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Climate variability, land cover change and soil erosion risk implications for water quality of a humid tropical river basin in sub-Saharan Africa

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Abstract

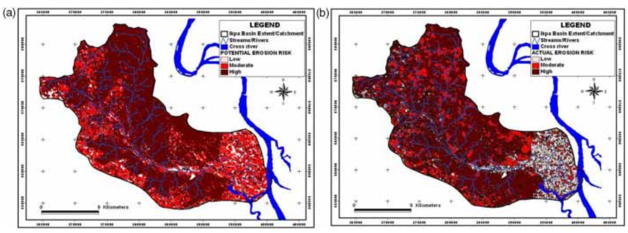
Climate variability land cover/use and soil erosion risk are important contributors to surface water quality. In this work, their implications for surface water quality of a humid tropical river in sub-Saharan Africa (the Ikpa River Basin) was assessed. The results revealed that rainfall is the most important climatic parameter to assess the climate variability trend in the region and the most important contributor to surface water quality. The region has tended to record colder weather regimes in recent years. The soil erosion risk assessment revealed that because of land cover change, between 1986 and 2018, more than half of the area with high erosion risk potential was experiencing high actual erosion risk. This has contributed to the poor quality of surface water in the basin.

Key words: Africa, climate variability, humid tropical river, land use/cover change, soil erosion risk, water quality index

Highlights

- Rainfall is the most variable climate element in Nigeria.
- High rainfall and soil erosion affect surface water quality adversely.
- Between 1986 and 2018, vegetation cover reduced by a factor of 40%.
- The region has tended to record colder weather regimes in recent years.
- There is potential for high erosion risk in the area.

Graphical Abstract



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INTRODUCTION

The possible influences of long-term temporal climate variability on quantitative characteristics of surface waters have received great attention in the past. However, relatively little is known about the resulting effects on qualitative properties of water in terms of physicochemical and biological characteristics (Delpla *et al.* 2009; Whitehead *et al.* 2009). Although the effects of climate change are expected to be more pronounced in highly vulnerable regions such as Africa (Shiru *et al.* 2019), the knowledge gaps that exist further portend the inability of the region to proffer suitable adaption and/or mitigation measures.

An overview of climate change impacts in Nigeria indicates general decrease in rainfall patterns within the last century (Odjugo 2010). However, increasing rainfall events are recorded in the coastal areas of the Niger Delta Region of the country (Odjugo 2010). The findings by Odjugo (2010) corroborate with the findings of Udosen (2008), where a substantial increase in the total rainfall was observed between 2004 and 2006. The study predicted renewed incision of gully erosion in the Ikpa River Basin, Niger Delta, Nigeria.

Land use refers to anthropogenic use of lands and their resources, and the physical conditions of these lands result from a long-term interaction between humans and natural environment (Camara *et al.* 2019). The land use within the watershed has great impacts on the water quality of rivers. The water quality of rivers may degrade due to the changes in the land cover patterns within the watershed as human activities increase (Ngoye & Machiwa 2004). Changes in the land cover and land management practices have been regarded as the key influencing factors behind the alteration of the hydrological system, which lead to the change in runoff as well as the water quality (Huang *et al.* 2013). In a study at Dongjiang River basin, a subtropical case study investigated the relationships between land use and water quality in the dry and rainy seasons based on data from 83 sites. The results show that forested land use was negatively associated with nutrients and organic parameters, especially for total nitrogen and NH_3-N. The proportion of urban land use was positively linked to increasing total nitrogen and NH_3-N concentrations in the receiving rivers. Moreover, forested and urban land uses had stronger impacts on water quality during the dry season than in the rainy season. Agricultural land use produced weak impacts on water quality in comparison with urban land use (Ding *et al.* 2015). Donohue *et al.* (2006) identified that urban, arable and pasture lands were the principal factors affecting water quality in Irish rivers. The higher percentages of land use associated with human activities and economic development in watersheds are often interrelated with high concentrations of water pollutants, while undeveloped areas such as natural forest areas are linked with good water quality (Rodrigues *et al.* 2018).

The Ikpa River is one of the major rivers in the urban areas of Uyo, the capital city of Akwa Ibom State, Nigeria. The river serves as a major source of water for irrigation and fishing purposes for the benefit of the city. Several studies have been carried out to assess the water quality status of this important surface water resource (Dennis *et al.* 2013; Inam *et al.* 2015; 2016, 2018). These studies largely ignored factors such as humidity, temperature, rainfall and erosion events in relation to measured qualitative parameters as well as temporal trends. Such climate-dependent factors have been found to have varying degrees of negative impact on water quality status of surface water bodies (Delpla *et al.* 2009; Whitehead *et al.* 2009). The aim of the present work is to carry out studies using geographic information systems (GIS), remote sensing techniques and advanced statistical tools to ascertain temporal changes and influence of climate variability on surface water quality in the Ikpa River Basin. The effect of soil erosion risks and land cover change on water quality index in the river basin were also assessed.

