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Quality Evaluation of River Chanchaga Using Metal Pollution Index and Principal Component Analysis

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Abstract

In this study, metal pollution index (MPI) and principal component analysis (PCA) techniques were applied to water quality data sets obtained from River Chanchaga, Minna, North-central Nigeria, to obtain the spatial and temporal changes in the river quality. Results show that the indices which changed the quality of the river water consist of natural (weathering and bedrock dissolution) and anthropogenic activities such as mining, agriculture, domestic and industrial wastes within its catchment. The result of the MPI indicates that the river is slightly affected with respect to heavy metal pollution, which can be attributed the gold mineralization and mining along the river course. Five principal factors were generated when the data was subjected to PCA and they correspond to five possible point source of pollution to the river. Factors 1 and 2 are naturally induced while factors 3, 4 and 5 are due to anthropogenic interference in the hydrological cycle. Although, the river quality does not pose any serious threat to human health presently, the various anthropogenic activities domiciled at the downstream should discontinue, in order restore the river water quality. The people living close to the river should adopt a good sanitary habit by not dumping waste into the river henceforth. Boiling of the water before consumption is advocated.

Keywords: water quality, metal pollution index, principal component analysis, Chanchaga River, Minna, North-central Nigeria

1. Introduction

River Water quality monitoring is necessary especially where the water serves as drinking water sources, are threatened by pollution resulting from various human activities along the river course (Ahmad et al., 2010; Amadi, 2011). Heavy metals contamination in river is one of the major quality issues in many fast growing cities, because maintenance of water quality and sanitation infrastructure did not increase along with population and urbanization growth, especially for the developing countries (Sundaray et al., 2006; Karbassi et al., 2007; Akoto et al., 2008; Amadi et al., 2010). Heavy metals contamination is important due to their potential toxicity for the environment and human beings (Gueu et al., 2007; Lee et al., 2007; Adams et al., 2008; Vinodhini & Narayanan, 2008). Some of the metals such as Cu, Fe, Mn, Ni and Zn are essential as micronutrients for the life processes in animals and plants while many other metals such as Cd, Cr, Pb and Co have no known physiological activities (Kar et al., 2008; Suthar & Singh, 2008; Aktar et al., 2010). Metals are non-degradable and can accumulate in the human body system, causing damage to nervous system and internal organs (Lee et al., 2007; Lohani et al., 2008). They enter into river water from mining areas through various ways such as mine discharge, run-off, chemical weathering of rocks and soils, wet and dry fallout of atmospheric particulate matter (Macklin et al., 2003; Bird et al., 2003; Kraft et al., 2006; Venugopal et al., 2009) or from industrial areas via discharge of untreated industrial effluent in the river (Singh et al., 2008). Rivers in urban areas have also been associated with water quality problems because of the practice of discharging of untreated domestic and small scale industries into the water bodies which leads to the increase in the level of metals concentration in river water (Rim-Rekeh et al., 2006; Khadse et al., 2008; Juang et al., 2009; Venugopal et al., 2009; Sekabira et al., 2010). However, rivers play a major role in assimilation or transporting municipal and industrial wastewater and runoff from agricultural and mining land (Singh et al., 2004).

Furthermore, Rivers are dynamic systems and may change in nature several times during their course because of changes in physical conditions such as slope and bedrock geology. They carry horizontal and continuous one-way flow of a significant load of matter in dissolved and particulate phases from both natural and anthropogenic sources. This matter moves downstream and is subject to intensive chemical and biological transformations. The surface water chemistry of a river at any point reflects several major influences, including the lithology of the catchment, atmospheric inputs, climatic conditions and anthropogenic inputs. Identification and quantification of these influences should form an important part of managing land and water resources within a particular river catchment (Bellos & Swaidis, 2005).

