Effect of environmental pollution on susceptibility of sesquioxide-rich soils to water erosion

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ABSTRACT
This work assessed the impact of environmental pollution on soils susceptibility to water erosion within South-eastern Nigeria. Sources of pollutants which could possibly affect the chemical composition of runoff; hence its pH, were first determined by remote sensing and field observations. Rain and runoff water samples collected within the study area were analysed for its physicochemical compositions. Soil samples were also collected and analysed for their geotechnical properties, and chemical composition of their fine fractions. An empirical method was then employed to determine the effect of change in chemical composition of runoff on the susceptibility of the studied soil to water erosion. This was achieved by conducting soil aggregate slaking, dispersion and dissolution tests on aqueous solutions of varying pH. Results from the experiment shows that the fine particle fractions of the soils are chiefly composed of sesquioxides. The slaking of these sesquioxide-cemented soils is not affected by the variations in pH of the solutions, but rather by the plasticity index of the soils. However, dispersion and dissolution of the soil samples where dependent on variations in the pH of the solutions. It was therefore concluded that environmental pollution has the potential of increasing runoff erosivity.

Introduction
Erosion in South-eastern Nigeria is a devastating natural geologic hazard causing loss of arable lands, damage to civil engineering constructions, and severing of underground utilities such as pipelines and cables which are exposed by deep gully erosions. The frequency of this gullies are common within the edges of urban areas, especial in unpaved surfaces which serves as flow channels for urban run-offs. Formation of these gullies has been previously attributed to the geology, geotechnical properties and geochemical composition of the underlying soils. Geologically, three formation which includes Ajali formation (cretaceous), Nsukka formation (cretaceous) and Nanka Sands (Eocene) have been identified to be more susceptible to erosion (Nwajide, 1979, 1992; Obi & Asiegbu, 1980; Okagbue, 1988; Akpokodje, Olurunfemi, & EtuEfeotor, 1986; Okagbue, 1988; Hudec, 2005; Igwe & Fukuoka, 2015; Emeh & Igwe, 2017). These low-moderate plastic fines are chiefly composed of Aluminium and iron oxides (sesquioxides) which serves as cement binding the individual soil matrix into bulk aggregates (Townsend & Reeds, 1971; Smith, 1990; Cornell & Schwertmann, 2003; Igwe et al., 2009; Peng & Sun, 2015). However, Oti (2002) reported that the resultant aggregates are relatively unstable when exposed to water; thus, leading to slaking and dispersion of the soil aggregate. This soil aggregate behaviour is attributed to its low exchangeable sodium percentage (ESP), reduced calcium-magnesium ratio due to its relatively high content of aluminium and iron, and low content of soil essential nutrients such as Na, Ca, and Mg, which helps in formation of water stable soil aggregates (Mbagwu & Auerswald, 1999; Oti, 2002).

Soil aggregate stability in water has been described as one of the major factor controlling soils susceptibility to water erosion (Egashira, Kaetsu, & Takuma, 1983; Igwe, 2005). However, this soil–water interaction is not only dependent of the chemical composition of the soil aggregate, but also on the chemical composition of the prevailing aqueous solution. Prove to this assertion was provided by Arlauckas, Hurowitz, Tosca,
and McLennan (2004) on the dissolution of iron oxide which was revealed to be dependent on the hydrogen ion concentration of the dissolving solution. Similarly Frenkel, Levy, and Fey (1992) suggested that the addition of humic acid to soil aggregate may be detrimental to its physical properties, as this acid promotes dispersion. Also Park, Seong, and Baik (2001) and Abdalla, Jaafar, Al-Othman, Alfadul, and Ali Khan (2011) demonstrated that iron hydroxides are readily precipitated out of Iron oxide bearing mineral in aqueous solution of ammonium hydroxide and ammonium acetate, while Mattson (1927) concluded that flocculation and dispersion of soil aggregate is controlled by the pH of the surrounding medium.

Meanwhile, several researches which focused on environmental pollution, such as works of Kjeldsen et al. (2002); Aluko, Sridhar, and Oluwande (2003); and Tiwari, Manoj, and Bisht (2007) have revealed the presence of these chemical compounds which causes deloculation, dispersion, and dissolution of soil aggregate in rain and run-off samples. The chemical composition of rain and storm water is greatly influenced by anthropogenic activities. These include emissions from hydrocarbon production and usage which generates gases such as SO4 and NOx that reacts with water vapour in the atmosphere, which subsequently results to acidic precipitation (Hill, 2010; Efe & Mogborukor, 2012). Similarly, agricultural wastes, industrial effluents, dumpsite leachates, and other non point source of environmental pollutants have been found to be a major determinant of chemical composition of run-off (Horner, Skupien, Livingston, & Shaver, 1994; Hall & Anderson, 1988). This phenomenon is common in industrial and commercial areas and is particularly higher in areas where these wastes are improperly disposed to the environment, thereby exposing them to direct contact with rain and storm water which dissolves them; hence affecting the chemical composition of the resultant run-off (Horner et al., 1994).

