water streams in Niger Delta water in Nigeria which were considered poor for drinking purposes. Similarly, Ogbozige et al. (2017) reported the WQI of 44.95–60.80 from River Kaduna, Nigeria. Edwin & Murtala (2013), Ochuko et al. (2014), Otene & Nnadi (2019), and Madilonga et al. (2021) reported the WQI of 41.3–52.9, 51–70, 29.732–79.342, and WQI > 100 for River Asa Ilorin, Nigeria, River Ase Southern Nigeria, Minichinda Stream, Port Harcourt, Nigeria, and Mutangwi River, Limpopo Province, South Africa respectively. The water was classified as poor for human consumption.

In a relative study done by Ramakrishna, Sadashivaiah & Ranganna (2009) in Tumkur Taluk India, the authors reported the WQI values of 89.21 to 660.56 which was about 63% of the water, was considered poor and 27% was considered okay for drinking. Abbasnia et al. (2018a), and (2018b) investigated the surface water in Baluchistan province in Iran. The authors reported that about 25% of the water was evaluated poor for consumption, 25% was excellent, and 50% was okay for drinking. RadFard et al. (2019) investigated the WQI of groundwater in Bardaskan villages Iran of 23.3 and 13.3% poor and very poor correspondingly. Meanwhile, 3.3 and 60% of the water were excellent and good respectively.

It was observed that the quality of water in this ecosystem was likely influenced by both anthropogenic; mainly agronomic activities, petrochemical influences, and natural processes. This finding is similar to the work by Naveedullah Hashmi et al. (2014) on the evaluation of Siling surface reservoir in China which linked human activities as one of the major sources of water contamination. This was also collaborated by the works of Anani & Olomukoro (2018), Kumar, Singh & Ojha (2018), Olomukoro & Anani (2019), and Olutunji & Anani (2020). More so, the findings from the WQI in this study revealed that the water was influenced by seasonality and Cd sourced from agronomic influence. This leads to a change in the water quality characteristics and possible health risks if the water is consumed without proper treatment.

The potential health risk from heavy metals exposure through the dermal and ingestion routes of the water sourced from Ossiomo River after quantification and evaluation was considered not too high in terms of possible human impacts. This finding is not far different from what was obtained by Naveedullah Hashmi et al. (2014); 41.0 µg/L for Fe, Mn 37.32 µg/L, and Cd 1.18 µg/L from Siling surface reservoir in China for the summer/raining season period.

The observed values for the HQ and HI via the ingestion (Hling) pathway were considered to be greater than 1 (>1). Thus, there were possible non-carcinogenic health risks via direct ingestion of the water. Similar results were also obtained by Li & Zhang (2010) for Han River, China. On the contrary, Naveedullah Hashmi et al. (2014) reported
the HQ (0.554) and HI (0.985) < 1 for the ingestion and dermal pathways. On the other hand, Anyanwu & Nwachukwu (2020) evaluated the possible ingestion hazard a South-eastern Nigeria River might pose if consumed without treatment. In their study, an HI > 1 for all the stations was recorded. This was dissimilar from what was obtained in this study. However, an HQ > 1 was obtained by the same authors for Fe, Cd, and Mn. Contrarily in this study, an HQ > 1 was obtained for only Cr.

It was obvious that in the ingestion pathway, the observed values fluctuated within the safe unity limit of < 1 for the HQ and > 1 for the HI. These findings indicated non-carcinogenic health risks via direct ingestion contact with inhabitants. This is similar to what was obtained by Iqbal & Shah (2012) on the hazard quotients (HQ > 1) of heavy metals in Simly (23.00) and Khanpur (18.85) freshwater lakes Pakistan respectively. There was no potential risk posed by the dermal pathway. However, most of the \( \Sigma \) Hing/derm of metals which were Fe, Zn, Mn, Cu, Cr, and Ni, fluctuated within the unity limit set by US EPA (2004). The likely main contributors to the non-carcinogenic health risks in this current study could be linked to Cr and Mn influence on the ecosystem. This finding is not far different from the works of Naveedullah Hashmi et al. (2013, 2014), He et al. (2004) and Wu et al. (2009) proposed that insecticides, from farm practice and sewage from domestic activities, might increase the concentration of Zn, Fe, and Mn. This, in turn, can affect the water quality parameters. This shows that the heavy metals present in the ecosystem may harm human health if consumed without proper treatment using conventional methods like boiling and chlorination.