Rapid urbanization and industrial development during last decade have provoked some serious concerns for the environment. Usually in unaffected environments, the concentration of most of the metals is very low and is mostly derived from the mineralogy and the weathering (Karbassi et al., 2008). Main anthropogenic sources of heavy metal contamination are mining, disposal of untreated and partially treated effluents contain toxic metals, as well as metal chelates from different industries and indiscriminate use of heavy metal-containing fertilizer and pesticides in agricultural fields (Hatje et al., 1998; Amman et al., 2002; Nouri et al., 2006; Nouri et al., 2008). The mine water, runoff from abandoned watersheds and associated industrial discharges are the major source of heavy metal contamination, total dissolved solid (TDS) and low pH of rivers (USEPA, 1997; Mohanty et al., 2001; Cravotta, 2008; Shahtaheri et al., 2008). The present study aimed at assessing the quality status of River Chanchaga with emphasis on heavy metal and bacteriological contaminations.

2. Materials and Methods

2.1 Location, Geology and Hydrogeology of the Area

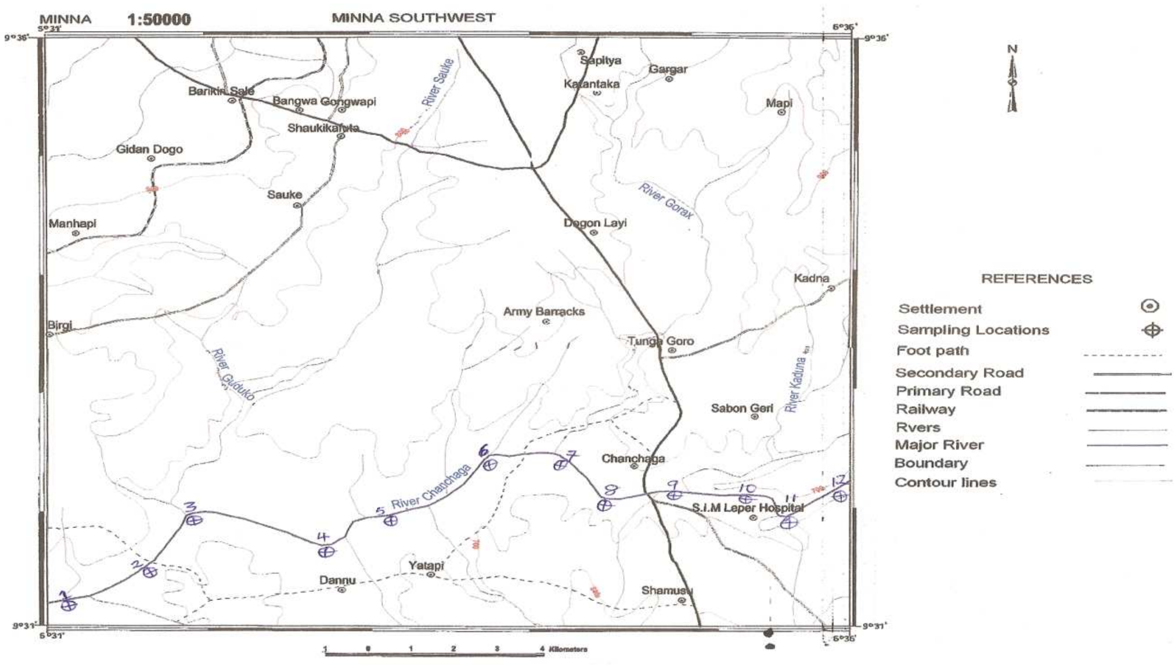

Figure 1. Topo map of Minna showing River Chanchaga (NGSA, 2004)

River Chanchaga is located at the southern part of Minna, Niger State Capital, and lies between latitudes 6°31^{I}N to 6°36^{I}N and longitudes 9°31^{I}E to 9°36^{I}E (Figure 1). The study area is predominantly underlain by the pre-Cambrian Basement Complex rocks. The local lithological units in the study area are granite, gneiss and schist. The granite is the most wide spread rock unit and are porphyritic, medium-coarse-grained in texture. The granites mostly occur as intrusive, low-lying outcrops into the gneisses. They are severely jointed and fairly incised by quartz veins. The major structural features in the study area are fractures and lineaments. North of the river, the lineaments trend NE-SW direction while in the south, close to River Chanchaga, lineaments trend

NW-SE. This implies that the NW-SE flow of River Chanchaga is structurally controlled (Figure 2). Evidence from satellite imagery of the area revealed that the southeastern part of the study area with low fracture density correspond with areas covered by soil and highly weathered thick overburden (Figure 3). The major fractures observed in the area are the signatures of the Pan African Orogeny (600ma), which is the major tectonic event that produced structural deformation of the area (Ajibade & Wright, 1988).