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MATERIALS AND METHODS

Location of the study area

Ikpa River Basin is located between latitudes 5° 0′ 3.80″ N and 5°16′ 49.12″ N of the equator, longitude 7°46′ 34.9″ E and 8°7′ 11.9″ E of the Greenwich Meridian. It is relatively positioned on a stretch across four distinct local government areas of Ibiono, Itu, Uruan and Uyo in Nigeria, and empties into the Cross River Estuaries (Figure 1). It covers an area of approximately 501.35 km^2. For descriptive purposes, the summary of morphometric parameters for the entire basin are presented in Tables S1 and S2 in the supplementary material.

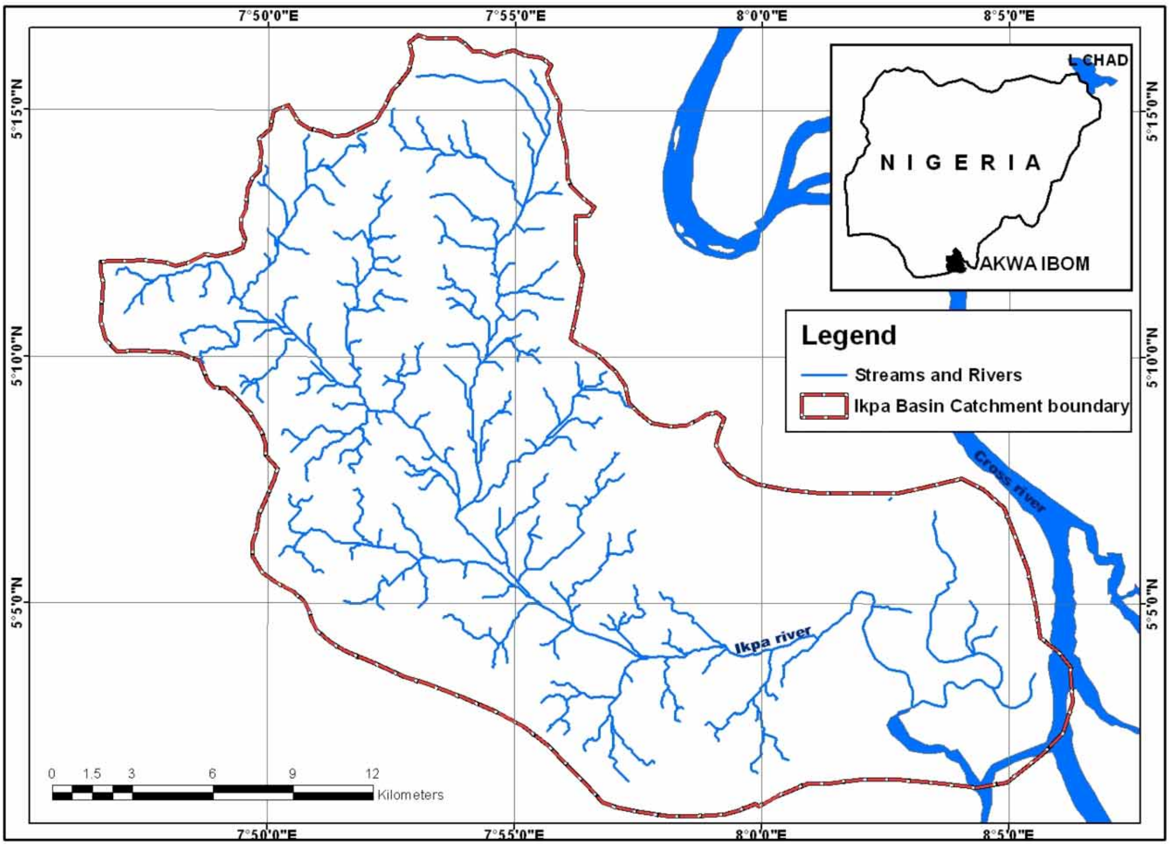

Figure 1 | Ikpa river basin showing its location, streams and rivers.

