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Research article

CHEMICAL CHARACTERISTICS OF STORMWATER RUNOFF ACROSS RESIDENTIAL AREAS IN CALABAR MUNICIPALITY, SOUTHERN NIGERIA

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ABSTRACT

Stormwater runoff generated from urban catchments is a major non-point source of environmental contaminants, yet its chemical composition varies markedly with the land use and socioeconomic character of the catchment it drains, a relationship that remains under-documented for many rapidly urbanising Nigerian cities. This study examined the chemical characteristics of stormwater runoff and their variation across high-income, medium-income, and low-income residential areas of Calabar Municipality, Cross River State, Southern Nigeria. Using a stratified and random sampling design, three residential areas were selected from each of the three income categories, nine in all, and thirty-six grab samples of stormwater runoff were manually collected from storm outfalls across the residential types during active storm events. Samples were analysed for pH, electrical conductivity, turbidity, total dissolved solids, ammonia, sulphate, phosphate, total hardness, calcium, magnesium, nitrate, nitrite, ammonium, chloride, salinity, biological oxygen demand, and dissolved oxygen, and the data were subjected to descriptive statistics and one-way analysis of variance (ANOVA). Results showed the stormwater to be mildly alkaline (pH 7.06-7.38), with the medium-income area recording the highest pH and the highest chloride concentration, while phosphate and turbidity were most elevated in the high-income area and nitrate and nitrite were highest in the low-income area, several of these exceeding World Health Organisation permissible limits. One-way ANOVA showed statistically significant spatial variation ($p < .05$) in pH, phosphate, magnesium, nitrate, ammonium, chloride, and biological oxygen demand across the three residential categories, while conductivity, turbidity, total dissolved solids, ammonia, sulphate, total hardness, calcium, nitrite, salinity, and dissolved oxygen did not vary significantly. The study concludes that the chemical quality of stormwater runoff in Calabar Municipality is shaped jointly by residential land use and the socioeconomic activities of residents, and recommends improved solid- and liquid-waste disposal practices across all residential categories to reduce the nutrient and organic loading of stormwater runoff and the surface waters into which it ultimately drains.

KEYWORDS

Stormwater runoff; Chemical characteristics; Residential land use; Water quality; Urban hydrology; Calabar Municipality

INTRODUCTION

Stormwater runoff generated from urban catchments is widely recognised as a major source of environmental contaminants that induces flooding and degrades the receiving water bodies of many urbanised areas. As land is converted from rural to urban uses through the complex process of urbanisation, impervious surfaces such as roads, roofs, and paved compounds replace vegetated and permeable land cover, so that a growing proportion of rainfall is converted directly into surface runoff rather than being infiltrated or evapotranspired. This runoff, in the course of flowing over roads, compounds, refuse dumps, drainage channels, and other impervious surfaces, picks up a wide range of chemical and biological substances, so that the types and levels of pollutants it carries are directly related to the particular land use and human activities of the catchment it drains.

A considerable body of international research, reviewed in detail in the following section, has established that urbanisation causes the largest changes of any land use to the volume and pattern of flow moving from catchments to streams and rivers, that the associated impervious surfaces and engineered drainage networks substantially alter the water balance of cities, and that anthropogenic activities on these impervious surfaces measurably increase both the pollutant loading rate and the variety of pollutants discharged into receiving waters. Within this broader pattern, land use has repeatedly been identified as one of the strongest determinants of stormwater quality, so that catchments differing in their dominant land use, whether industrial, commercial, or residential of varying socioeconomic character, would be expected to generate stormwater runoff of correspondingly different chemical composition.

Building on this recognition, a growing number of studies have gone further to characterise how stormwater chemistry varies not merely between broad land-use classes but within a single land-use category, most notably across residential areas of differing socioeconomic status, on the reasoning that income level shapes the density of construction, the intensity of vehicular traffic, the type and adequacy of waste-disposal practices, and the general pattern of domestic activity within a neighbourhood, all of which influence what accumulates on impervious surfaces between storm events and is subsequently washed into stormwater runoff.

Despite this recognition, the mechanisms of non-point-source pollutant transport and the influence of the hydrologic regime on pollutant loading remain comparatively unclear in tropical environments, owing to the limited number of studies conducted there relative to the temperate cities in which much of the foundational stormwater literature originated, and this scarcity is particularly acute for comparative, income-stratified assessments of residential stormwater quality in tropical West African cities such as Calabar, where rapid, largely unplanned urban growth continues to reshape land use across residential areas of markedly different socioeconomic character.

