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Full Length Research Paper

Influence of particle size and total organic carbon on heavy metal concentrations in sediments of Lake Baringo, Kenya

Koskey J. C.^{1*}, Ogendi G. M.¹, M' Erimba C. M.² and Tamba C. L.³

¹Department of Environmental Science, Egerton University, P. O. Box 536-20115, Egerton, Kenya.

²Department of Biological Sciences, Egerton University, P. O. Box 536-20115, Egerton, Kenya.

³Department of Mathematics, Egerton University, P. O. Box 536-20115, Egerton, Kenya.

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Heavy metals impair water and sediment quality and thus, can cause adverse impacts on aquatic organisms especially when they exceed the recommended threshold levels. Heavy metal concentrations in water and sediments are a reflection of the anthropogenic activities on the watershed as well as the geology of the area. Metal concentrations and subsequently their bioavailability are influenced by the sediment characteristics including particle size and total organic carbon among others. This study determined the concentration of heavy metals - cadmium (Cd), copper (Cu) mercury (Hg) and lead (Pb) in the sediments in relation to grain size and total organic carbon in Lake Baringo. Samples were collected from five sites using a grab sampler and analyzed for total heavy metals using AAS. Particle size classification was done using the sieve method, while organic carbon (OC) was estimated using the Loss on Ignition (L.O.I) method. One way ANOVA revealed significant difference in mean Cu concentrations amongst the sampling sites at $P < 0.05$ ($F(4, 14) = 6.945$ $p = 0.01$). However, there was no significant differences in the levels of Cd and Hg, that is, $F(4, 14) = 0.03$, $p = 1.0$ and $F(4, 14) = 0.36$ $p = 0.83$ respectively. However, there was no significant difference in the levels of Cd and Hg. Sites with higher percentages of silt and clay recorded a higher concentration of Cd and Cu as well as percentage of TOC. The results indicated the pollution of the lake by heavy metals presented an ecological and a human health concern requiring monitoring.

Key words: Sediment quality, heavy metals, particle size, total organic carbon.

INTRODUCTION

Aquatic systems are important ecosystem services such as hydrological cycling climate regulation, and habitat for aquatic organisms (Xu et al., 2014). The intensity of

anthropogenic activities in the recent past has affected the existing balance of the nature. Water pollution is one of the serious environmental problems that have been

*Corresponding author. E-mail: judithkoskeyc@gmail.com. Tel: +254719440054.

caused by the increase in human activities (Petrosyan et al., 2019). Sediment is considered as the largest pool of heavy metals in the aquatic environment and they are considered to be the ultimate sink for a variety of toxicants (Xu et al., 2017; Soares et al., 1999). In the hydrologic systems, sediments reflect the pollution status and concentrations of heavy metals in the sediment are usually four or five times higher than that found in the overlying water (Hu et al., 2013).

Heavy metals enter the aquatic ecosystems naturally for example through rock weathering or atmospheric deposition. They can also enter through anthropogenic activities such as industrial wastewater discharge and agricultural fertilizer leaching (Xu et al., 2018). Heavy metals are of major concern to human health workers, tourist entrepreneurs, wildlife, fisheries managers, and conservationists due to their long residual time, strong concealment and toxicity among other characteristics. Heavy metals in the surrounding and/or underlying environments enter into water bodies and have been shown to affect aquatic life depending on their chemical speciation, toxicity, bioavailability, the rate of uptake and metabolic regulation by specific organisms (Karadede-Akin and Unlü, 2007).

Xu et al. (2017) and Soares et al. (1999) reported that sediments have the capacity to accumulate and integrate low concentrations of trace elements in water over time. This allows the possibility for metal determination even when levels in overlying waters are extremely low and undetectable. Increased metal loads in lake water and sediments are of human health concern due to biomagnification of metals along the aquatic and terrestrial food chains (Ogendi et al., 2007). Human health risks are primarily due to the elevated concentrations of heavy metals in water and fisheries that are part of the local people's diet.