However, the effect of this chemically modified run-off on its erosivity to the underlying soils has not been previously considered in soil erodibility studies. Since increase in population and urbanization is associated with increase in environmental pollution especially in developing countries such as Nigeria (Hill, 2010; Ubani & Onyejeke, 2013), it is imperative to investigate its contribution to the chemical composition of run-offs; hence its effect on the rapid degradation of land by water erosion within South-eastern Nigeria. Thus, the objectives of this work are; (i) to determine the geo-technical properties of the prevailing eroding soils, (ii) ascertain the chemical composition of fine particle portion of the soils, (iii) determine some of the chemical compositions and physicochemical properties of the prevailing rainwater and run-offs, and then (iv) evaluate the effect of change in chemical composition of run-off on slaking, dispersion and dissolution of the soil aggregates.

**Study area**

The study area lie within longitude 7° 1′ 8.0″–7° 27′ 44.1″ E and latitude 6° 52′ 7.7″–6° 2′ 5.1″ N in South-eastern part of Nigeria (Figure 1). It is been underlain by cretaceous to tertiary sediments within the Anambra Basin (Table 1). Three formations within this basin have been identified to be relatively more susceptible to water erosion. They include the Nanka sands in Ameki formation (Eocene), Ajali formation (cretaceous), and Nsukka formation (cretaceous) (Nwajide, 1979, 1992; Obi & Asiegbu, 1980; Akpokodje et al., 1986; Okagbue, 1988; Akpokodje et al., 2010). The Ajali formation comprises about 400 m thick fine, medium to coarse-grained sub-angular to subrounded quartz arenites with occasionally thin layer of grey-coloured silty shale (Reyment, 1965; Hoque & Ezepue, 1977). Ibe and Akaoila (2010) following Reyment (1965) suggestion, subdivides this formation into two; the iron-rich and the Akosic variety. The Ajali Formation is conformably over lain by the Nsukka formation, which comprises successive layers of shales and sandstone units, with occasional occurrences of coal seams (Reyment, 1965; Nwajide, 1979). The Nanka sands which is a member of the Ameki Formation lies within the adjacent Niger delta basin that was deposited during the Eocene. The Eocene Ameki Formation comprises a succession of fine to coarse-grained tidally influenced fluvial and fluvial sandstones at the basal part. This is successfully overlain by intercalations of clay, shale and limestone, with coarse-grained cross-bedded sandstones and clays at the uppermost part (Reyment, 1965; Nwajide, 1979; Arua & Rao, 1987).

However, these rock Formations have so far undergone severe tropical weathering which results in formation of dark-red coloured soils (oxisols), with occasional thick layers of laterites. The oxisols are relatively less resistant to water erosion than the laterites. This is as a result of their PSD which mostly comprises uniformly graded fine-silt sands, with average coefficient of uniformity (cu) of about 3.2 (Okagbue & Ezephi, 1988; Emeh & Igwe, 2017), compared with the laterites which are composed of concretions ranging from boulder to clay sized particles. The groundwater level within the studied areas varied greatly. From 7 m within some area directly underlain by the Ajali Fm (Omeukwa, Uma, & Eziegbog, 2004), to about 160 m in areas underlain by the Nsukka Fm (Offodile, 2002).

The area is characterized by a tropical climate with maximum temperature of 30.64 °C in the month of March and a minimum of 15.86 °C in the month of December. The total annual rainfall is 1580.66 mm with the lowest rainfall of about 16 mm occurring in February and the highest about 350 mm in July (Eze, 2007). The vegetation ranges from tropical rain forest
in the southern part to tropical savannah with numerous scrubs in the northern part. However, most of these vegetations have been removed as a result of urbanization and agricultural activities, thus exposing the soils to water erosion (Figure 2a and b). The studied areas are mostly densely populated with slums, markets, and many small-scale industries. The towns lack proper landfill disposal system; hence wastes are indiscriminately disposed in urban drainage channels, open empty lands, and inside the nearby gullies (Figure 3a and b).

**Methods**

The study combines field observations and laboratory experiments. Though prior to the field survey and observations, a digital elevation model (DEM) was acquired from the United States geological survey (USGS) online archives. Topographical map of the areas were thus generated from the DEM, and was analysed with the aid of Surfer 11; a geospatial information system (GIS) software. This helped in determining different areas with varying gully erosion density and urban run-off...
Field sampling

Eight disturbed soil samples were collected from each of the three geological formations (Ameki, Ajali, and Nsukka) that are easily susceptible to water erosion. The sampling points were selected considering the erosion density within a giving area, and the proximity to sources of pollutants which could possibly affect the chemical composition of the prevailing run-off. The samples were collected at approximately 2 m away from the gully walls in a hand dug hole of about 2 m deep within an area which have not been previously cultivated. This was to ensure that relatively fresh representative soil samples devoid of humus and/or artificial fertilizer were obtained. The soil samples were then bagged in waterproof bags to keep moisture from entering it before subjecting it to laboratory analysis.