The results of the CRing risk via ingestion for Pb, Cr, and Cd were slightly higher than the target remedial goal of carcinogenic risks (1.0 × 10\(^{-6}\) to 1.0 × 10\(^{-4}\)) for surface water intake as set by (US EPA, 1989; US EPA, 2004; Vieira et al., 2011; Yu, Fang & Ru, 2010). This finding was quite dissimilar to what was obtained by Iqbal & Shah (2012) in Simly and Khanpur lakes for Pb (5.4 × 10\(^{3}\) and 5.9 × 10\(^{3}\)), Cr (1.2 × 10\(^{5}\) and 7.2 × 10\(^{2}\)), and Cd (3.2 × 10\(^{3}\) and 3.9 × 10\(^{3}\)), respectively. George, David & Joseph (2015), obtained 1.50 × 10\(^{-6}\) and 50.15 × 10\(^{-7}\) for Cr and Cd respectively. The implication here is that there might be a potential carcinogenic risk if the water is consumed when the metal contents are higher than the target limits set.

**CONCLUSIONS**

The computed details of all the values of the chemical elements, WQI, and health indices gave a better picture of the overall status of Ossiomo River and also reflect the parameters of most importance. The WQI indicated that likely, station 1 is fit for consumption as at the time of this study and indicated stations 2, 3, and 4 as unfit for consumption. The health risk assessment revealed likely non-carcinogenic risks via the ingestion contacts and possible carcinogenic risks if the water is consumed when the metal contents are higher than the target limits set. Sustainable farming and treatment of wastes from industrial outputs should be the main management of this watercourse. Proper treatment using conventional methods like boiling and chlorination should be recommended.
ACKNOWLEDGEMENTS
We thank Mr. Ifeanyi Maxwell Ezenwa and Dr. Abdul-Rahman Dirisu respectively for their technical support and fair criticism.

ADDITIONAL INFORMATION AND DECLARATIONS

Funding
The authors received no funding for this work. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Competing Interests
The authors declare that they have no competing interests.

Author Contributions
- Osikemekha Anthony Anani conceived and designed the experiments, performed the experiments, analyzed the data, prepared figures and/or tables, authored or reviewed drafts of the paper, and approved the final draft.
- John Ovie Olomukoro conceived and designed the experiments, performed the experiments, analyzed the data, prepared figures and/or tables, authored or reviewed drafts of the paper, technical supervision, and approved the final draft.

Data Availability
The following information was supplied regarding data availability:
- The raw data is available in the Supplemental File.

Supplemental Information
Supplemental information for this article can be found online at http://dx.doi.org/10.7717/peerj.12487#supplemental-information.

REFERENCES
Abbasnia A, Alimohammadi M, Mahvi AH, Nabizadeh R, Yousefi M, Mohammadi AA, Pasalari H, Mirzabeigi M. 2018a. Assessment of groundwater quality and evaluation of scaling and corrosiveness potential of drinking water samples in villages of Chabahr city, Sistan and Baluchistan province in Iran. Data in Brief 16(2):182–192 DOI 10.1016/j.dib.2017.11.003.

Abbasnia A, Radfard M, Mahvi AH, Nabizadeh R, Yousefi M, Soleimani H, Alimohammadi M. 2018b. Groundwater quality assessment for irrigation purposes based on irrigation water quality index and its zoning with GIS in the villages of Chabahar, Sistan, and Baluchistan, Iran. Data in Brief 19:623–631 DOI 10.1016/j.dib.2018.05.061.