The physical and chemical properties of sediments (grain size, surface to volume ratio, heavy metal contents of the main geochemistry phase), are the main factors that influence heavy metals content in sediments, of which grain size is the primary controlling parameter (Zhu et al., 2006; Jernström et al., 2010; Maslennikova et al., 2012). It is believed that coarse sediments contain a lower concentration of heavy metals than finer sediments partly due to the low clay content and higher surface-to-volume ratio (Yao et al., 2015). However, some studies have indicated that coarser particles show similar or even higher heavy metal concentrations than finer ones and the residence time of coarser particles are possibly responsible for the higher metal content (Zhu et al., 2006; Jernström et al., 2010; Maslennikova et al., 2012). Sediment grain size is also associated with the availability of contaminants. Fine grain sediments tend to be higher in clay content and they contain higher levels of organic carbon, which is an indication of organic pollution.

Organic matter controls the distribution of trace elements such as mercury in soil as well as, suspended

and bottom aquatic sediments. This makes the measurement of the total organic carbon present in the sediments an important parameter (Hedges and Keil, 1995; Goodarzi and Sanei, 2006). The capacity of organic matter to concentrate traces elements; however, varies with the amount and type of organic matter. Various factors that affect the ability of organic matter to concentrate elements include chemical and physical factors such as large surface area, high cation - exchange capacity and high negative ability (Baran et al., 2019). The chemical relationship between organic matter and trace elements at the molecular level has been described and focuses primarily on the role of organic complex materials, such as humic substances in concentrating trace elements during geochemical processes in sediments (Gomez et al., 2007). The organic matter present in the form of surface coatings provides a larger surface area since it is able to concentrate on the small sediment size fractions leading to the accumulation of toxicants including heavy metals (Goodarzi and Sanei, 2006).

Anthropogenic activities such as farming, livestock rearing and charcoal burning on the shores as well as in the drainage basin of Lake Baringo are responsible for the degradation of the lake and the land-water ecotone (Johansson and Svensson, 2002). The lake basin is shallow and has no known surface outlet. The waters are believed to seep through lake sediments into the faulted volcanic bedrock. Studies on basic physicochemical characteristics carried out in various rivers and lakes in Kenya have focused on the water quality parameters with little or no consideration given to the sediment characteristics. Recently, sediment studies have gained importance and are carried out to evaluate the quality of a water body as well as the overall ecosystem health (Petrosyan et al., 2019; Nnaji et al., 2010). This is because the sediments have the ability to absorb heavy metals, the so-called hidden pollution which in under external conditions could turn into real pollution (Petrosyan et al., 2019). The goal of this study therefore was to assess the influence of sediment particle size and organic carbon on the concentration of heavy metals and distribution in Lake Baringo.

MATERIALS AND METHODS

Sampling sites and sample collection

An ecological survey research design was used and based on the research objective, five sampling sites were selected viz: Kampi Samaki (S1), Salabani (S2), Molo River mouth (S3) and Endao River mouth (S4) (Figure 1). These sites are impacted by human activities such as rapid over water movement, solid and liquid waste disposal, tree removal and constructions near the shorelines, pastures, and cropland near the shorelines and the river banks. Communities that live around Lake Baringo, Kampi Samaki, Salabani, Molo River and Endao River are pastoralists who graze large numbers of livestock around the lake, causing soil



Figure 1. Map showing water sampling sites: S1-Kampi yaSamaki, S2- Salabani, S3- Endao River mouth, S4-Molo River mouth and S5- OIKokwa Island.

degradation resulting in soil erosion. They also fell trees to clear land for cultivation or to harvest wood for fuel, leaving the land bare and exposed to soil erosion. During the rains around the lake, there are flush-floods from inflowing rivers due to poor farming practices carrying along pesticides and fertilizers some which contain heavy metals which end up in the lake. These rivers also carry enormous amounts of soils into the lake (Aloo, 2002).

Endao River, one of the main rivers draining into Lake Baringo has been dammed to create the Chemeron dam whose water is being used for irrigating the surrounding farmlands where maize, onions, tomatoes and bananas are being grown. The Molo River has been diverted for agricultural purposes around Marigat and Bogoria areas (Aloo, 2002). River Ol Arabel River has also been diverted for agricultural purposes has been seasonal and has dried since the last heavy El Nino due to damming. OIKokwa sampling point, (S5) was used as the control due to its low population and fewer human activities. Global Positioning System (GPS) (Garmin 2 model) was used to mark the sampling sites.

Sediment sample collection and analysis

Two replicate sediment samples were collected from each of the five sampling sites during each sampling period) using a grab sampler. The samples were then placed and wrapped in polythene bags and kept in ice boxes before being transported to the laboratory for analysis. Thus, a total of 40 samples of sediments (5 sites, 2 replicates and 4 sampling periods) were collected by the end of the study. This sampling strategy captured the spatial variation of heavy metal concentrations in sediments.