To determine the chemical composition of the prevailing run-offs, 20 water samples were collected from stagnant water in drainage channels of urban commercial area and urban residential area, run-offs from agricultural farmlands, and run-offs from dumpsites after a precipitation event. Similarly, to determine the chemical composition of the prevailing rainfall, 20 rainwater samples were collected during the beginning of the rainy season (March-May). Water samples collection was done following the methods outlined in standard methods for sampling of water and wastewater of the American public health association (APHA, 1998).

Sample preparation

Soil aggregate preparation

About 90 gram of the air dried soil sample passing through ASTM sieve number 60 was thoroughly mixed with tap water using a spatula until the soil is slightly above its plastic limit. The mixture was then divided into three equal parts. Each portion was moulded into a ball-shaped soil aggregate of about 3 cm in diameter. The resultant soil aggregate samples were then allowed to air dry for about 80 days. While drying the samples, it was periodically moistened by spraying water on it using a small hand-held aerosol can sprayer. This is to prevent the soil samples from desiccation and to allow the sample to attain near field condition of about 3 months dry period.

Aqueous solution preparation

Three aqueous solutions labelled A, B, and N was prepared using Nitric acid (HNO₃), Sulphuric acid (H₂SO₄), Ammonium hydroxide (NH₄OH), and deionized water. Acidic solution (A) was prepared using a mixture of concentrated HNO₃ and H₂SO₄ acids which was diluted with deionized water till a concentration of about 0.001 M and a pH of 3.5 is attained. Similarly, a basic solution (B) was prepared by diluting concentrated NH₄OH with deionized water till a concentration of about 0.01 M and
than 63 μm) of six soil samples, two representative samples each from the three different geologic Formations, were further subjected to pH test following the method described by Hendershot, Lalande, and Duguette (1993), and also to X-ray fluorescence (XRF) analysis to determine their chemical composition.

**Labouratory tests and experiments**

**Rain and run-off chemical composition**

Chemical compositions of the rain and run-off water samples such as sulphate (SO$_4^{2-}$), nitrate (NO$_3^-$), carbonate (HCO$_3^-$) and ammonium (NH$_4^+$) were determined following the methods outlined in standard methods for the examination of water and wastewater of the American public health association (APHA, 1998) unless otherwise stated. pH and Electrical conductivity (EC) were tested immediately in the field using a handheld pH-meter and EC-metre, respectively. Total dissolved solute (TDS) was calculated from the theoretical relationship between TDS and EC (Lloyd & Heathcote, 1985).

**Soil geotechnical and chemical tests**

In order to determine the PSD of the soils, air dried sample were subjected to sieve analysis using the American standard of testing materials (ASTM) sieve mesh numbers 5, 10, 18, 40, 60, 100 and 230 stacked on an electrically controlled sieve shaker and was allowed to vibrate for about 25–30 min. Particles passing sieve number 40 were used to determine the soils liquid and plastic limit; hence its plasticity index following ASTM standard procedures. The fine particle fractions (particles less than 63 μm) of six soil samples, two representative samples each from the three different geologic Formations, were further subjected to pH test following the method described by Hendershot, Lalande, and Duguette (1993), and also to X-ray fluorescence (XRF) analysis to determine their chemical composition.

**Slaking, dispersion and dissolution experiment**

Three 250 ml glass beaker were filled up to 200 ml point with the prepared aqueous solution A, B, and N; each solution in a separate beaker. The prepared soil samples were then soaked in these solutions; each solution containing a replicate of the same soil sample. The samples were observed every 0, 10, 30, and 60 min for the degree of slaking and dispersion. The degree of slaking was determined similarly to that of Emerson (1967); by recording the quantity of soil particles (crumbs) that fail off from the soil aggregate in a given time, and the time it took the aggregate to completely crumble. After 60 min, the samples were thoroughly stirred for about 2 min using a glass rod. The resultant suspensions were then allowed to stand undisturbed for 48 h after stirring. The degree of dispersion of the soil samples were determined by noting the following: (i) the time it took the supernatant to settle; hence the suspension becoming clear again after stirring, and (ii) the crumb size of the settled soil after stirring. The clarity of the suspension is determined when a dark round dot of about 1 cm in diameter pasted on the glass beaker can be clearly seen through the suspension (Figure 4a and b). After 48 h, the solutions were carefully filtered through a 63 μm sieve into another container, ensuring that larger particles do not pass through. The resultant suspensions were then analysed for dissolved cations such as; Calcium (Ca), potassium (K), Sodium (Na), Magnesium (Mg), Aluminium (Al) and Iron (Fe), using atomic absorption spectroscopy (AAS) chemical analytical method. Solute dissolution was determined by summation of Al, Fe, K, Ca, Mg, and Na ions present in the resultant solution.