It is against this background that the present study was designed, with the broad aim of examining the chemical characteristics of stormwater runoff across different residential land uses in Calabar Municipality, Cross River State, Southern Nigeria. Specifically, the study sought to determine the chemical characteristics of stormwater runoff across high-income, medium-income, and low-income residential areas of the Municipality, and to examine whether these chemical characteristics vary significantly among the three residential categories, on the hypothesis that there are significant variations in the chemical characteristics of stormwater runoff across the different urban residential areas.

LITERATURE REVIEW

Global Evidence on Stormwater Runoff Quality and Land Use

Studies from across the world have consistently linked the chemical characteristics of stormwater runoff to the land use of the catchment from which it is generated. Ha and Stenstrom (2003) demonstrated, using a neural-network approach applied to water-quality data, that land use could be identified from the chemical signature of the stormwater it produced, underscoring the strength of the land use-water quality relationship. In the Amman-Zarqa basin of Jordan, Al-Mashaqbeh, Jiries and El-HajAli (2014) compared stormwater runoff generated from urban and rural catchments and found systematic differences in pollutant concentration attributable to the intensity of anthropogenic activity in the urban catchment. Similarly, Maharjan, Pachel and Loigu (2017) modelled stormwater runoff quality and pollutant loads in a large urban catchment and confirmed that impervious surface cover and the associated accumulation of solids, nutrients, and organic matter between storm events are primary drivers of the pollutant concentrations subsequently observed in runoff.

The physical mechanisms underlying these patterns have also received sustained attention. Walsh, Fletcher and Burns (2012) observed that, of all land uses, urbanisation causes the largest changes to the volume and pattern of flow moving from catchments to receiving streams and rivers, while Kennedy, Cuddihy and Engel-Yan (2007) showed that the imported water supply and exported wastewater characteristic of modern cities substantially alter the overall water balance of the urban environment. Mitchell, McMahon and Mein (2003) further decomposed the components of the total water balance of an urban catchment, providing a framework within which the pollutant loading associated with stormwater runoff can be understood as one component of a broader hydrological transformation wrought by urbanisation. Gunawardana, Goonetilleke, Egodawatta, Dawes and Kokot (2012) examined the specific role of solids in the build-up of heavy metals on urban road surfaces, demonstrating a direct pathway by which traffic-related and construction-related solids accumulate on impervious surfaces and are subsequently mobilised by stormwater runoff, while Fletcher, Andrieu and Hamel (2013), in a comprehensive review, summarised the understanding, management, and modelling of urban hydrology and its consequences for receiving waters, noting the persistent challenge that urban stormwater poses for water resource managers worldwide. Li, Shen, Tian, Liu and Qiu (2012) further demonstrated, through a study of the temporal variation of heavy metal pollution in urban stormwater runoff, that pollutant concentrations in stormwater are not static but vary systematically with the pattern of dry-weather accumulation and storm-event characteristics, a finding with direct relevance for the sampling protocols used in stormwater characterisation studies.

Regional and Comparative Tropical Evidence

Within the African and tropical context more specifically, Adedeji and Olayinka (2013) examined heavy metal concentrations in urban stormwater runoff and receiving streams in Abeokuta, Southwestern Nigeria, reporting pH values of 7.72 to 9.85, total hardness of 103 to 140 mg/l, and biological oxygen demand values considerably higher than those subsequently recorded elsewhere, findings that this study draws on as a comparative benchmark for South-South Nigeria. In Ethiopia, Wondie (2009) assessed the impact of urban stormwater runoff and domestic waste effluent on the water quality of Lake Tana and local groundwater near Bahir Dar, reporting electrical conductivity values of 107.7 to 346 µs/cm and attributing elevated conductivity to the accumulation of dissolved solids from urban and domestic sources, a mechanism consistent with that proposed for other tropical cities. Outside Africa but within comparable tropical climatic conditions, Chow and Yusop (2014) characterised and identified the sources of stormwater runoff in tropical urban catchments in Malaysia, while Chow, Yusop and Shirazi (2013) quantified storm runoff quality and pollutant loading from commercial, residential, and industrial catchments in the tropics, both studies confirming that the land use-water quality relationship established in temperate settings holds, with some modification, under tropical rainfall regimes characterised by high-intensity, short-duration storms.