Akinbile CO, Omoniyi O. 2018. Quality assessment and classification of Ogbese river using water quality index (WQI) tool. Sustainable Water Resources Management 4:1023–1030 DOI 10.1007/s40899-018-0226-8.

America Public Health Association (APHA). 1998. Standard methods of examination of water and wastewaters. 20th edition. Washington, DC: APHA, 1213.

American Public Health Association (APHA). 2005. Standard methods for the examination of water and wastewater. 21st edition. Washington DC: APHA, 120.
Anani OA, Olomukoro JO. 2018. Trace metal residues in a tropical watercourse sediment in Nigeria: health risk implications. *IOP Conference Series: Earth and Environmental Science* 210:012005 DOI 10.1088/1755-1315/210/1/012005.

Anani OA, Olomukoro JO, Enuneku AA. 2020. Geospatial mapping, environmetrics and indexing approach for a tropical River sediment in Southern Nigeria. *Pakistan Journal of Scientific and Industrial Research Series A: Physical Sciences* 63A(3):176–187 2020 DOI 10.52763/PJSIR.PHYS.SCI.63.3.2020.176.187.

Anani OA, Olomukoro JO, Ezenwa IM. 2020. Limnological evaluation in terms of water quality of Ossiomo River, Southern Nigeria. *International Journal of Conservation Science* 11(2):571–588.

Anyanwu ED, Nwachukwu ED. 2020. Heavy metal content and health risk assessment of a South-eastern Nigeria River. *Applied Water Science* 10(9):210 DOI 10.1007/s13201-020-01296-y.

Ayandiran TA, Ayandele AA, Dahunsi SO, Ajala OO. 2014. Microbial assessment and prevalence of antibiotic resistance in polluted Oluwa River, Nigeria. *The Egyptian Journal of Aquatic Research* 40(3):291–299 DOI 10.1016/j.ejar.2014.09.002.

Ayandiran TA, Fawolea OO, Dahunsi SO. 2018. Water quality assessment of bitumen polluted Oluwa River, South-Western Nigeria. *Water Resources and Industry* 19(5):13–24 DOI 10.1016/j.wri.2017.12.002.

Azizullah A, Khattak MNK, Richter P, Hader DP. 2011. Water pollution in Pakistan and its impact on public health – a review. *Environment International* 37(2):479–497 DOI 10.1016/j.envint.2010.10.007.

Briki M, Zhu Y, Gao Y, Shao M, Ding H, Ji H. 2017. Distribution and health risk assessment to heavy metals near smelting and mining areas of Hezhang, China. *Environmental Monitoring and Assessment* 189(9):381 DOI 10.1007/s10661-017-6153-6.

Casanovas-Massana A, Blanch AR. 2013. Characterization of microbial populations associated with natural swimming pools. *International Journal of Hygiene and Environmental Health* 216(2):132–137 DOI 10.1016/j.ijheh.2012.04.002.

Chinedu S, Nwinyi O. 2011. Assessment of water quality in Canaanland, Ota, Southwest Nigeria. *Agriculture and Biology Journal of North America* 2(4):577–583 DOI 10.5251/abjna.2011.2.4.577.583.

Cude CG. 2001. Oregon water quality index: a tool for evaluating water quality management effectiveness. *Journal of the American Water Resources Association* 37(1):125–137 DOI 10.1111/j.1752-1688.2001.tb05480.x.

Dahunsi SO, Ayandiran TA, Oranusi US, Owamah HI. 2014. Drinking water quality and public health of selected communities in South Western Nigeria. *Water Quality, Exposure and Health* 6(3):143–153 DOI 10.1007/s12403-014-0118-6.

De Miguel A, Iribarren I, Chacon E, Ordonez A, Charlesworth S. 2007. Risk-based evaluation of the exposure of children to trace elements in playgrounds in Madrid (Spain). *Chemosphere* 66(3):505–513 DOI 10.1016/j.chemosphere.2006.05.065.

Dzulfakar MA, Shaharuddin MS, Muahmin AA, Syazwan AI. 2011. Risk assessment of aluminum in drinking water between two residential areas. *Water* 3(3):882–893 DOI 10.3390/w3030882.