**Results**

**Physicochemical properties of rainwater and run-off**

The rainwater samples were acidic with an average pH value of 4.99 (Table 2). The minimum pH of 3.3 was recorded at location 9 which is at the southernmost part of the study area, while the maximum pH of 6.1 was recorded at location 14 in the northernmost part of the study area (Figure 1); noting that the southern part is more urbanized and industrialized than the northern part. The run-off water samples were generally basic with an average pH value of 8.94 (Table 2). The maximum pH of 10.2 was recorded in run-off from an urban dumpsite, while the minimum pH of 7.4 was recorded in run-off from urban residential areas. Generally, the pH
of run-off water samples from dumpsites, agricultural farms, and stagnant water in urban drainage channels were relatively higher than pH of run-offs from urban residential areas. The EC values of run-off water samples were very much higher than the EC values of rainwater (Table 2). Figure 5 revealed that the EC values of both the rainwater and run-off samples tends to increase away from the Neutral pH in both direction, with R-squared ($R^2$) of –0.702 and 0.703, respectively. This trend in EC values were also observed in the values of the TDS (Figure 6); hence dissolution of solutes appears to be dependent on the pH with $R^2 = –0.702$ and 0.703, for rainwater and run-off, respectively.

The average concentration values of $SO_4^{2−}$, $NO_3^−$, $HCO_3^−$ and $NH_4^+$ in the rainwater samples were 38.1, 19.8, 2.98, and 2.63 ppm, respectively, while their values in run-off samples were 283, 317, 68, and 735 ppm (Table 2). Generally, the acidic nature of the rain could be attributed to its relatively high concentration of $SO_4^{2−}$ and $NO_3^−$ which could react with hydrogen ion ($H^+$) in water to form acids, while the basic nature of the run-off could be attributed to its relatively high concentrations of $NH_4^+$ which could react with hydroxyl ion ($OH^−$) in water to form a base.

**Geotechnical properties of soil**

The structures of the in situ soils were generally homogenous and are reddish in colour. They appear cohesive in nature under its dry condition and were relatively stiff that it cannot be indented by the thumb. The geotechnical properties of the soil such as PSD, coefficient of uniformity (Cu), and consistency limits were summarized in Table 3. The PSD (Figure 7) revealed that the soils are coarse-grained with coefficient of uniformity ranging from 2.74 to 5.99, with an average value of 3.98; hence the soils are uniformly graded. The plasticity index (PI) of the soils in the area underlain by Nsukka Fm and Nanka sands which are moderately plastic, while those underlain by Ajali Formation are of low plasticity with average PI of 19.11 indicates that they are moderately plastic, while those underlain by Ajali Formation are of low plasticity with average PI of 3.59. In general, the soils could be classified as silty sands (SM) of low-medium plasticity according to unified soil classification system (USCS).

**Table 2.** Some physicochemical properties of the studied run-off and rainwater.

| Parameter          | Source       | Runoff | Rainwater |
|--------------------|--------------|--------|-----------|
|                    | Mean | Max  | Min  | Mean | Max  | Min  |
| $SO_4^{2−}$ (ppm)  | 282.6 | 501  | 19   | 38.1 | 63   | 27   |
| $NO_3^−$ (ppm)     | 316.7 | 978  | 109  | 19.1 | 48   | 7    |
| $HCO_3^−$ (ppm)    | 67.6  | 167  | 13   | 2.98 | 5    | 0.8  |
| $NH_4^+$ $NH_4^+$ (ppm) | 734.5 | 1567 | 205  | 2.63 | 4    | 0.9  |
| pH                 | 8.94 | 10.2 | 7.4  | 4.98 | 6.1  | 3.3  |
| EC ($μS/cm)$       | 568.8 | 890  | 89   | 82.6 | 186  | 21   |
| TDS (ppm)          | 387   | 605  | 61   | 56   | 126  | 14   |

**Geochemical composition of the fine fraction of the soil samples**

The pH and chemical compositions of the fine fraction of the soils were summarized in Table 4. pH of the soil samples were all acidic with an average value of 5.1. Apart from silicon oxide ($SiO_2$) which contributes about 51% of the total oxide in the soil's fine fraction, iron oxide ($Fe_2O_3$) is the next most abundant oxide, contributing an average of 36.30%, followed by aluminium oxide ($Al_2O_3$) with an average of 7.15%. The percentages of all other oxides are in insignificant quantity with respect to their contribution as a cementing material. This result of the chemical composition of the soils is similar with that of Ibe and Akaolisa (2010) and Igwe et al. (2009) on the same study area. However, the percentage of $SiO_2$ is relatively higher, and that of $Fe_2O_3$ is relatively lower in the above author’s results compared with the result of this work. The reason for these variations in $SiO_2$ and $Fe_2O_3$ composition could be attributed to the fraction of the soil sample analysed. While the other authors analysed the bulk aggregate sample of the soil, this work focused on the fine particle fraction of the soil. Noting that $SiO_2$ is relatively stable to weathering, and will constitute the majority of the coarse grains in the bulk aggregate; hence the observed variation.