Batisani and Yarnal (2009), examining urban expansion in Centre County, Pennsylvania, demonstrated more broadly how landscape transformation accompanying urban growth alters catchment hydrology and, by extension, the character of the runoff generated, a process mirrored in rapidly urbanising Nigerian cities such as Calabar, where unplanned expansion of residential, commercial, and industrial land uses has been documented to outstrip the capacity of urban management systems to provide adequate drainage and waste-management infrastructure.

Local Research Gap

Within Cross River State and Calabar Municipality specifically, existing environmental research has documented the drivers of the city's rapid land-use change and its consequences for gully erosion and urban drainage, but comparative, income-stratified assessments of the chemical characteristics of stormwater runoff generated from the city's high-income, medium-income, and low-income residential areas remain scarce, so that the extent to which socioeconomic status of residential catchments shapes stormwater chemical quality in this tropical, rapidly urbanising South-South Nigerian city has not been empirically established. The present study therefore addresses this gap by systematically sampling and comparing the chemical characteristics of stormwater runoff across nine residential areas stratified into three income categories in Calabar Municipality, providing an empirical basis for understanding how residential socioeconomic status shapes stormwater chemical quality in the study area.

METHODOLOGY

Study Area

Calabar Municipality lies between latitudes 4°54'00"N to 5°04'00"N of the equator and longitudes 8°18'00"E to 8°24'00"E of the Greenwich Meridian. It is bounded by the Calabar River to the west, the Great Kwa River to the east, Odukpani Local Government Area (LGA) to the north, and Calabar South LGA to the south. The Municipality covers a land area of 103.491 square kilometres, having a larger coverage than its counterpart, Calabar South (33.548 square kilometres), with which it forms Calabar Metropolis. Calabar is one of the oldest trading centres in Nigeria, having been established as a centre of the transatlantic slave trade by the British in the seventeenth century.

Under the Köppen climate classification, the Municipality experiences a tropical monsoon climate with a lengthy wet season spanning eight to nine months and a short dry season covering the remaining three to four months. The harmattan, which significantly influences weather across West Africa, is noticeably less pronounced in the city. Temperatures are relatively constant throughout the year, with average high temperatures ranging from 25 to 28 degrees Celsius. Calabar is an inter-fluvial city drained by the Calabar River and the Great Kwa River, both of which empty into the Atlantic Ocean via the Cross River estuary to the south of the town, and this hydrological pattern strongly influences the conventional rainfall pattern experienced in the city. The natural and artificial drainage pattern of Calabar has also been identified as a remote factor responsible for gully erosion in the city (NEWMAP, 2015). The physical environment of Calabar Municipality is situated on low-lying, gentle, and undulating terrain forming the coastal plain of South-Eastern Nigeria, with locations closer to the coast lying at an average altitude of about 10 metres above mean sea level and areas farther north of the metropolis rising to between 40 and 80 metres above mean sea level, an undulating relief that encourages the speed of gully-erosion agents. Rapid population expansion in Calabar Municipality over the past two and a half decades has led to unprecedented urban growth and the alteration of several land uses, giving way to new roads, new residential and industrial layouts, and recreation and amusement parks, so that the resulting expansion of urban population has, in combination with other factors, outstripped the capacity of urban management systems to provide adequate services (Obia, Itam & Archibong, 2015).

Research Design

The study adopted a comparative cross-sectional survey research design, in which primary stormwater runoff samples were collected concurrently from residential areas representing three predetermined socioeconomic strata, high-income, medium-income, and low-income, so that observed differences in the chemical characteristics of stormwater runoff could be systematically compared and, where statistically significant, ascribed to the residential income category from which the sample was drawn.

Data Collection

The study relied on primary data obtained through the physical estimation of stormwater runoff quality. A stratified sampling technique was first used to divide the urban residential areas of Calabar Municipality into three residential types, high-income, medium-income, and low-income. Random sampling was then employed within each stratum: nine residential areas were randomly selected in all, giving three high-income residential areas, State Housing, Federal Housing, and Parliamentary Extension, three medium-income residential areas, Lemna, 8-Miles, and Big Qua, and three low-income residential areas, Ikot Ansa, Ekorinim II, and Akim. Within each of the nine selected residential areas, three points, described in this study as receiving water channels or basins that receive stormwater runoff from two or three collection points, were randomly delineated for stormwater sample collection, giving thirty-six points in total, twelve from each residential income category.