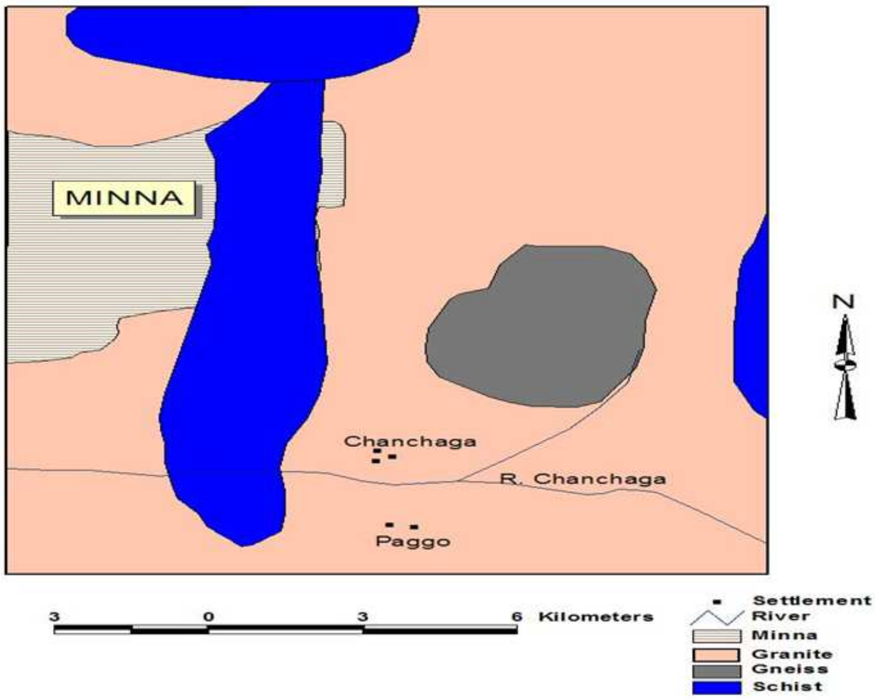

Figure 2. Geological map of parts of Minna (Source: NGSA, 200)

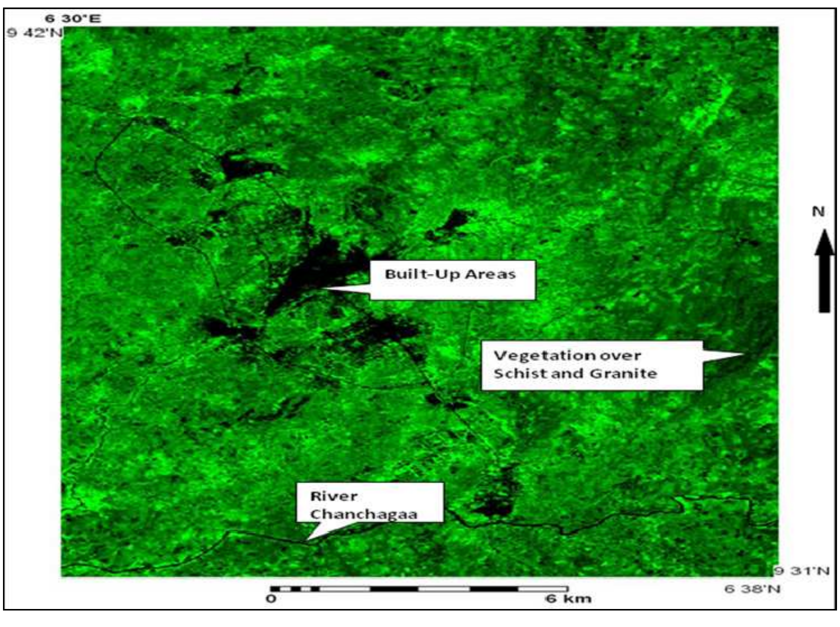

Figure 3. Interpreted band four imagery on stretching (Source: Amadi & Olasehinde, 2010)