The samples for heavy metal determination were digested using the multi-acid digestion method as described by Briggs and Meier (1999). The heavy metals (Pb, Cd, Cu, and Hg) were analyzed using Perkin Elmer Atomic Absorption Mass Spectrophotometer (AAS) Analyst 800 according to APHA (2005). Sediment organic carbon (OC) was determined, using the Loss on Ignition method as described by Ball (1964). Sediment particle size classification was done by standard sieve method following Dishman (2000). The heavy metal data was tested for normality and homogeneity of variance using Kolmogorov-Smirnov Normality Test and Levene's Test for equal variances respectively (Minitab Ver. 14). Using data that satisfy the assumptions of normality, heavy metal concentrations in sediment samples were compared using one-way analysis of variance (ANOVA) to test for significant differences ($P < 0.05$) among sites.

RESULTS AND DISCUSSION

Heavy metal concentration in sediments

The means obtained for the concentrations of heavy metal in the sediments (pooled data) from all the sampling sites are presented in Table 1. They were as follows in mg/kg, Cu = 12.97 ± 1.0 , Cd = 1.15 ± 0.4 , Hg = 0.25 ± 0.1 ; while Pb concentrations were below limits of detection by the machine type that used. The study showed variations in heavy metal contents among the

Table 1. Heavy metal concentrations (Mean±SE) in sediments (Mg/Kg).

Site	Cu	Cd	Hg	Pb
S1	6.95±2.32	1.20±0.98	0.18±0.10	ND
S2	17.01±1.25	1.34±0.98	0.19±0.10	ND
S3	13.17±0.18	1.03±0.84	0.39±0.14	ND
S4	13.09±0.53	1.98±0.96	0.25±0.14	ND
S5	14.61±1.64	1.14±0.93	0.26±0.05	ND
P value	0.01**	1.0	0.83	

Significance levels *=0.05 and **=0.01. df =4 and n=14. WHO limits for sediment: Cd = 0.6 mg/kg; Cu = 16 mg/kg; Pb = 31 mg/kg (Ozturk et al., 2009); ND: Not Detected.

sites. Cu was the most predominant heavy metal in the lake sediments. One-way ANOVA revealed a significant difference ($P<0.05$) in Cu between the sampling sites. S1 was significantly lower compared to the other sampling sites (Table 1). Cu concentrations in S2 was 17.01 mg/kg, which exceeded the WHO limits for sediments (that is 16 mg/kg); thus, likely to adversely impact aquatic organisms particularly the diversities of benthic communities (Ali and Fishar, 2005; Ogendi et al., 2007). Rivers Molo and Endao are considered to be a major source of heavy metals into this lake as they drain through agricultural areas where there is a high usage of pesticides and animal wastes. The mean Cu value from all the sites in this study was 12.97 mg/kg, which was relatively lower than 20.95 mg/kg as recorded by Ochieng et al. (2007) in Lake Baringo.

There was no significant differences ($P<0.05$) in Cd mean concentrations. Cadmium is highly toxic to both plant and animal species. Main anthropogenic sources relate to metallurgical industries, mine wastes, sewage sludge, and municipal effluents (Khan et al., 2017). The trend in Cd concentrations was similar to the Cu concentrations, where the sediment samples from S2 recorded the highest values. On the other hand, S1 and S2 recorded slightly lower values of Hg concentrations. Site 3 had the highest concentration though not significant. The concentrations of Cd in sediments collected from the five sampling sites exceeded the WHO recommended guidelines for sediments (0.6 mg/kg). Such elevated metal concentrations in sediments can be attributed to several factors including municipal runoff, atmospheric deposition, domestic and industrial effluents and agricultural activities in the catchment areas. It is, therefore, likely that sediment-dwelling organisms at these sites will be adversely impacted in terms of their growth, survival, and reproduction (Karadede-Akin and Ünü, 2007). There was no significant difference in the mean Hg concentrations. Levels of Hg in Lake Baringo were low compared to the other Cu and Cd. However, the existence of Hg in aquatic ecosystems is of concern. This is because compounds of Hg can be microbially transformed into methylmercury (MeHg) in water and sediments. Methylmercury can biomagnify in the food

web resulting in high Total mercury (THg) even in remote areas from industrial sources (Campbell et al., 2003). Presence of Hg in Lake Baringo can be attributed to biomass burnings. Plants assimilate Hg from the soil and when burnt they release stored Hg to the atmosphere (Campbell et al., 2003). Most of the precipitation to Lake Baringo is derived from the lake catchment which frequently experiences agricultural burning. Biomass burnings are a highly significant potential source of THg to African lakes (Campbell, 2001). Soil erosion aggravated by human activities in the catchment is another potentially important Hg source to Lake Baringo, as sequestered Hg in soil oxyhydroxide particles can be released rapidly upon reduction in water quantity (Roulet et al., 1998).