Assessment of climate variability and land cover changes

Data on climate for the period between 1989 and 2018 was obtained from the Nigerian Meteorological Station located in the University of Uyo, Uyo, Nigeria. Climatic parameters considered in this study included humidity, temperature and rainfall. We applied correlation analysis to determine significant differences between the climate parameters over a period of time. Based on data availability, climate parameters were grouped into 5 year intervals, except for temperature data which was between 1983 and 2016. These data are presented in Tables S3 to S5. Maps of Ikpa river basin showing its areal extent/catchment limit, streams/rivers, settlements, land use/land cover etc. were produced using Shuttle Radar Topographic Mission (SRTM) data and Landsat imagery. This was carried out with geospatial technologies, particularly Geographical Information System (GIS), remote sensing techniques and global positioning system (GPS). Based on the prior knowledge of the study area for years and reconnaissance survey with additional data from previous research in the

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study area, a classification scheme was developed for the study area. The classification scheme was used in producing the land cover maps of the area for different time periods. The scheme gives a rather broad classification where the land cover categories were identified: built up areas/bare-soil; farm/fallow land; secondary forest; and fresh water swamp forest.

Erosion risk assessment

Soil erosion is one of the major agents of water and land degradation and, as such, poses among other things severe limitations to water security. The main factors affecting the amount of soil erosion include vegetation cover, topography, soil, and climate (Issaka & Ashraf 2017). In order to determine erosion risk areas, erosion risk maps were generated based on these factors using the most common empirical erosion prediction model–the Co-ordination of information on the Environment (CORINE). There are many expert-based and model-based approaches that have been used for the development of erosion risk maps of various parts of Europe (Zhu 2012; Drzewiecki *et al.* 2014; Parsakho *et al.* 2014; Cieślak *et al.* 2020). Of these models, the CORINE model was adopted in this study because the required datasets were available. The required database parameters were soil erodibility, erosivity, topography (slope), and land cover. The methodology considered two different indices of soil erosion risk. They were potential soil erosion risk and actual soil erosion risk. The logic behind the methodology used in the CORINE model is presented in Figure 2.

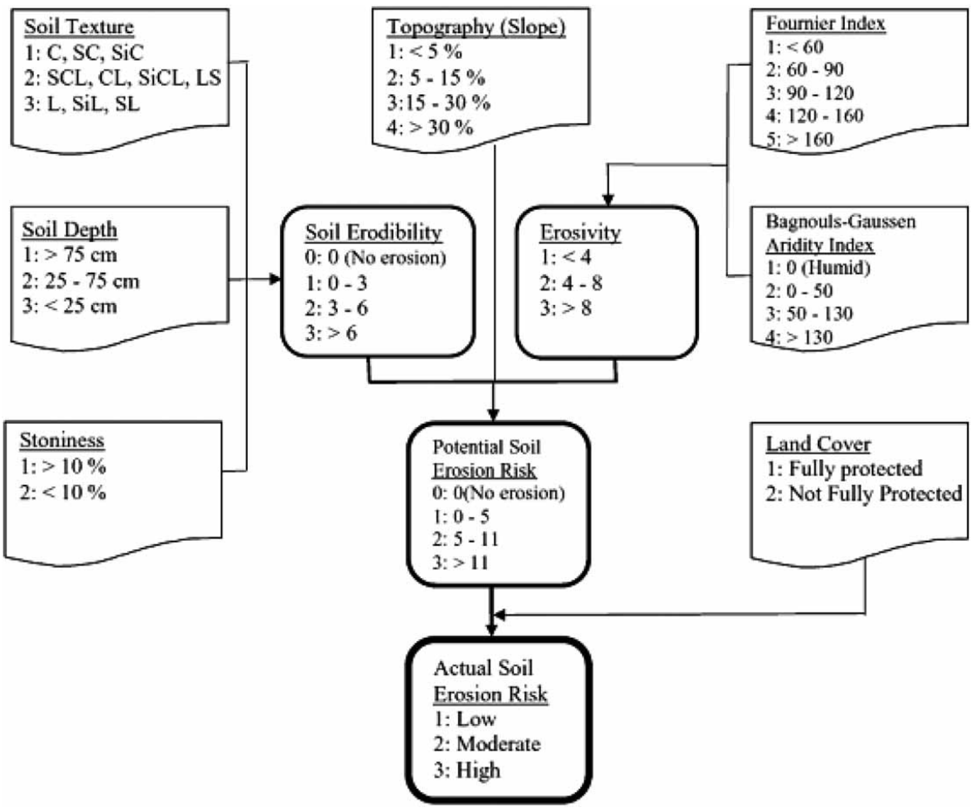

Figure 2 | Flow diagram of CORINE methodology (CORINE 1992).

Using the Geographic Information System (GIS) technology, base maps of the area showing soil topography, land cover and climate were produced. Based on the CORINE model, these maps were recoded and analyzed (using GIS spatial analysis tool and the overlay operations) to produce the potential erosion risk map. Using 2018 Landsat imagery of the area, a CORINE-based landcover map of the area was produced and then combined through the overlay operation with the potential erosion risk map to produce

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the actual erosion risk map for 2018. The identification of areas that are vulnerable to soil erosion can be helpful for improving our knowledge about the extent of the areas affected and, ultimately, for developing measures to control the problem so as to reduce the risk of water pollution.