**Slaking, dispersion, and dissolution**

The degree of slaking and dispersion as determined from the experiment were scored from 1 to 5, and were tabulated in Tables 5 and 6. The mean value of about 3.5 of the slaking score (Table 7) revealed that most of the samples were moderately-strongly slaked. However, a careful observation revealed that the degree of slaking was not determined by variations in pH of the solution, but rather by the plasticity index of the soil samples (Figure 8), with ($R^2$) value of –0.907. The degrees of slaking of soils within the area underlain by Ajali Fm were severe, while that of the ones within the areas underlain by Nsukka Fm and Nanka sands shows slight-strong degree of slaking. This was because the plasticity of soils within Ajali Fm are relatively low compared with the one within Nsukka Fm and Nanka sands which are moderately plastic (Table 7).

Furthermore, the mean of the dispersion score was plotted against the pH of the dispersing solutions. This reveals that the dispersion of the soil samples were dependent on the pH of the solutions. Most of the samples in neutral solutions ($N_s$) did not show any sign of dispersion, the ones in acidic solution ($A_s$) were moderately dispersed, while samples in the basic solutions ($B_s$) were all strongly dispersed (Figure 9). The pattern that exists in the soils dispersion was also observed in the dissolution of the soil samples in aqueous solutions of varying pH. Basic solutions ($B_s$) has more dissolved cations with an average value of 40 ppm, followed by
the acidic solutions (ADi) with an average of 20.31 ppm, and neutral solution (NDi) has the least dissolved cations with an average value of 11.59 ppm (Figure 10). It was observed that iron contributes about 60% to the quantity of the dissolved cations in the basic solution, while contributing just about 11 and 4% in the Acidic and Neutral solution, respectively (Figure 11).

### Discussion

The studied soils are majorly composed of medium-fine-grained sands with about 6% of low-medium plastic fines. About 43% of the fine particle fractions of these soils are chiefly composed of Iron and Aluminium oxide (sesquioxides). These oxides have been attributed to be the major cement binding the individual soil particles into larger aggregates (Cornell & Schwertmann, 2003; Peng & Sun, 2015). Valentin (1986b), and Van der Walt and Valentin (1992) also suggested that these oxides are responsible for encrusting of soil surfaces; hence reducing infiltration and promoting run-off. However, the instability of these soils to water erosion has been seen to be dependent not only on the chemical composition of the soils, but also on the chemical composition of the prevailing aqueous environment. While these soil aggregates maybe relatively stable in aqueous solution of neutral pH – which may not be naturally attainable,

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**Figure 5.** Relationship between EC and pH of run-off and rainwater samples.

**Figure 6.** Relationship between TDS and pH of run-off and rainwater samples.

**Table 3.** Some geotechnical properties of the studied soils.

| Sample location | G (>2 mm) | CS-MS (<2–0.25 mm) | FS (<0.25–0.063 mm) | FINES (<0.063 mm) | Cu | LL | PL | PI |
|----------------|----------|-------------------|-------------------|-----------------|----|----|----|----|
| 1*             | 0        | 37.06             | 58.51             | 4.25            | 3.43 | 30.4 | 10.6 | 19.80 |
| 2*             | 0        | 36.07             | 60.20             | 3.86            | 3.42 | 30.00 | 12.80 | 17.20 |
| 3*             | 0        | 40.45             | 54.66             | 5.30            | 3.49 | 34.6 | 15.9 | 18.70 |
| 4*             | 0        | 38.40             | 61.30             | 6.10            | 3.50 | 32 | 15.1 | 16.90 |
| 5*             | 0        | 33.24             | 57.93             | 4.34            | 3.38 | 40 | 19.9 | 20.10 |
| 6*             | 0        | 41.22             | 59.10             | 4.26            | 3.34 | 41.8 | 22 | 19.80 |
| 7*             | 0        | 36.89             | 58.56             | 3.48            | 3.41 | 38.3 | 20.9 | 17.40 |
| 8*             | 0        | 39.87             | 63.89             | 4.93            | 3.47 | 42.3 | 23.5 | 18.80 |
| 9**            | 0        | 32.73             | 57.94             | 8.38            | 5.82 | 45 | 21.7 | 23.30 |
| 10**           | 0        | 32.90             | 61.56             | 7.58            | 5.20 | 42.5 | 26.1 | 16.40 |
| 11**           | 0        | 29.23             | 64.12             | 9.45            | 5.99 | 38.7 | 17.1 | 21.60 |
| 12**           | 0        | 26.95             | 59.22             | 9.00            | 5.98 | 37.8 | 18.3 | 19.50 |
| 13**           | 0        | 28.22             | 56.97             | 6.90            | 4.80 | 43.4 | 24.7 | 18.70 |
| 14**           | 0        | 36.23             | 60.85             | 7.89            | 5.20 | 31.2 | 13.3 | 17.90 |
| 15**           | 0        | 33.14             | 62.78             | 7.23            | 5.46 | 40 | 19.7 | 20.30 |
| 16**           | 0        | 29.99             | 60.12             | 8.84            | 5.63 | 36.8 | 17.4 | 19.40 |
| 17**           | 0        | 29.61             | 65.08             | 4.61            | 3.2 | 26 | 22.4 | 3.60 |
| 18**           | 0        | 32.12             | 72.80             | 3.78            | 2.90 | 32.8 | 29.2 | 3.60 |
| 19**           | 0        | 27.84             | 63.39             | 4.20            | 3.00 | 28.2 | 25.4 | 2.80 |
| 20**           | 0        | 28.34             | 69.20             | 4.32            | 3.11 | 25.7 | 21.5 | 4.20 |
| 21**           | 0        | 30.45             | 66.80             | 5.23            | 3.30 | 29.1 | 24.3 | 4.80 |
| 22**           | 0        | 30.56             | 71.12             | 3.67            | 2.78 | 25.4 | 21.5 | 3.90 |
| 23**           | 0        | 23.98             | 59.55             | 3.33            | 2.74 | 26.7 | 24 | 2.70 |
| 24**           | 0        | 31.34             | 68.20             | 4.86            | 2.89 | 30.6 | 27.3 | 3.30 |