Manually grabbed stormwater samples were taken from the thirty-six separate storm outfalls using 750 millilitre SMART plastic containers, following the sampling approach described by Li et al. (2012). Depending on the size of the storm, samples were collected at one- to ten-minute intervals on the rising limb of the hydrograph and at ten- to twenty-minute intervals on the falling limb, with sampling beginning at the onset of the storm event and ending when flow receded to the dry-weather water level. Storm events were selected for sampling on the basis of rainfall amount exceeding 3 millimetres, with at least one dry week separating successive storms (Al-Mashaqbeh et al., 2014), dry weather being defined as the absence of rainfall in the twenty-four hours preceding sampling. Samples were stored at 4 degrees Celsius and transported to the laboratory within twenty-four hours for the determination of pH, total dissolved solids, biological oxygen demand, chemical oxygen demand, nitrate, ammonia, turbidity, nitrite, sulphate, phosphate, total hardness, calcium, magnesium, ammonium, chloride, salinity, and dissolved oxygen, using standard laboratory procedures.

Data Analysis

Data obtained from the laboratory analyses were analysed using both descriptive and inferential statistical techniques. Descriptive statistics, means in particular, were used to characterise the chemical composition of stormwater runoff within each residential income category, while one-way analysis of variance (ANOVA) was used to test the hypothesis that there are significant variations in the chemical characteristics of stormwater runoff across the three urban residential categories, at the .05 level of significance. All statistical analyses were performed using the Statistical Package for Social Sciences (SPSS), Version 22.0, and Microsoft Excel spreadsheet.

RESULTS

Chemical Characteristics of Stormwater Runoff Across Residential Areas

Table 1 presents the chemical characteristics of stormwater runoff recorded across the high-income, medium-income, and low-income residential areas of Calabar Municipality. The pH of the stormwater runoff ranged from 7.06 in the low-income area to 7.38 in the medium-income area, with the high-income area recording an intermediate value of 7.17. Electrical conductivity ranged from 131.59 µs/cm in the low-income area to 200.75 µs/cm in the medium-income area, while turbidity was highest in the high-income area (127.18 mg/l), followed by the low-income area (124.65 mg/l), and lowest in the medium-income area (107.49 mg/l). Total dissolved solids followed a similar pattern to conductivity, ranging from 79.77 mg/l in the low-income area to 120.27 mg/l in the medium-income area.

Ammonia ranged from 0.20 mg/l in the low-income area to 0.37 mg/l in the medium-income area, with the high-income area recording an intermediate value of 0.27 mg/l. Sulphate and phosphate were both highest in the high-income area, at 16.14 mg/l and 21.47 mg/l respectively, and lowest in the low-income area, at 9.02 mg/l and 9.26 mg/l respectively. Total hardness was highest in the low-income area (81.72 mg/l) and lowest in the medium-income area (64.87 mg/l), while calcium content was highest in the low-income area (33.92 mg/l) and lowest in the high-income area (30.41 mg/l); magnesium content ranged from 34.74 mg/l in the medium-income area to 47.39 mg/l in the low-income area.

Nitrate and nitrite concentrations were both highest in the low-income area, at 30.85 mg/l and 2.21 mg/l respectively, and lowest in the high-income area, at 7.93 mg/l and 1.76 mg/l respectively, with the medium-income area recording intermediate values of 16.30 mg/l and 1.46 mg/l. Ammonium was highest in the high-income area (0.32 mg/l) and lowest in the medium-income area (0.06 mg/l), while chloride was highest in the medium-income area (17.86 mg/l), followed by the high-income area (15.28 mg/l), and lowest in the low-income area (9.62 mg/l). Salinity was generally low across all residential areas, ranging from 0.14 ppm in the low-income area to 0.20 ppm in the high-income area. Biological oxygen demand was highest in the medium-income area (6.52 mg/l) and lowest in the low-income area (4.61 mg/l), while dissolved oxygen was highest in the high-income area (12.29 mg/l) and lowest in the medium-income area (11.55 mg/l), with the low-income area recording a close value of 11.58 mg/l.