Water quality analysis and assessment

In this study, data on physiochemical properties of surface water within the Ikpa River basin were collected from secondary sources such as published journal articles and completed research projects archived in the University of Uyo library. The list of the sources of data are presented in Table S6 in the supplementary material. These data were used to determine the water quality index. Water quality index is a mathematical model for representing water quality data in simple terms (e.g. excellent, good, bad, etc.); it reflects the level of water quality in rivers, streams, and lakes (Lumb *et al.* 2011).

The Water Quality Index (WQI) for Ikpa river was calculated from at least nine physiochemical parameters, namely: biological oxygen demand (BOD), total dissolved solids (TDS), pH, dissolved oxygen (DO), turbidity, PO_4, NO_3, chlorides, total hydrocarbon (TH), electrical conductivity (EC), and alkalinity. The WQI was calculated using the weighted arithmetic water quality index method in which water quality parameters are multiplied by a weighting factor and are then aggregated using a simple arithmetic mean as shown in Equations (1)–(3) (Ewaid & Abed 2017).

$$Qi = \frac{[Mi - li]}{[Si - Ii]} \times 100 \tag{1}$$

$$Wi = K/Si \tag{2}$$

$$WQI = \sum_{i=1}^{n} \frac{WiQi}{\sum_{i=1}^{n} Wi} \tag{3}$$

where, Q*i* is the sub-index of the *i*th parameter, W*i* is the unit weightage of the *i*th parameter, n is the number of parameters included, M*i* is the monitored value of the parameter, I*i* is the ideal value and S*i* is the standard value of the *i*th parameter. The ideal value for pH = 7, dissolved oxygen = 14.6 mg/l, and for other parameters, is equal to zero (Ewaid & Abed 2017). The weightage unit (W*i*) of each parameter was calculated as a value inversely proportional to the standard of the World Health Organization (S*i*) World Health Organization, 2011. Based on the calculated WQI, the category of water quality types is presented in Table 1 according to Ewaid & Abed (2017). Bio-indicator monitoring was not considered in this study because the data were not available for most of the sampled points. This is one of the limitations of studies carried out so far on water quality in the area. This limitation will need to be addressed in future studies by researchers.

Table 1 | Categories of water quality types and their index levels

Water Quality Index level	Water quality type
0–25	Excellent water quality
26–50	Good water quality
51–75	Poor water quality
76–100	Very poor water quality
>100	Unsuitable for drinking

Source: Ewaid & Abed (2017).

Furthermore, stepwise multiple regression analysis was used to determine the contributions of climatic factors (mainly rainfall, humidity and temperature) to the quality of water in the basin.

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RESULTS AND DISCUSSION

Climate variability

The trend of mean rainfall data between 1989 and 2018 are presented in Figure 3. There seems to be a general increase in the amount of rainfall above 190 mm from the early 2000s to 2018. The average rainfall between 2004 and 2018 was more than that obtained between 1989 and 2003. The data presented for each range of years are statistically different at $p = 0.05$. Rainfall variabilities are better displayed in the rainy season between May and October (Figure 4). This period revealed high variability between the data sets as presented in Figure 4. However, in the last five years, the average annual rainfall peaked above 500 mm, which is the highest in the past 30 years. This was closely followed by the data for years 2009–2013.

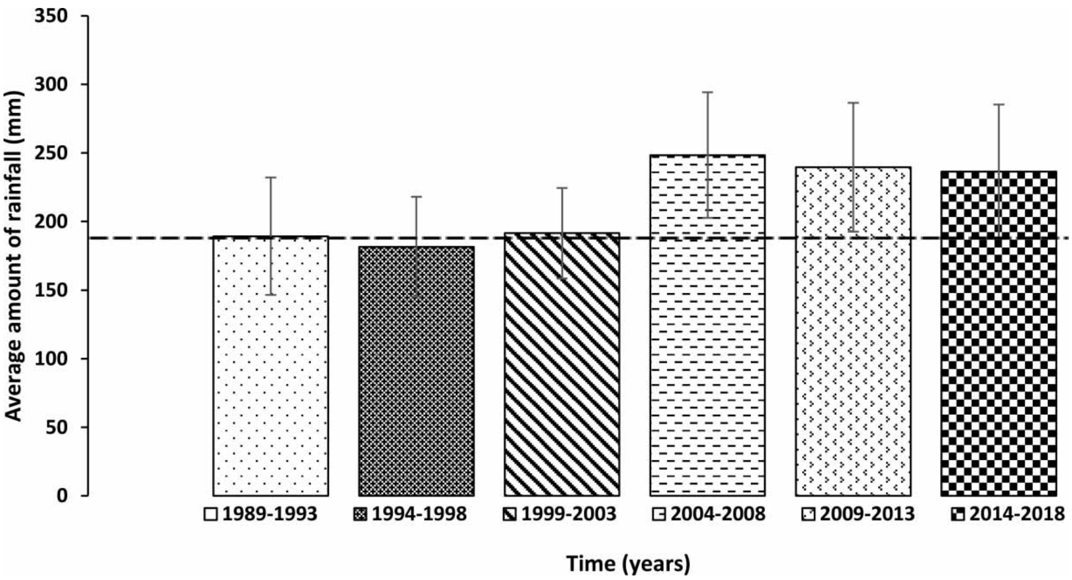

Figure 3 | Trend of mean rainfall over 30 year period in the study area.