2.2 Water Sampling and Laboratory Analysis

Twelve sampling stations were established along the river course in order to obtain a good knowledge of the overall quality of the river and this was monitored for a period of one year by taking samples from each sampling station once in every month. Water samples were taken from 10 to 15 cm below the water surface using acid washed plastic container to avoid unpredictable changes in characteristic as per standard procedures (APHA, 1998). Samples for metal analysis were collected separately and acidified at site (pH<2) with concentrated nitric acid (HNO_3). All the samples collected in tight capped high quality polyethylene bottles were immediately transported the laboratory under low temperature conditions in ice-boxes for relevant chemical and microbial analysis. Prior to chemical and microbial analysis physical parameters such as temperature, pH, and conductivity were determined insitu using mercury thermometer, pH meter (model 744, Metrohm, Switzerland) and conductivity meter (model 162A, ThermOrion, USA). Major anions (Cl^-, SO_4^{2-}, NO_3^-, HCO_3^- and CO_3^-) were analyzed using modular Ion Chromatograph (Metrohm, Switzerland) while Na^+ and K^+ were analyzed by Flame Photometer (model CL-360, Elico, India). The analysis of Ca^{2+}, Mg^{2+}, Pb, Mn, Fe, Cu, Zn and As was done using AAS (model Analyst 300, Perkins-Elmer, USA) while microbial analyses of E.coli and total coliform were carried out using presumptive count.

2.3 Metal Pollution Index

Metal Pollution index (MPI) is a method of rating that shows the composite influence of individual parameters on the overall quality of water (Tamasi & Cini, 2004). The rating is a value between zero and one, reflecting the relative importance individual quality considerations. The higher the concentration of a metal compared to its maximum allowable concentration, the worse the quality of the water (Amadi, 2011). It is also a combined physio-chemical and microbial index which makes it possible to compare the water quality of various water bodies (Filatov et al., 2005). It has wide application and it is used as the indicator of the quality of sea (Filatov. et al., 2005) and river water (Lylko et al., 2001; Amadi, 2012), as well as drinking water (Nikoladis et al., 2008; Amadi et al., 2010). The MPI represents the sum of the ratio between the analyzed parameters and their corresponding national standard values (Tamasi and Cini, 2004) as shown below:

$$MPI = \sum_{i=1}^{n} [\frac{Ci}{(MAC)i}]$$

where: Ci: mean concentration

MAC: maximum allowable concentration

Water quality and its suitability for drinking purpose can be examined by determining its metal pollution index (Mohan et al., 1996; Prasad & Kumari, 2008).

2.4 Principal Component Analysis (PCA)

The principal component analysis (PCA) technique extracts the eigenvalues and eigenvectors from the covariance matrix of original variables, thus, reducing the dimensionality of the data set. The principal components (PCs) are the uncorrelated (orthogonal) variables, obtained by multiplying the original correlated variables with the eigenvector (loadings). The eigenvalues of the PCs are the measure of their associated variance, the participation of the original variables in the PCs is given by the loadings, and the individual transformed observations are called scores (Prasad & Mondal, 2008; Amadi, 2011). PCA was performed on normalized (z-scale transformation) on 20 variables after sorting out the highly correlated variable from the data sets. The Bartlett's sphericity test was applied to the correlation matrix of variables for assessing the adequacy of PCA in water quality studies (Lambarkis et al., 2004). The PCs with eigenvalues > 1 were retained and are used to assess the compositional, temporal and spatial variations in the river quality due to anthropogenic activities domiciled along the river course (Singh et al., 2008; Sundarary, 2009; Amadi, 2012).

3. Results

The results the laboratory analysis of the river water data is summarized in Table 1 while water quality classification according to metal pollution index are shown in Table 2. The hydrochemical data were subjected to principal component analysis and the result illustrated in Table 3.