Table 1. Chemical characteristics of stormwater runoff across residential areas

Parameter	High-income	Medium-income	Low-income
pH	7.17	7.38	7.06
Conductivity (µs/cm)	153.80	200.75	131.59
Turbidity (mg/l)	127.18	107.49	124.65
TDS (mg/l)	86.98	120.27	79.77
Ammonia (mg/l)	0.27	0.37	0.20
Sulphate (mg/l)	16.14	14.95	9.02
Phosphate (mg/l)	21.47	18.98	9.26
Total hardness (mg/l)	73.16	64.87	81.72
Calcium (mg/l)	30.41	30.49	33.92
Magnesium (mg/l)	46.29	34.74	47.39
Nitrate (mg/l)	7.93	16.30	30.85
Nitrite (mg/l)	1.76	1.46	2.21
Ammonium (mg/l)	0.32	0.06	0.08
Chloride (mg/l)	15.28	17.86	9.62
Salinity (ppm)	0.20	0.19	0.14
BOD (mg/l)	6.31	6.52	4.61
DO (mg/l)	12.29	11.55	11.58

Source: Authors' Field Report, 2025

Variation in Chemical Characteristics Across Residential Areas

Table 2 presents the one-way ANOVA result testing the hypothesis that there are significant variations in the chemical characteristics of stormwater runoff across the three residential income categories. The result showed that pH (F = 4.254, p = .023), phosphate (F = 13.870, p = .000), magnesium (F = 3.921, p = .030), nitrate (F = 30.178, p = .000), ammonium (F = 3.514, p = .041), chloride (F = 5.719, p = .007), and biological oxygen demand (F = 4.637, p = .017) varied significantly across the three residential income categories at the .05 alpha level. Conductivity, turbidity, total dissolved solids, ammonia, sulphate, total hardness, calcium, nitrite, salinity, and dissolved oxygen did not vary significantly across the residential categories.

Table 2. ANOVA result of the variation in chemical characteristics of stormwater runoff across residential areas

Parameter	F-value	Sig.
pH	4.254*	0.023
Conductivity (µs/cm)	2.650	0.086
Turbidity (mg/l)	0.130	0.879
TDS (mg/l)	2.697	0.082
Ammonia (mg/l)	2.247	0.122
Sulphate (mg/l)	2.910	0.069
Phosphate (mg/l)	13.870*	0.000
Total hardness (mg/l)	1.442	0.251
Calcium (mg/l)	0.308	0.737
Magnesium (mg/l)	3.921*	0.030
Nitrate (mg/l)	30.178*	0.000
Nitrite (mg/l)	2.093	0.139
Ammonium (mg/l)	3.514*	0.041
Chloride (mg/l)	5.719*	0.007
Salinity (ppm)	1.112	0.341
BOD (mg/l)	4.637*	0.017
DO (mg/l)	2.323	0.114

**Significant at the 5% alpha level. Source: Authors' Field Report, 2025*

DISCUSSION OF FINDINGS

The pH values recorded across the residential areas, ranging from 7.06 to 7.38, indicate stormwater runoff that is close to neutral but tending towards mild alkalinity, within the World Health Organisation's maximum tolerable level of 8.5. A markedly wider range of pH (7.72 to 9.85) was reported in Abeokuta by Adedeji and Olayinka (2013), suggesting that the stormwater sampled in Calabar carries a comparatively lower buffering load of carbonate, bicarbonate, and hydroxide ions than that of the Abeokuta catchments. The mild alkalinity recorded in the present study nonetheless indicates a stormwater runoff capable of supplying carbonate, bicarbonate, and hydroxide ions in solution sufficient to bind free protons and metals (Ipeaiyeda & Onianwa, 2011), and the observed rise in pH may be linked to the solids and detergent- and soap-based products used in domestic activities such as clothes- and car-washing (Adedeji & Olayinka, 2013), consistent with the significant variation in pH found across the residential categories.

Electrical conductivity, ranging from 131.59 to 200.75 µs/cm and falling within the WHO maximum permissible limit of 200 µs/cm, is considerably narrower than the 107.7 to 346 µs/cm range reported in Ethiopia by Wondie (2009), and, as in that study, is most plausibly attributed to the presence of dissolved solids together with chloride, phosphate, and nitrate, inorganic constituents recognised to raise conductivity. Solids in stormwater runoff typically derive from landscaping activities, the erosion of pervious surfaces, dust from road shoulders, and litter and other particles deposited on impervious surfaces from human activities and construction sites (Al-Mashaqbeh et al., 2014). The absence of a statistically significant difference in conductivity across the residential categories suggests that these solid-loading processes operate at broadly comparable intensity across the study area's residential land uses, notwithstanding their differing income character.