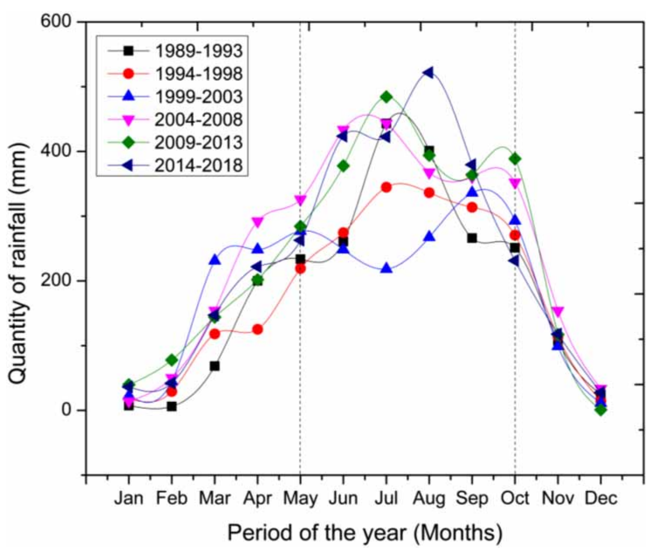

Figure 4 | Monthly variabilities in mean rainfall data over 30-year period.

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Relative humidity is one of the most varied climate parameters in the study area. The curves are generally similar (Figure 5). However, a sharp drop is observed for the relative humidity between July and December in 2014 through 2018.

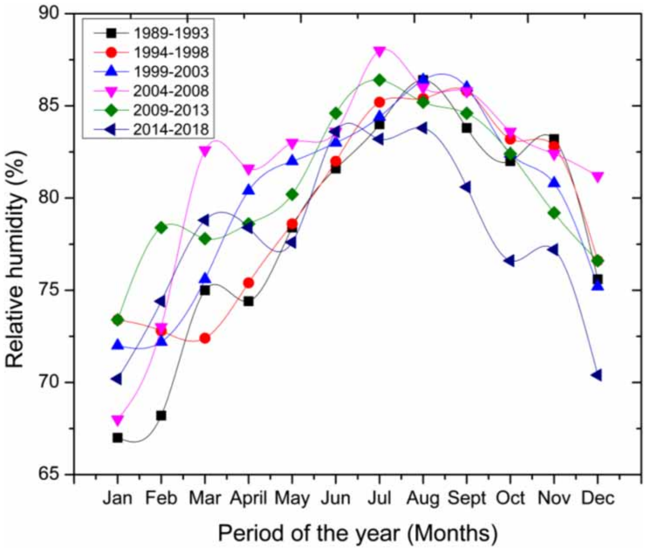

Figure 5 | Trend of mean humidity over 30-year period in the study area.

During the period between 1983 and 1986, high temperatures were recorded (Figure 6). During this period, the temperature peaked during the dry season between January and March. Lowest temperatures were recorded recently, between 2012 and 2016, especially during rainy seasons (Jul-Aug). The result implies that the region is recording colder seasons in recent times, most prominently July, August and September (Figure 6).

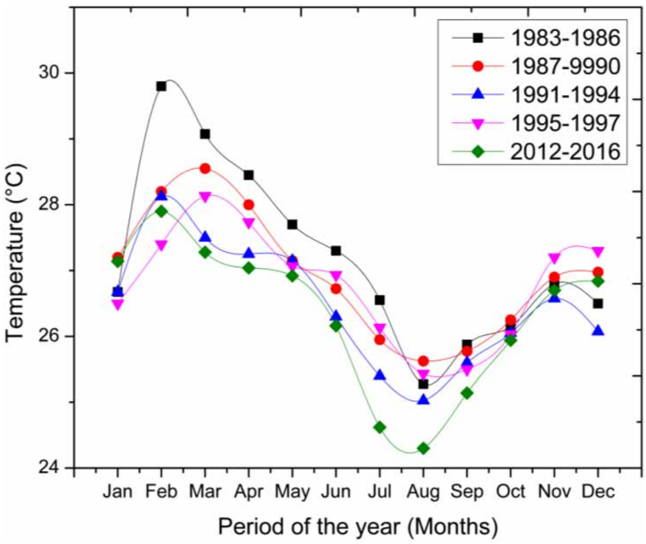

Figure 6 | Trend of temperature over 30-year period in the study area.