Edokpayi JN, Enitan AM, Mutileni N, Odiyo JO. 2018. Evaluation of water quality and human risk assessment due to heavy metals in groundwater around Muledane area of Vhembe District, Limpopo Province, South Africa. *Chemistry Central Journal* 12(1):2 DOI 10.1186/s13065-017-0369-y.
Edwin AI, Murtala AI. 2013. Determination of water quality index of river Asa, Ilorin, Nigeria. *Advances in Applied Science Research* 4(6):277–284.

Elizabeta CA, Michael GH, Andrzej K, Paul SA. 2010. Assessment of pollutant transport and river water quality using mathematical models. *Academia Romana* 55(4):285–291.

Emenike D, Tenebe I, Ogarekpe N, Omole D, Nnaji C. 2019. Probabilistic risk assessment and spatial distribution of potentially toxic elements in groundwater sources in Southwestern Nigeria. *Scientific Reports* 9(1):15920 DOI 10.1038/s41598-019-52325-z.

Emenike CP, Tenebe IT, Omole DO, Ngene BU, Oniemayin BI, Maxwell O, Onoka BI. 2017. Accessing safe drinking water in sub-Saharan Africa: issues and challenges in South-West Nigeria. *Sustainable Cities and Society* 30(3):263–272 DOI 10.1016/j.scs.2017.01.005.

Enuneku A, Omoruyi O, Tongo I, Ogbomida E, Ogbeide O, Ezemonye L. 2018. Evaluating the potential health risks of heavy metal pollution in sediment and selected benthic fauna of Benin River Southern Nigeria. *Applied Water Science* 8(3):278–400 DOI 10.1016/j.toxrep.2018.11.010.

Fakhri Y, Mohseni-Bandpei A, Conti GO, Ferrante M, Cristaldi A, Jeihooni AK, Dehkordi MK, Alinejad A, Rasoulzadeh H, Mohseni SM. 2018a. Systematic review and health risk assessment of arsenic and lead in the fished shrimps from the Persian gulf. *Food Chemical and Toxicology* 113:278–400 DOI 10.1016/j.fct.2018.01.046.

Fakhri Y, Mohseni-Bandpei A, Conti GO, Ferrante M, Cristaldi A, Jeihooni AK, Dehkordi MK, Alinejad A, Rasoulzadeh H, Mohseni SM. 2018b. Carcinogenic and non-carcinogenic health risks of metal (oids) in tap water from Ilam city, Iran. *Food and Chemical Toxicology* 118:204–211 DOI 10.1016/j.fct.2018.04.039.

George YH, David KE, Joseph KA. 2015. Distribution and risk assessment of heavy metals in surface water from pristine environments and major mining areas in Ghana. *Journal of Health and Pollution* 5(9):86–95 DOI 10.5696/2156-9614-5-9.86.

Giridharan L, Venugopal T, Jayaprakash M. 2010. Identification and evaluation of hydrogeochemical processes on river Cooum, South India. *Environmental Monitoring and Assessment* 162(1–4):277–289 DOI 10.1007/s10661-009-0795-y.

He ZL, Zhang MK, Calvert DV, Stoffella PJ, Yang XE, Yu S. 2004. Transport of heavy metals in surface runoff from vegetable and citrus fields. *Soil Science Society of America Journal* 68(5):1662 DOI 10.2136/sssaj2004.1236.

Iqbal J, Shah MH. 2012. Health risk assessment of metals in surface water from freshwater source lakes Pakistan. *Human and Ecological Risk Assessment: An International Journal* 19(6):1530–1543 DOI 10.1080/10807039.2012.716681.

Iwar RT, Utsev JT, Hassan M. 2021. Assessment of heavy metal and physico-chemical pollution loadings of River Benue water at Makurdi using water quality index (WQI) and multivariate statistics. *Applied Water Science* 11(7):124 DOI 10.1007/s13201-021-01456-8.