Turbidity values, at 107.49 to 127.18 mg/l, considerably exceed the WHO recommended limit of 5 mg/l across all three residential areas, reflecting the amount of suspended and dissolved solids the runoff carries. The comparatively high turbidity recorded in the high-income area is attributable to the variety of wastewater discharges typical of such areas, while the elevated turbidity generally observed across the study area is consistent with runoff or soil erosion from construction sites, domestic wastewater discharge, and urban runoff from roads, parking lots, and other impervious surfaces. Ammonia, at 0.20 to 0.37 mg/l, remained well within the WHO permissible limit of 2 mg/l and close to the typical natural level of below 1 mg/l in surface water, its presence attributable to animal wastes, failing septic systems, and domestic discharges; the low levels recorded imply that the stormwater runoff is unlikely to promote excessive algal growth, though ammonia, while non-toxic to humans, remains toxic to aquatic life at elevated concentrations.

Sulphate concentrations, at 9.02 to 16.14 mg/l, fell far below the WHO maximum permissible level of 250 mg/l, with the comparatively higher concentrations recorded in the high- and medium-income areas plausibly attributable to the dissolution of sulphide minerals such as gypsum present in the granite used in road construction, as well as effluents from sewage. Phosphate, by contrast, at 9.26 to 21.47 mg/l, considerably exceeded the WHO limit of 2 mg/l for the discharge of wastewater across all three residential areas, the highest values in the high-income area indicating that effluents from cleansing chemicals are discharged into the stormwater runoff there in appreciable quantity. Although phosphate is not toxic to people or animals except at very high concentrations, its presence in stormwater runoff at the levels recorded is capable of stimulating the growth of plankton and aquatic plants, with downstream consequences for the food web that depends on them (Oram, 2020).

Total hardness, at 64.87 to 81.72 mg/l, falls well within the WHO maximum permissible limit of 500 mg/l and below the 103 to 140 mg/l range reported in Abeokuta by Adedeji and Olayinka (2013), classifying the stormwater runoff of the study area as soft water that is unlikely to adversely affect detergent performance and that increases water membrane permeability in the gills of aquatic organisms (Lenntech, 2021). The comparatively higher hardness recorded in the low-income area, together with its correspondingly higher calcium content, is plausibly linked to runoff from mechanic workshops containing used batteries, since calcium is present in construction materials such as cement, brick lime, and concrete as well as in batteries, all of which can influence calcium content in water sources (Lenntech, 2021). Calcium content overall remained within the WHO maximum permissible limit of 200 mg/l, though below the 75 mg/l desirable limit set by the Indian Standards Institution (1993), while magnesium content across the study area remained within the WHO permissible limit of 150 mg/l.

Nitrate and nitrite concentrations, both highest in the low-income area, exceeded the WHO maximum permissible levels of 10 mg/l and 0.1 mg/l respectively in the low- and medium-income areas, though nitrate remained within the permissible limit in the high-income area. Anthropogenic sources of nitrate include animal waste, fertiliser, and landfills (Al-Mashaqbeh et al., 2014), and the comparatively low nitrate content recorded in the high-income area is plausibly attributable to the greater availability of waste-collection bins there, which helps control effluent discharge relative to the low- and medium-income areas; if uncontrolled, the elevated nitrate discharges recorded in the low- and medium-income areas could, over time, accelerate eutrophication of the receiving water bodies (Akan et al., 2010). The elevated nitrite levels recorded across all three residential areas relative to the WHO limit similarly implicate effluents from sewer systems, household wastes, and animal wastes as sources of nutrient input into the stormwater runoff of the study area, a pattern consistent with the findings of Ha and Stenstrom (2003) that the types and levels of pollutants carried by stormwater runoff are directly related to land use and human activity.

Ammonium, chloride, and salinity, by contrast, remained well within their respective WHO permissible limits of 30 mg/l, 600 mg/l, and 1,000 mg/l across all three residential areas, indicating that the residential land uses of the study area generate or make use of comparatively low quantities of these particular substances, and that the stormwater runoff sampled is not saline. The comparatively elevated chloride recorded in the medium- and high-income areas, which the ANOVA result confirms as a statistically significant source of variation, is consistent with chloride's origin in sewage and industrial effluents and in urban runoff, and is unlikely, at the concentrations recorded, to impart a noticeable taste to the receiving water (WHO, 2011).