Sediment characteristics (Grain size and TOC)

There was a significant difference ($P<0.05$) in the percentage of sand amongst sediment samples collected from all the sites. Similarly, percentage silt and clay also showed significant difference amongst the sampling sites as shown in Table 2. The amount of sand contained in the sediment samples collected ranged from 38.9 to 71.6% and the highest value was recorded at S1. The lowest value for clay was also recorded in this site 28.3%. Post-Hoc test (LSD) showed that at the level of 0.05, the mean differences of sand, silt and clay in S1 varied significantly. S3 had the lowest amount of sand but recorded the highest values for silt and clay. Site 4 and S5 almost had the same amounts of silt and clay.

The highest percentage of sand with low silt and clay particles was recorded at S1. However, it recorded low amounts of Cu and relatively low amounts of Hg. This can be attributed to the low water levels as the sampling site was near the bank and that the coarser particles were easily transported and deposited there and due to the strong hydrodynamical disturbance at low lake level the finer particles were washed away easily (Chen et al., 2004) resulting in larger sediment particle sizes deposition. The other sampling sites had low percentages of silt and clay as the locations were far from the banks

Table 2. TOC and grain size distribution of sediments (means \pm SE) in Lake Baringo.

Variable	Sites					P value
	S1	S2	S3	S4	S5	
Coarse particles (Sand) (%)	71.6	47.2	38.9	44.0	46.9	0.03
Fine particles(silt and clay)	28.3	52.8	61.2	56.0	53.1	0.02
TOC	12.3	11.8	9.41	10.1	11.2	0.02

and the depth was relatively deeper. Hence, the coarser particles have little chance of drifting to this site due to the weak hydrodynamical forces that instead facilitate sedimentation of finer particles (Svetlana et al., 2012). The other sites had a higher percentage of fine particles allowing the heavy metals to accumulate in them due to their high surface-to-volume ratio (Zhu et al., 2006; Jernström et al., 2010; Maslennikova et al., 2012; Svetlana et al., 2012). Results showed that municipal and domestic discharges to the lake through the populated urban area contained high concentrations of heavy metals.

The highest concentrations of Cu were recorded at S2 and S5 sampling sites and S3 had a high concentration of Hg. The sites recorded 52 and 53% respectively. The sediments from these sites consisted of fine grain particles which act as effective collectors and carriers of dissolved metals from the water column to the sediments and thus elevated concentrations of heavy metals in sediments. The abundance of fine particles is assumed to be due to the anthropogenic input associated with erosion of upstream agricultural areas and settling out of the sediments in the lake due to low water currents. Similar findings were observed by Chouba et al. (2007) where absence of strong water currents led to accumulation of fine sediments with high metal concentrations.

The mean TOC values in the five sediment samples collected ranged from 9.4 to 12.3% and showed variations for the different sampling sites. TOC was significantly difference ($P \leq 0.05$). The relatively lower TOC levels in the S3 and S4 indicated a higher contribution of autochthonous organic matter to the sediments. In S2 and S5 sites, the autochthonous organic matter probably contributed to an increasing amount of organic matter in the sediments. The variations of the levels of TOC in the lake sediments were possibly ascribed to the mixed contribution of autochthonous and allochthonous organic matter (Kritzberg et al., 2004).

The TOC levels in S1 was the highest since the region was a major nutrient enriched area, fed by the large amount of industrial, domestic sewage and agricultural wastewater loading with relative high TOC from the catchment. Sites S2 and S5 recorded the highest readings of copper and relatively high TOC. Areas that are rich in organic matter are also richer in heavy metals due to the fact that organic matter has the ability to form

complexes with heavy metals (Marchand et al., 2011). Mercury tends to bond strongly to particulate matter in freshwater, largely in inorganic mercuric form. The behavior of Cu in aquatic ecosystems often is influenced by its strong affinity for organic matter (Ogendi et al., 2007) and clay and organic carbon can substantially influence metal binding and extraction from sediments.