Table 1. Statistical summary of the river water data and the maximum allowable concentration by the Nigerian Standard for Drinking Water Quality (NSDWQ, 2007)

Parameters (mg/l)	Minimum	Maximum	Mean (Ci)	NSDWQ, 2007
Temperature (^oC)	27.00	33.00	30.00	Ambient
pH	6.60	9.50	7.80	6.50-8.50
Conductivity (µs/cm)	115.00	1570.00	553.00	1000.00
Chloride	0.75	220.00	58.12	250.00
Sulphate	0.20	118.00	24.82	100.00
Nitrate	0.30	58.00	12.86	50.00
Bicarbonate	0.05	120.00	38.66	100.00
Carbonate	0.00	67.00	9.04	100.00
Calcium	3.32	225.00	85.65	200.00
Magnesium	4.31	212.00	78.32	200.00
Sodium	0.80	106.00	57.30	200.00
Potassium	0.10	85.00	32.60	150.00
Lead	0.00	0.05	0.02	0.01
Manganese	0.00	0.27	0.13	0.20
Iron	0.00	2.10	0.50	0.30
Copper	0.00	2.03	1.04	1.00
Zinc	0.01	3.45	2.60	3.00
Arsenic	0.00	0.02	0.01	0.01
E.coli (cfu/100ml)	0.00	6.00	2.00	0.00
Total coliform (cfu/ml)	0.00	35.00	13.00	10.00

Table 2. Water Quality Classification using MPI (Lyulko et al., 2001; Caerio et al., 2005)

Class	Characteristics	MPI
I	Very pure	<0.3
II	Pure	0.3-1.0
III	Slightly affected	1.0-2.0
IV	Moderately affected	2.0-4.0
V	Strongly affected	4.0-6.0
VI	Seriously affected	>6.0

Table 3. Principal component analysis of the river water data

Parameters (mg/l)	PC-1	PC-2	PC-3	PC-4	PC-5
Temperature (^oC)	0.012	0.268	**0.785**	0.206	-0.195
pH	0.170	**0.609**	0.158	-0.186	0.235
Conductivity (µs/cm)	**0.812**	0.375	0.174	0.103	0.202
Chloride	**0.728**	0.304	0.158	0.250	0.158
Sulphate	0.390	**0.627**	0.345	0.109	0.050
Nitrate	0.232	0.230	**0.617**	0.220	0.105
Bicarbonate	0.343	**0.590**	0.384	0.037	-0.246
Carbonate	0.482	**0.661**	-0.195	0.134	0.328
Calcium	**0.831**	0.402	0.109	0.240	0.270
Magnesium	**0.615**	0.013	0.374	0.202	0.216
Sodium	**0.745**	0.193	-0.281	0.152	0.317
Potassium	**0.693**	0.145	0.365	0.138	0.202
Lead	0.234	-0.013	0.417	0.105	**0.845**
Manganese	-0.310	0.250	0.309	**0.610**	0.128
Iron	0.112	**0.523**	0.234	0.103	0.240
Copper	0.021	0.163	0.270	**0.549**	0.101
Zinc	0.239	0.321	0.378	**0.652**	0.321
Arsenic	-0.090	0.123	0.205	0.145	**0.654**
E.coli (cfu/100ml)	0.174	0.231	**0.562**	-0.298	0.245
Total coliform (cfu/ml)	0.312	-0.200	**0.684**	0.311	0.320
Eigenvalue	4.792	3.458	2.215	1.840	1.132
% of Variance	28.567	22.714	15.361	11.852	8.684
Cumulative %	28.567	51.281	66.642	78.494	87.178

4. Discussions

The temperature values ranged between 27.00 ^oC to 33.00 ^oC and an average temperature 30.00 ^oC while the pH varied from 6.60-9.50 with a mean value of 7.80. The conductivity values ranged between 115.00 mg/l to 1570.00 µs/cm with a mean value of 553.00 µs/cm (Table 1). The natural and anthropogenic inference in the river course may be responsible for the the slightly alkalinity and conductivity of the river water. All the major anions (chloride, sulphate, bicarbonate and carbonate) have the concentrations below the maximum permissible limit postulated by the Nigerian Standard for Drinking Water Quality (NSDWQ, 2007) for a safe drinking water except nitrate, whose concentration in some sampling points is slightly higher than the 50.00 mg/l maximum acceptable values (NSDWQ, 2007). The application of fertilizer by farmers along the river banks and urban runoff might be contributing factors.