Based on the analyses, among the elements of climate considered, rainfall is the most variable in the study area. This is in line with the findings of previous studies that among all the climatic elements, rainfall is the most variable element in Nigeria, both temporally and spatially and such variations can have

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significant impacts on human activities, rate of soil erosion, and surface water quality among other things (Mortimore & Adams 2001). Observed variation can be attributed to a number of natural and anthropogenic factors such as deforestation, industrialization and urbanization, to mention just a few.

Land use/cover changes in Ikpa River Basin

Changes in land use and land cover are presented in Figure 7. The changes are for 1986, 2007, and 2018. These dates coincided with the periods before Akwa Ibom State was created and the period after its creation when massive development took place. Based on computation from these maps, 73% of the area had vegetation cover (i.e. secondary and swamp forest, which helped to reduce soil erosion) in 1986. This reduced to 35% in 2007 and 29% by 2018. These changes are an indication of a high rate of deforestation in the area. Also during the period, there was an increase in the size of farm/fallow land and built up areas/baresoil. These changes no doubt encouraged a high rate of soil erosion, land degradation and altimately water pollution in locations with high rainfall like the Ikpa river basin. Studies have shown that water quality of rivers may degrade due to changes in the land cover patterns within the watershed as human activities increase (Sliva & Williams 2001; Yong & Chen 2002; Ngoye & Machiwa 2004; Bai *et al.* 2010).

Erosion risk in Ikpa River Basin

The result of erosion risk analysis is presented in Figure 8. Based on computations from Figure 8, about 70% of the study area has high potential erosion risk, while about 52% of the study area has high actual erosion risk. This implies that because of changes in land cover between 1986 and 2018, more than half of the area with high erosion risk potential was experiencing high actual erosion risk. Since studies revealed that the main activity in this section of the river is erosion and transportation (Allan 2004; UNEP 2008; Wohl 2018), one can safely state that these high actual erosion risk areas are the sources of materials (pollutants) found/eroded into streams/rivers in the area.

Water quality index of Ikpa River Basin

The summary of yearly mean of the physicochemical parameters is presented in Table S7 in the supplementary material. Temperature data ranged from 24.4 °C to 29.35 °C, with the highest in 2004; electrical conductivity values ranged from 0.063 μs/cm to 297.14 μs/cm with the highest in 2013. Values for TDS ranged from 0.058 mg/l to 452.5 mg/l, with the highest in 2000, while pH ranged from 5.5 to 7.9 with the highest in 2004. Total suspended solids ranged from 0.001 mg/l to 334.94 mg/l with the highest in 2016, while the BOD ranged from 0.09 mg/l to 7.12 mg/l with the highest in 2001. Alkalinity ranged from 0.27 to 280.01 mg/l with the highest in 2017. Dissolved oxygen ranged from 1.6 mg/l to 15.534 mg/l with the highest in 2013. Calcium ranged from 1.64 mg/l to 64.91 mg/l with the highest in 2017, while nitrate ranged from 0.027 mg/l to 53.65 mg/l with the highest in 2012. Phosphate ranged from 0.18 mg/l to 50.99 mg/l with the highest in 2005 while sulphate ranged from 0.07 to 290.22 mg/l with the highest value in 2016. Chloride had the highest value in 2016, ranging from 0.13 mg/l to 92.17 mg/l.

In Table 2, the annual water quality index of Ikpa river basin between 1994 and 2017 is presented based on the classification by Ewaid & Abed (2017). The result revealed that out of the 16 years of water quality index results, nine years accounted for poor water quality, two accounted for good water quality, two accounted for unsuitable and three for very poor. Most of the years had unsafe water quality for domestic and other uses. The WQI was not computed for years with less than 13 water quality parameters because the parameters were assumed to be incomplete for the model to be applied. When considering individual years, a trend could not be established for the WQI.