CONCLUSION AND RECOMMENDATIONS

The concentrations of heavy metals in Lake Baringo followed the order of $Cu > Cd > Hg$ and Pb was below the limit detection. Cu was the major polluting heavy metal since its mean concentration was much higher than the recommended limits. The concentrations of Cd also exceeded WHO levels for lake sediments and the levels of Hg were below the recommended levels. The heavy metals mostly originated from the lake's catchment area, the most important sources being agricultural, horticultural and the waste disposal activities.

The metal content of the lake sediments could also be influenced by textural characteristics (silt and clay-sized grains which provided a larger surface area that retained high amounts of heavy metals. Percent silt and clay were high in all sampling sites apart from Kampi Samaki which had a high percentage of coarse particles also recorded high amounts of TOC. The TOC levels were high in the lake sediments was predominantly allochthonous. The study presents an overall pollution status of heavy metals in the surface sediments; thus providing the government and researchers working on management and restoration of the lake with some useful information for drafting remediation measures because of the bioaccumulative and biomagnifying nature of heavy metals. In spite of the low observed sediment metal concentrations, continuous monitoring is recommended to protect human and environmental health.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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Full Length Research Paper

Spatio-temporal characterization of the physico-chemical quality of groundwater: Case of the Lobo watershed (Centre-west of Côte d'Ivoire)

Kamenan Yiwa Monique¹, Dibi Brou^{1*}, Eblin Sampah Georges¹, Konan Kouakou Seraphin¹, Kouassi Kouakou Lazare¹ and Plagnes Valerie²

¹Laboratory of Environmental Science and Technology, University of Jean Lorougnon Guedé, Côte d'Ivoire.

²UMR METIS, Sorbonne University, Paris, France.

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Drinking water supply to rural communities is increasingly relying on finding groundwater. However, groundwater resources, although believed to be safe and free of pollution, are subjects to local and diffusive pollution. This work aims at assessing the groundwater quality in the Lobo catchment area in Nibéhibé and addressing the mineralization phenomena. To achieve such an objective, a statistical approach was applied to physical-chemical analyses data recorded from two sampling campaigns during the dry and rainy seasons, respectively. The adopted approach consisted first in performing comparative analysis, second in investigating the chemical specificities within the water classes using the piper diagram, and lastly in classifying the water based on their physical-chemical similarities using the Kohonen Self-Organized Map (SOM). The reported results disclose that the investigated groundwater is acidic and weakly mineralized during rainy and dry seasons. The diagram of Piper revealed the waters are mostly chlorinated, sulphated, and calco-magnesian type. The SOM method was used to highlight water pollution especially the acid hydrolysis of rock minerals.

Key words: Characterization, spatio-temporal, physico-chemical quality, groundwater, Lobo watershed, Côte d'Ivoire.

INTRODUCTION

Water is the source of life and one of the most important factors in achieving sustainable development. Water resource management is among the issues raised, particularly in developing countries (Djaffar and Kettab, 2015). Indeed, good water management leads to economic

and social progress; conversely, poor water management hinders development and causes the suffering of populations (GWP, 2009). According to a joint report by the World Health Organization (WHO) and the United Nations Children's Fund (UNICEF) published in July 2017,

*Corresponding author. E-mail: dibibrou2018@gmail.com.

about 2.1 billion people, or 30% of the world's population, do not have access to drinking water (WHO and UNICEF, 2017). In Côte d'Ivoire, access to drinking water remains a key issue for the population (Awomon et al., 2018). Given the low flow rates in the basement zone (Dibi, 2008), surface water, which is an abundant and perennial resource, is exploited to meet the drinking water needs of populations in large urban centers such as Daloa. In the commune of Daloa, the Lobo River, which is the main source of drinking water for the population, is subject to disturbances due to climatic variability, anthropic activities and eutrophication (Labe et al., 2018) as well as silting (Kouadio et al., 2019). Consequently, groundwater appears as one of the alternative sources for supplying drinking water to the population. In addition, a study by Yao et al. (2016) on the mapping of potential water sites shows that almost all (93% of the total area) of the Lobo basin has good and excellent groundwater availability. However, in agricultural countries with humid climates, water contamination is very pronounced due to the intensive use of fertilizers and pesticides to improve production and protect crops (FAO, 2019). According to Bendra et al. (2005), agriculture is considered to be the main cause of the increase in concentrations of plant protection products in the receiving environment, the first emitter of nitrogen pollution and the second emitter of phosphorus. It is therefore necessary to understand the impact of these activities on the quality of water resources in order to set up a management strategy. However, the objective of groundwater quality management is to preserve the overall quality of these resources with a principle of systematic prevention, which is far preferable to their treatment when their quality is deteriorated (Mourey and Vernoux, 2000). It is in this context that this study aims to assess the physico-chemical quality of groundwater in the watershed of the Lobo River at Nibéhivé. More specifically, it is a question of determining the main families of water in the basin and explaining the phenomena at the origin of the mineralization of these waters.