Biological oxygen demand, at 4.61 to 6.52 mg/l, remained below the WHO minimum allowable limit of 10 mg/l across all three residential areas and considerably below the 36 to 94.5 mg/l range reported in Abeokuta by Adedeji and Olayinka (2013), yet the comparatively higher BOD recorded in the medium- and high-income areas indicates a greater quantity of effluent from household wastes mixing with stormwater through runoff in those areas, since the more organic material present in wastewater discharged into stormwater runoff, the higher the resulting BOD (Chukwu, 2008), a pattern plausibly linked to construction activity in those areas. Dissolved oxygen, at 11.55 to 12.29 mg/l, was well above the WHO permissible limit of 8 mg/l for the discharge of wastewater and far above the 2.08 to 4.36 mg/l range reported by Adedeji and Olayinka (2013), the comparatively higher value recorded in the high-income area suggesting a correspondingly higher organic pollution load requiring oxidation there, a finding that, taken together with the elevated turbidity, phosphate, and BOD also recorded in the high-income area, implies that the stormwater runoff of the study area, as currently constituted, would not effectively sustain aquatic life if discharged untreated into receiving water bodies.

Taken together, the statistically significant variation recorded for pH, phosphate, magnesium, nitrate, ammonium, chloride, and biological oxygen demand, set against the non-significant variation recorded for the remaining ten parameters, indicates that the chemical characteristics of stormwater runoff in Calabar Municipality are shaped by residential income status for some, but not all, water quality determinants. This selective pattern of variation is consistent with the land use-water quality relationship established globally by Ha and Stenstrom (2003), Al-Mashaqbeh et al. (2014), and Gunawardana et al. (2012), and extends this relationship to a tropical, rapidly urbanising West African city in which residential socioeconomic status, rather than land use category alone, measurably shapes the chemical quality of the stormwater runoff generated, thereby addressing the gap identified in the local literature regarding comparative, income-stratified assessment of residential stormwater chemistry in the study area.

CONCLUSION

This study examined the chemical characteristics of stormwater runoff and their variation across high-income, medium-income, and low-income residential areas of Calabar Municipality, Cross River State, Southern Nigeria. The quality status of stormwater runoff was found to vary spatially due to variation in location and the nature of activities carried out in the respective residential areas, with phosphate, turbidity, nitrate, and nitrite exceeding World Health Organisation permissible limits across the study area, and pH, phosphate, magnesium, nitrate, ammonium, chloride, and biological oxygen demand varying significantly across the three residential income categories. The high- and medium-income residential areas were identified as generating comparatively higher chloride and phosphate loading, and the low-income area comparatively higher nitrate and nitrite loading, patterns that can be attributed to the socioeconomic status and associated activities of residents in the respective areas, including the density of traffic, the adequacy of waste-collection infrastructure, and the discharge of effluents from household wastes and defective septic systems. The study concludes that the chemical quality of stormwater runoff in Calabar Municipality is jointly shaped by residential land use and the socioeconomic character of the residents that generate it.

RECOMMENDATION

Based on the findings, it is recommended that wastes from residential and other areas of Calabar Municipality be properly collected and disposed of, and should not be allowed to litter the environment, in order to control the effects of effluents on stormwater runoff and, by extension, on the surface water bodies into which the runoff ultimately drains.

It is further recommended that waste-collection infrastructure be expanded and made more equitably available across the low-, medium-, and high-income residential areas of the Municipality, given the evidence that the availability of waste-collection bins is associated with lower nutrient loading of stormwater runoff, and that residents in all three residential categories be sensitised on the consequences of indiscriminate waste disposal and the use of excessive detergent and soap-based products for the chemical quality of stormwater runoff and receiving water bodies.

Finally, it is recommended that regular, seasonally distributed stormwater monitoring programmes be instituted across Calabar Municipality's residential areas to track the parameters identified in this study as varying significantly with residential income status, and that future research extend the present comparative approach to heavy metal and microbiological characteristics of stormwater runoff across the same residential categories, so as to build a fuller picture of the environmental and public health implications of residential stormwater quality in the study area.

DECLARATIONS

Ethical approval: Institutional research ethics clearance was obtained prior to sample collection.

Informed consent: Not applicable, as the study involved the collection of environmental stormwater samples rather than human participants.

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Conflict of interest: The authors declare no conflict of interest.

Data availability: The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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