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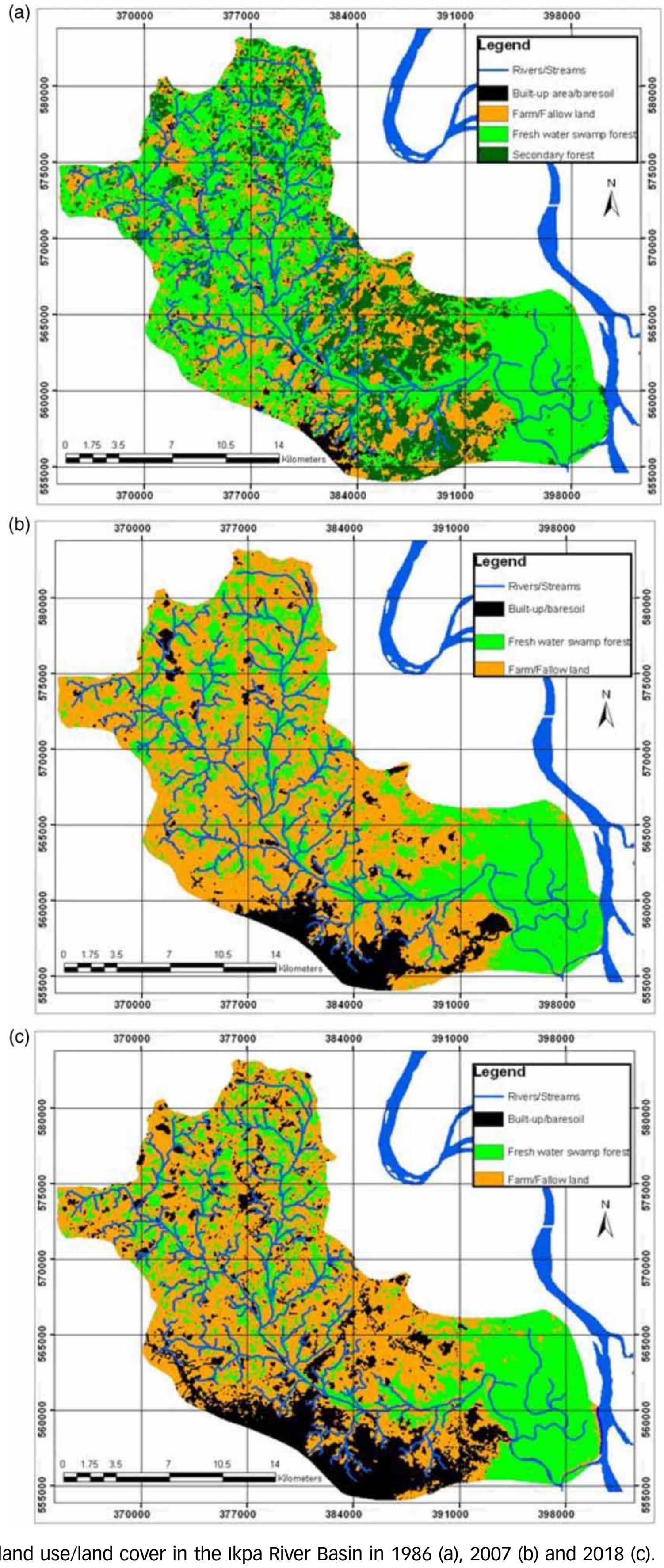

Figure 7 | Changes in land use/land cover in the Ikpa River Basin in 1986 (a), 2007 (b) and 2018 (c).

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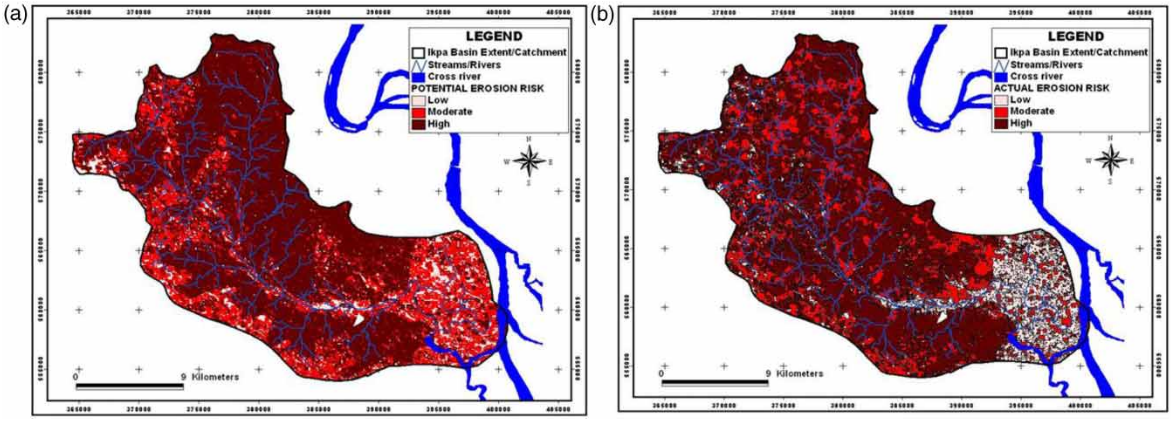

Figure 8 | Potential (a) and actual (b) erosion risk in the Ikpa River Basin.