Kamarehie B, Jafari A, Zarei A, Fakhri Y, Ghaderpoori M, Alinejad A. 2019. Non-carcinogenic health risk assessment of nitrate in bottled drinking waters sold in Iranian markets: A Monte Carlo simulation. *Accreditation and Quality Assurance* 24(6):417–426 DOI 10.1007/s00769-019-01397-5.

Kayode AAA, Babayemi JO, Abam EO, Kayode OT. 2011. Occurrence and health implications of high concentrations of Cadmium and Arsenic in drinking water sources in selected towns of Ogun State South-West Nigeria. *Journal of Toxicology and Environmental Health Sciences* 3:385–391.
Kazi TG, Arain MB, Jamali MK, Jalbani N, Afridi HI, Sarfraz RA, Baig JA, Shah AQ. 2009. Assessment of water quality of polluted lake using multivariate statistical techniques: a case study. Ecotoxicology and Environmental Safety 72:301–309 DOI 10.1016/j.ecoenv.2008.02.024.

Khan MYA, Gani KM, Chakrapani GJ. 2015. Assessment of surface water quality and its spatial variation. A case study of Ramganga River Ganga Basin India. Arabian Journal of Geosciences 9(1):1–9 DOI 10.1007/s12517-015-2134-7.

Kumar B, Singh UK, Ojha SN. 2018. Evaluation of geochemical data of Yamuna River using WQI and multivariate statistical analyses: a case study. International Journal of River Basin Management 17(2):143–155 DOI 10.1080/15715124.2018.1437743.

Li SY, Zhang QF. 2010. Spatial characterization of dissolved trace elements and heavy metals in the upper Han River (China) using multivariate statistical techniques. Journal of Hazardous Materials 176(1–3):579–588 DOI 10.1016/j.jhazmat.2009.11.069.

Liang Z, He Z, Zhou X, Powell CA, Yang Y, He LM, Stoffella PJ. 2013. Impact of mixed land-use practices on the microbial water quality in a subtropical coastal watershed. Science of The Total Environment 449:426–433 DOI 10.1016/j.scitotenv.2013.01.087.

Liang F, Yang SG, Sun C. 2011. Primary health risk analysis of metals in surface water of Taihu lake, China. Bulletin of Environmental Contamination and Toxicology 4(4):404–408 DOI 10.1007/s00128-011-0379-8.

Madilonga RT, Edokpayi JN, Volenzo ET, Durowoju OS, Odiyo JO. 2021. Water quality assessment and evaluation of human health risk in Mutangwi River, Limpopo Province, South Africa. International Journal of Environmental Research and Public Health 18(13):6765 DOI 10.3390/ijerph18136765.

Manahan SE. 2010. Environmental chemistry. 9th edn. Boca Raton: CRC Press, 52.

Muhammad S, Shah MT, Khan S. 2011. Health risk assessment of heavy metals and their source apportionment in drinking water of Kohistan region, northern Pakistan. Microchemical Journal 98(2):334–343 DOI 10.1016/j.microc.2011.03.003.

Naveedullah Hashmi MZ, Yu C, Shen H, Duan D, Shen C, Lou L, Chen Y. 2013. Risk assessment of heavy metals pollution in agricultural soils of Siling Reservoir Watershed in Zhejiang Province, China. BioMed Research International 2013(2):1–10 DOI 10.1155/2013/590306.

Naveedullah Hashmi MZ, Yu C, Shen H, Duan D, Shen C, Lou L, Chen Y. 2014. Concentrations and human health risk assessment of selected heavy metals in surface water of the Siling reservoir watershed in Zhejiang Province, China. Polish Journal of Environmental Studies 23(3):801–811.

Naz A, Mishra BK, Gupta SK. 2016. Human health risk assessment of chromium in drinking water: a case study of Sukinda Chromite Mine, Odisha, India. Exposure and Health 8(2):253–264 DOI 10.1007/s12403-016-0199-5.