**Summary statistics**

| Mean          | 32.78 | 62.24 | 5.66 | 3.98 | 34.55 | 20.61 | 13.95 |
| Max           | 41.22 | 72.8  | 9.45 | 5.99 | 45    | 29.2  | 23.3  |
| Min           | 23.98 | 54.66 | 3.33 | 2.74 | 25.4  | 10.6  | 2.7   |

**Notes:** G = Gravel, CS-MS = Coarse to medium grain sand, FS = Fine sand, FINES = Silt and clay size particles, Cu = Coefficient of uniformity, LL = Liquid limit, PL = Plastic limit, PI = Plasticity index.

*Nanka Fm.; **Nsukka Fm.; ***Ajali Fm.*
The results from this research have shown that the chemical composition of the prevailing run-off is determined by the type and amount of pollutant which are present in rainwater, dumpsites, sewages, and agricultural wastes. Amongst these chemical pollutants are sulphuric acid, nitric acid, and ammonium hydroxide. These chemical compounds appear to be the major compounds affecting the chemical composition of the run-off since they are found in appreciable percentage in the run-off samples that was analysed. This result is consistent with the work of other researchers working on environmental pollution (Hall & Anderson, 1988; Sumner & McLaughlin, 1996; Aluko et al., 2003; Tiwari et al., 2007). Run-off generated from agricultural active areas and those from industrial/commercial areas, especially those sourced from urban dumpsites appears to have higher concentration of these chemicals, compared with those from residential and economic less active areas.

they disperse and dissolve in acidic and/or basic aqueous solutions which are typical of run-offs within the study area.

### Table 4. Chemical composition of some of the studied soil samples.

| Parameter | Concentration values (%) |   |
|-----------|--------------------------|---|
|           | Mean | Max | Min |   |
| pH*       | 5.12 | 5.6 | 4.8 |   |
| SiO₂      | 51.22 | 66.4 | 34.8 |   |
| TiO₂      | 0.44 | 0.83 | 0.05 |   |
| Al₂O₃     | 7.15 | 20.32 | 1.39 |   |
| Fe₂O₃     | 36.3 | 50.97 | 18.86 |   |
| MnO       | 0.03 | 0.05 | 0.01 |   |
| MgO       | 0.36 | 0.5 | 0.1 |   |
| CaO       | 0.5 | 0.88 | 0.1 |   |
| Na₂O      | 0.04 | 0.07 | 0.02 |   |
| K₂O       | 0.05 | 0.07 | 0.04 |   |
| P₂O₅      | 0.44 | 0.97 | 0.05 |   |
| LOI       | 3.38 | 7.07 | 2.1 |   |

### Table 5. Laboratory observation results of slaking of the soil samples.

| Parameters used in determining the degree of slaking | Slaking score | Degree of slaking |
|----------------------------------------------------|---------------|------------------|
| Soil aggregate remains intact after 60 min with no crumbs falling off it | 1 | Non |
| Few crumbs fall off from the soil aggregate, but aggregate remains spherical after 30 min | 2 | Slight |
| About 40% of crumbs fall off from the soil aggregate after 10 min, but the aggregate still partly maintained its spherical shape after 30 min | 3 | Moderate |
| About 75% of crumbs fall off from the soil aggregate after 10 min, forming a conical shape, and soil lump completely collapsed into crumbs after 30 min. |
| 100% of the soil aggregate completely collapsed into crumbs immediately it is been soaked in the solution | 5 | Severe |