Table 2 | Annual water quality index of Ikpa River Basin

Year	Water quality index	Remark
2017	75.39	Very poor
2016	58.69	Poor
2015	58.92	Poor
2014	68.52	Poor
2013	77.26	Very poor
2012	135.63	Unsuitable
2010	56.23	Poor
2008	57.94	Poor
2007	61.25	Poor
2006	67.11	Poor
2005	128.29	Unsuitable
2004	59.68	Poor
2001	88.80	Very poor
2000	42.32	Good
1998	63.79	Poor
1997	67.39	Poor
1994	49.33	Good

However, when the data were grouped at interval of 4 years, the WQI gradually increased (worsened) between 2004 and 2013 (Figure 9). During the same period, the highest rate of rainfall was recorded (Figure 10). This implies that increased rainfall contributed to poor surface water quality in the river basin. The grouped data were statistically different at $p = 0.05$.

The relationship between climatic parameters and water quality index revealed that each relate differently. The correlation coefficient of 0.42 for the relationship between temperature and water quality index showed that the relationship was moderate, while 0.193 for the relationship between humidity and water quality shows that the relationship was very weak, and 0.507 for the relationship between rainfall and water quality showed that the relationship was relatively strong. The correlation between water quality and temperature is significant, between water quality and rainfall is strongly significant (since $p = 0.05$, $p < 0.05$) but the relationship with humidity was not statistically significant since $p > 0.05$.

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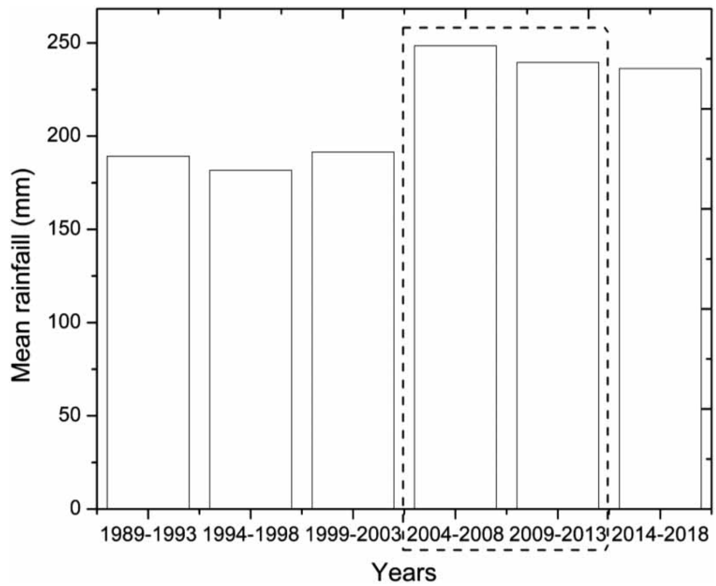

Figure 9 | Analogy of rainfall in the study area.

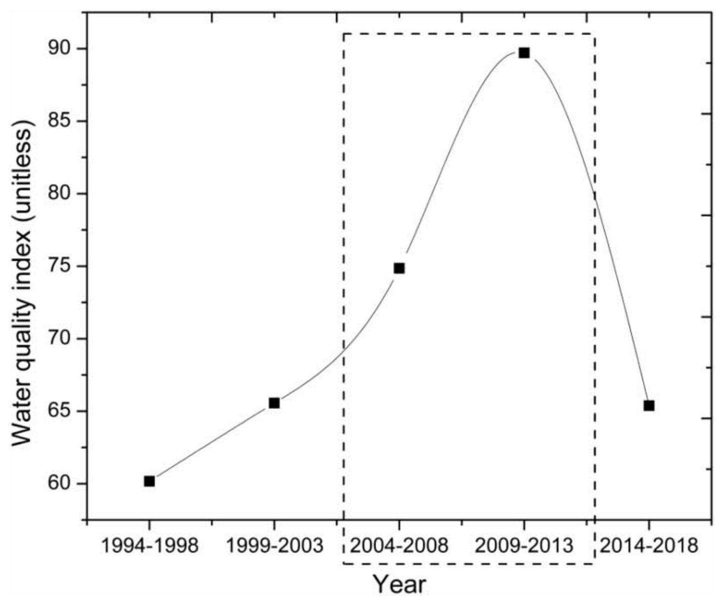

Figure 10 | Trend of water quality index of the study area.

CONCLUSION

The aim of this study was to ascertain the influence of climate variability, land cover/land use, and soil erosion risk on the water quality status of surface water in Ikpa River basin. It is obvious from the findings/result of the study that high rainfall and soil erosion have over the years contributed to degrading the surface water quality. This was through anthropogenic activities including agricultural, industrial and municipal wastes and other pollutants entering the river system through direct discharges or surface runoff. There is therefore a need to control changes in land cover in order to reduce soil erosion risk and the pollution of surface water in the area.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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