Oboh P, Agbala CS. 2017. Water quality assessment of the Siluko River southern Nigeria. African Journal of Aquatic Science 42(3):279–286 DOI 10.2989/16085914.2017.1371579.

Ochuko U, Thaddeus O, Oghenero O-A, John EE. 2014. A comparative assessment of water quality index (WQI) and suitability of river Ase for Domestic Water Supply in Urban and Rural Communities in Southern Nigeria. International Journal of Humanities and Social Science 4:1.

Ogbozige FJ, Adie DB, Igboro SB, Giwa A. 2017. Evaluation of the water quality of River Kaduna, Nigeria using water quality index. Journal of Applied Sciences and Environmental Management 21(6):1119–1126 DOI 10.4314/jasem.v21i6.21.

Okorafor AM, Agbo BE, Johnson AM, Chiorhe M. 2012. Physicochemical and bacteriological characteristics of selected steams and borehole in Akankpa and Calabar municipality Nigeria. Archives of Applied Science Research 4(5):2115–2121 DOI 10.1016/j.wri.2017.12.002.
Olatunji EO, Anani OA. 2020. Bacteriological and physicochemical evaluation of River Ela, Edo State Nigeria: water quality and perceived community health concerns. *Journal of Bio Innovation* 9(5):736–749 DOI 10.46344/JBINO.2020.v09i05.09.

Olomukoro JO, Anani OA. 2019. Evaluation of aquatic macro-invertebrate populations: a model for emergent bio-monitoring guide for quantifying uncleanness of some Rivers in Northern Central Nigeria. *Nigerian Journal of Technological Research* 114(2):54–62 DOI 10.4314/njtr.v14i2.7.

Olmukoro JO, Anani OA. 2019. Evaluation of aquatic macro-invertebrate populations: a model for emergent bio-monitoring guide for quantifying uncleanness of some Rivers in Northern Central Nigeria. *Nigerian Journal of Technological Research* 114(2):54–62 DOI 10.4314/njtr.v14i2.7.

Pradyusa S, Basanta KM, Chitta RP, Swoyan RP. 2009. Assessment of water quality index in Mahanadi and Atharabanki Rivers and Taldanda Canal in Paradip Area, India. *Journal of Human Ecology* 26(3):153–161 DOI 10.1080/09709274.2009.11906177.

Qasemi M, Farhang M, Biglari H, Afsharnia M, Ojrati A, Khani F, Samiee M, Zarei A. 2018. Health risk assessments due to nitrate levels in drinking water in villages of Azadshahr, northeastern Iran. *Environmental Earth Science* 77(23):782 DOI 10.1007/s12665-018-7973-6.

Qu L, Huang H, Xia F, Liu Y, Dahlgren RA, Zhang M, Mei K. 2018. Risk analysis of heavy metal concentration in surface waters across the rural-urban interface of the Wen-Rui Tang River, China. *Environmental Pollution* 237:639–649 DOI 10.1016/j.envpol.2018.02.020.

RadFard M, Sei M, Hashemi AHG, Zareid A, Saghi MH, Shalyari N, Morovati R, Heidarinejad Z, Samaei MR. 2019. Protocol for the estimation of drinking water quality index (DWQI) in water resources: Artificial neural network (ANFIS) and Arc-Gis. *MethodsX* 6:1021–1029 DOI 10.1016/j.mex.2019.04.027.

Ramakrishna CR, Sadashivaiah C, Ranganna G. 2009. Assessment of water quality index for the groundwater in Tumkur Taluk, Karnataka State, India. *E-Journal of Chemistry* 6(2):523–530 DOI 10.1155/2009/757424.

Sener S, Sener E, Davraz A. 2017. Evaluation of water quality using water quality index (WQI) method and GIS in Aksu River (SW-Turkey). *Science of The Total Environment* 584–585(3–4):131–144 DOI 10.1016/j.scitotenv.2017.01.102.