### Table 6. Laboratory observation results of dispersion of the soil samples.

| Parameters used in determining the degree of dispersion | Dispersion score | Degree of dispersion |
|------------------------------------------------------|------------------|----------------------|
| Solution remains clear after soaking the sample, and reappears clear within 10 min after stirring; crumb size appears larger 2 mm. | 1 | Non |
| Solution remains clear after soaking the sample, but took about 30 min for solution to clear out after stirring; crumb size appears less than 2 mm but not powdered. | 2 | Slight |
| Solution remains clear after soaking the sample, but took about 1 h for solution to clear out after stirring; crumb size appears less than 2 mm, and about 30% appears powdered. | 3 | Moderate |
| Solution remains clear after soaking the sample, but took about 1 hour for solution to clear out after stirring; crumb size appears less than 2 mm and about 50% appears powdered. | 4 | Strong |
| Solution becomes unclear immediately the sample is soaked in it, and remains unclear after 48 h; crumb size cannot be determined because the solution appears very cloudy (muddy). | 5 | Severe |
areas – which reflected in the values of their pH, EC, and TDS.

The degree of dispersion and dissolution of soil aggregates and its constituent elements, respectively, are found to be higher in basic aqueous solution of ammonium hydroxide compared with acidic aqueous solution of sulphuric and nitric acid mixture. The reason for this could be as a result of the higher concentration of NH₄OH which is about 0.01 M in the basic solution that was used compared with 0.001 M of the acid mixture that was used. NH₄OH of 0.01 M was used because similar concentration was observed in most of the sampled runoff. The same reason was used to condition the aqueous mixture of H₂SO₄ and HNO₃ at a concentration level of 0.001 M. Though this experiment was conditioned at a constant hydrogen ion concentration, solubility of metallic oxides such as iron oxide have been found to increase with increase in hydrogen ion concentration in aqueous acidic solution (Arlauckas et al., 2004). Thus, increase in the molar concentration of the acidic mixture used may subsequently increase the solubility of soil constituent elements; hence leading to aggregate instability. Another reason for this observed variation as discussed by Park et al. (2001) is that hydroxides of Fe and Al in sesquioxide-rich soils are readily precipitated out in basic aqueous solution of ammonium compounds, such as ammonium hydroxide and ammonium acetate, while iron and aluminium

Table 7. Experimental results of slaking, dispersion, and dissolution of the soil samples.

| Sample location | Slaking (S) | Dispersion (D) | Dissolution (Di) ppm | Dissolved iron (Fe) ppm |
|-----------------|------------|---------------|----------------------|------------------------|
|                 | Aₙ         | Bₙ            | Aₛ                 | Bₛ                    |
| 1*              | 2          | 3             | 2                  | 3                     |
|                 | 5          | 1             | 25.33              | 41.01                  |
| 2*              | 2          | 3             | 3                  | 3                     |
|                 | 5          | 2             | 22.14              | 51.22                  |
| 3*              | 3          | 2             | 4                  | 5                     |
|                 | 1          | 2             | 23.16              | 43.76                  |
| 4*              | 3          | 3             | 3                  | 4                     |
|                 | 5          | 1             | 17.50              | 54.98                  |
| 5*              | 2          | 2             | 2                  | 3                     |
|                 | 5          | 1             | 19.64              | 39.27                  |
| 6*              | 2          | 3             | 2                  | 3                     |
|                 | 5          | 2             | 24.34              | 51.33                  |
| 7*              | 3          | 4             | 3                  | 3                     |
|                 | 5          | 1             | 18.75              | 58.19                  |
| 8*              | 3          | 2             | 3                  | 5                     |
|                 | 5          | 1             | 20.48              | 44.56                  |
| 9**             | 2          | 2             | 2                  | 2                     |
|                 | 5          | 1             | 21.26              | 26.52                  |
| 10**            | 3          | 4             | 3                  | 2                     |
|                 | 5          | 1             | 22.12              | 29.17                  |
| 11**            | 2          | 2             | 2                  | 2                     |
|                 | 5          | 1             | 18.39              | 24.98                  |
| 12**            | 2          | 3             | 2                  | 2                     |
|                 | 5          | 1             | 19.98              | 24.78                  |
| 13**            | 3          | 2             | 2                  | 2                     |
|                 | 5          | 1             | 22.98              | 27.74                  |
| 14**            | 2          | 3             | 2                  | 3                     |
|                 | 5          | 1             | 19.70              | 23.80                  |
| 15**            | 2          | 3             | 2                  | 3                     |
|                 | 5          | 1             | 16.43              | 28.12                  |
| 16**            | 2          | 3             | 2                  | 2                     |
|                 | 5          | 1             | 19.49              | 26.72                  |
| 17**            | 5          | 5             | 5                  | 3                     |
|                 | 5          | 1             | 22.77              | 42.20                  |
| 18**            | 5          | 5             | 5                  | 3                     |
|                 | 5          | 1             | 18.56              | 49.33                  |
| 19**            | 5          | 5             | 5                  | 3                     |
|                 | 5          | 1             | 19.45              | 33.37                  |
| 20**            | 4          | 5             | 5                  | 3                     |
|                 | 5          | 1             | 18.90              | 44.57                  |
| 21**            | 5          | 4             | 4                  | 2                     |
|                 | 5          | 1             | 22.67              | 56.42                  |
| 22**            | 5          | 4             | 3                  | 3                     |
|                 | 5          | 1             | 11.89              | 42.73                  |
| 23**            | 5          | 5             | 3                  | 3                     |
|                 | 5          | 1             | 17.56              | 39.12                  |
| 24**            | 5          | 5             | 3                  | 3                     |
|                 | 5          | 1             | 23.89              | 56.23                  |