The concentration of sodium ranged between 0.80 mg/l to 106.00 mg/l with an average concentration of 53.30 mg/l while potassium concentration varied from 0.10-85.00 mg/l with a mean concentration of 32.60 mg/l. These values fall below the allowable limits of 200.00 mg/l and 150.00 mg/l for sodium and potassium respectively (NSDWQ, 2007). Calcium concentration ranged between 2.32 mg/l to 225.00 mg/l with an average value of 85.65 mg/l while the concentration of magnesium varied from 4.31-212.00 mg/l with a mean value of 78.32 mg/l (Table 1). The slightly high concentration of Calcium and magnesium (> 200.00 mg/l) in some locations can be attributed to bedrock dissolution and chemical weathering of ferromagnesian minerals. The concentration of lead varied from 0.00-0.05 mg/l and a mean value of 0.02 mg/l while the concentration of manganese ranged between 0.00-0.27 mg/l with an average concentration of 0.13 mg/l (Table 1). The concentration of iron ranged between 0.00 mg/l to 2.10 mg/l and a mean of 0.50 mg/l while that of copper varied from 0.00-2.03 mg/l with average of 1.04 mg/l. Zinc concentration ranged between 0.01 mg/l to 3.45 mg/l with a mean value of 2.60 mg/l while arsenic concentration varied from 0.00-0.02 mg/l with an average value of 0.01 mg/l.

The concentration of these heavy metal (Pb, Mn, Fe, Cu, Zn and As) were introduced into the river water system probably through exploration and exploitation of gold on the downstream of the river. These metals occur in association with gold and are usually discarded due to economic reasons and because of their biodegradable nature, they accumulate over the years in soils and are carried by runoff into the river system. Also, the discharge of untreated urban waste in the vicinity of the river may enrich the river with some of these metals. The mean concentration of E.coli and total coliform are 2.00 cfu/100mgl and 13.00 cfu/ml respectively (Table 1). These may be due to dumping of human and animal faeces/wastes by people into or near the rivers.

The five principal components were identified to be responsible for the deterioration of the river water and accounts for 87.18% of the overall total variance. The first principal component accounts for 28.57% of the total variance and is characterized by high loading for conductivity, chloride, calcium, magnesium, sodium and potassium. The presence of these elements shows some degree of mineralization of river water due to high rates of evaporation and dissolution processes. The second major component accounts for 22.71% and comprises of pH, sulphate, bicarbonate, carbonate and iron. Chemical weathering of rock-forming minerals may be a source of their enrichment in the surface water. From the geological mapping carried out, the dominant rock unit in the area is granite, and the major cations and anions in the river water are likely from the lithology via weathering/dissolution processes and it is a function of pH. Their presence increases the conductivity of the water (Khadse et al., 2008; Kar et al., 2008).

The third principal component consists of temperature, nitrate, E.coli and total coliform which accounts for 15.36% of the total variance. Agricultural activities taking place along the river course may be responsible for the high nitrate concentration at some sampling points. The presence of E.coli and total coliform in water signifies faecal contamination due to dumping of human and animal faeces into and or near the river and the growth of these microbes in water is a function of the water temperature. The fourth principal component has a moderate loading of 11.85% of the total variance and contains Manganese, Copper and Zinc while the fifth principal component represents 8.68% of the total variance with lead and Arsenic as the contributors. The gold mining and other anthropogenic activities at the downstream of the river may be responsible for the presence of these heavy metals in the surface water. Pyrite (FeS2), galena (PbS) and other accessory mineral which occurs simultaneously with gold are discarded and are transported in form of runoff to the river system thereby contaminating it.

5. Conclusion

The quality of River Chanchaga has been evaluated using metal pollution index and principal component analysis. The result of the MPI suggests that the river is slightly affected with respect to heavy metal pollution and it is attributed the gold mineralization and mining near the river course. Five possible sources of pollution to the river were revealed by PCA and they are categorized into natural and anthropogenic factors. Chemical weathering/lithologic dissolution, gold mining, fertilizer application and waste disposal are the major contributors whose signatures deteriorate the river quality. The presence of E.coli and total coliform in water is an indication of faecal contamination and the water should be boiled before consumption as these bacteria cannot withstand elevated temperature. Mining and farming activities in downstream of the river should not continue due to their negative impact on the river quality. Good sanitary habit should be adopted people living close to the river and the use of the river as toilet should and dumpsite should stop without any further delay. The effectiveness of MPI and PCA in river water quality studies has been demonstrated in this study.

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