Shams M, Nezhad NT, Dehghan A, Aliyadi H, Paydar M, Mohammadi AA, Zarei A. 2020. Heavy metals exposure, carcinogenic and non-carcinogenic human health risks assessment of groundwater around mines in Joghatai, Iran. *International Journal of Environmental Analytical Chemistry* 15:1–16 DOI 10.1080/03067319.2020.1743835.

Shil S, Singh UK, Mehta P. 2019. Water quality assessment of a tropical river using water quality index (WQI), multivariate statistical techniques and GIS. *Applied Water Science* 9(7):629 DOI 10.1007/s13201-019-1045-2.

Sojobi SO, Owamah HI, Dahunsi SO. 2014. Comparative study of household water treatment in a rural community in Kwara state Nigeria. *Nigerian Journal of Technology* 33(1):134–140 DOI 10.4314/njt.v33i1.18.

Soleimani H, Nasri O, Ojaghi B, Pasalar H, Hosseini M, Hashemzadeh B, Kavosi A, Masoumi S, Radfard M, Adibzadeh A. 2018. Data on drinking water quality using water quality index (WQI) and assessment of groundwater quality for irrigation purposes in Qorveh & Dehgolan, Kurdistan, Iran. *Data in Brief* 20(67):375–386 DOI 10.1016/j.dib.2018.08.022.
Song J, Li F, Li Q, Liu Q. 2012. Distribution and contamination risk assessment of dissolved trace metals in surface waters in the Yellow River Delta. Human and Ecological Risk Assessment: An International Journal 19(6):1514–1529 DOI 10.1080/10807039.2012.708254.

Tyagi P, Sharma B, Singh P, Dobhal R. 2013. Water quality assessment in terms of water quality index. American Journal of Water Resources 1(3):34–38 DOI 10.12691/ajwr-1-3-3.

US EPA. 2004. Risk assessment guidance for superfund Volume I: human health evaluation manual (Part E supplemental guidance for dermal risk assessment). Washington, DC: Office of Superfund Remediation and Technology Innovation, 156.

US EPA. 1989. Risk assessment guidance for superfund. Vol. I: human health evaluation manual (Part A) EPA/540/1- 89/002. 291. Available at https://www.epa.gov/sites/production/files/2015-09/documents/rags_a.pdf.

US EPA. 1993. Reference dose (RfD): description and use in health risk assessments|| background document 1A, Integrated risk information system. Available at http://www.epa.gov/IRIS/rfd.htm
go.

USEPA. 2002. Supplemental guidance for developing soil screening levels for superfund sites, OSWER 9355. Washington, DC: Office of Emergency and Remedial response, 4–24.

USEPA. 2010. Risk-based concentration table. United States Environmental Protection Agency. Available at http://www.epa.gov/reg3hwmd/risk/human/index.htm.

USEPA IRIS. 2011. Integrated risk information system. Washington, DC: US Environmental Protection Agency Region I. Available at http://www.epa.gov/iris/ (accessed 21 April 2017).

Vieira C, Morais S, Ramos S, Delerue-Matos C, Oliverira M. 2011. Mercury cadmium lead and arsenic levels in three pelagic fish species from the Atlantic Ocean: Intra- and inter-specific variability and human health risks for consumption. Food and Chemical Toxicology 49(4):923 DOI 10.1016/j.fct.2010.12.016.

WHO. 2004. Guidelines for drinking water quality. 3rd edition. Geneva: World Health Organization, 516.

WHO. 2008. Guidelines for drinking water quality: incorporating first and second addenda. Recommendations. 3rd edition. Geneva: WHO Press, 668.

Wu B, Zhao DY, Jia HY, Zhang Y, Zhang XX, Cheng SP. 2009. Preliminary risk assessment of trace metal pollution in surface water from Yangtze River in Nanjing Section, China. Bulletin of Environmental Contamination and Toxicology 82(4):405 DOI 10.1007/s00128-008-9497-3.

Yu FC, Fang GH, Ru XW. 2010. Eutrophication, health risk assessment and spatial analysis of water quality in Gucheng Lake, China. Environmental Earth Sciences 59(8):1741–1748 DOI 10.1007/s12665-009-0156-8.