Summary statistics

| Sum  | 76.00 | 85.00 | 75.00 | 68.00 | 120 | 27.00 | 487.38 | 960.11 | 278.24 | 54.56 | 572.77 | 11.68 |
| Mean | 3.17  | 3.54  | 3.13  | 2.83  | 5   | 1.13  | 20.31  | 40.00  | 11.59  | 2.27  | 23.87  | 0.49  |
| Max  | 5.00  | 5.00  | 5.00  | 4.00  | 5   | 2.00  | 25.33  | 58.19  | 17.40  | 5.30  | 40.12  | 1.35  |
| Min  | 2.00  | 2.00  | 2.00  | 2.00  | 5   | 1.00  | 11.89  | 23.80  | 4.46   | 0.56  | 8.19   | 0.02  |
| δ    | 1.28  | 1.15  | 1.24  | 0.62  | 0   | 0.33  | 2.91   | 11.24  | 3.31   | 1.35  | 10.87  | 0.39  |

Notes: A = Acidic solution, B = Basic solution, N = Neutral solution, δ = Standard deviation.
* Nanka Fm.; **Nsukka Fm.; ***Ajali Fm.

Figure 8. Relationship between slaking and Plasticity of the soil.

Figure 9. Relationship between dispersion and pH of the solutions.
The degree of dissolution of other non sesquioxides such as NaO₂, CaO, and MgO appears to be higher in the aqueous acidic solution. However, in the case of the studied soil, it may not be a major concern as these metal oxides constitutes very little fraction in the amount of cement within the soil aggregates which are predominantly sesquioxides. Moreover, the experiment reveals that sesquioxides of iron and aluminium are sparingly soluble in acidic solution of relatively low hydrogen ion concentration of about 0.001 M. However, there solubility may increase with increase in the concentration level of the aqueous solution (Arlauckas et al., 2004). Thus, increase in the concentration level of these compounds in the run-off may result to increase in the solubility of metallic oxides in the soil; hence leading to soil aggregate instability.

Another important component of run-off which could affect the deflocculation and dispersion of soil aggregate is the humic acid. This acid has been reported by (Frenkel et al., 1992) as a major chemical compound causing dispersion of soil aggregate. Though this compound was not analysed for in the run-off samples used for this experiment, its presence in dumpsites leachate, sewage, and composts have been reported by several authors.

Conclusion
This work has revealed that the studied soil is mainly composed of medium-fine-grained sands with little amount of low-moderate plastic fines which are chiefly composed of iron and aluminium oxides that serve as cement in the soil matrix. These sesquioxide cements disperses and dissolves in basic aqueous solution of ammonium hydroxide and in acidic aqueous solution of sulphuric and nitric acid mixture. However, the degree of dissolution and dispersion of iron oxide is more compared to that of aluminium oxide.

The degree of dispersion and dissolution of soil aggregate and its constituent element, respectively, is more in basic aqueous solution of ammonium hydroxide than in acidic aqueous solution of sulphuric and nitric acid mixture. Ammonium hydroxide, Sulphuric acid, and Nitric acid are found in appreciable quantity in the prevailing rainwater and run-offs. However, the concentration level of this chemical compounds are higher in run-offs that were generated from urban dumpsites and agricultural farmlands.

Therefore, in order to prevent the susceptibility of iron oxide-cemented soils to water erosion, it is imperative to determine the sources and chemical composition of the prevailing run-offs. This will help in proper run-off treatment and drainage system control to avoid the contact of chemically erosive run-offs with iron-oxide-cemented soils. Also it is important that urban dumpsites...
are properly designed, and indiscriminate disposal of both liquid and solid wastes should be highly discouraged in order to avoid direct contact with rainfall, which could generate chemically modified erosive run-offs.

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