MATERIALS AND METHODS

Presentation of the study area

The Lobo watershed, located in the centre-west of Côte d'Ivoire, between longitudes 6° 20' and 7° 55' West and latitudes 6° and 6° 55' North, is composed of three main regional departments (Daloa, Zoukougbeu and Vavoua) (Figure 1). The population size of the watershed is estimated at 1 103 059 inhabitants (INS, 2014), which corresponds to a population density of circa 165.67 inhabitants per km². The total surface area is of approximately 7000 km². On the investigated site, drinking water is supplied to towns and large rural communities by the SODECI water supply systems and, by home-made hydraulic water supply systems. The climate is of equatorial type of transition, characterized by a rainy season from March to October and a dry season from November to February with slight

temperature changes (Yao, 2015). The geological formations of the site are dominated by three geological entities, namely the granite which occupies almost the entire basin, the schists and flysch which are found in certain places (Pothin, 1988). These geological formations are covered by essentially ferrallitic and moderately desaturated soils made up of sands and clays. On the hydrogeological level, the aquifers are those of the fissured basement which are covered by an alteration level. There are two types of aquifers which are those of fissures and alterites.

To carry out this study, two sampling missions were carried out during the rainy season (September 2018) and in the dry season (February 2019). During each season, water samples were collected, stored at 4°C and analyzed in the laboratory. The material used for the acquisition of this database consists of:

- (1) Polyethylene bottles of capacity (1 L) were used to take water samples and kept in coolers;
- (2) A differential GPS (Leica 1200R) to record the coordinates of the various sampling points;
- (3) A portable HACH LANGE HQ40D multiparameter to measure *in-situ* parameters represented by physics parameters which are T (°C), pH, Eh, Conductivity and DO-Dissolved Oxygen. A HACH DR 6000 type spectrophotometer for determining the contents of chemical parameters analysis at the laboratory.

Determination of physical and chemical parameters

The quality of the physical and chemical data used in this study was shown by the determination of the ion balance. The results obtained from the assayed major ion contents are less than 5% in their majority; which shows a sufficient reliability of the laboratory analytical data and consequently of the interpretations resulting from them.

The determination of chemical parameters of water is an assessment way of its quality and the biological health of the ecosystem. Laboratory tests, have been adopted the Rodier methods (2009) shown in Table 1. In the field of water resources, the tests run are those of major elements (Mg²⁺, Ca²⁺, Na⁺, K⁺, HCO₃⁻, Cl⁻, NO₃⁻, SO₄²⁻, and NH₄⁺), nitrogen compounds (NO₂⁻), ortho-phosphate (PO₄³⁻) and metallic trace elements (Mn²⁺, Zn²⁺ and Fe²⁺). The physical parameters (T (°C), pH, Eh, Conductivity and DO) were directly measured on-site. This choice of those tests was based on the different types of activities in the area as well as on the nature of the different rocks involved.

Determination of the hydro-chemical facies of the waters of the basin

The hydro-facies determination was carried out by the means of the piper diagrams software (version 6.00). When performing, the diagram compares provided groups of samples to each other and discloses the dominant types of cations and anions to find the geological origin of the reservoir. It has been used in some reported works (Ohou, 2010; Eblin et al., 2014; Mangoua et al., 2018). When applied, the diagram allows water to be grouped by their similarities in terms of proportions of cations or anions. Typically, the Piper diagram is helpful for the establishment of groundwater's chemical facies. It is made up of two triangle shapes representing each the distribution of anions and cations, respectively, and an upper diamond shape representing the synthetic distribution of major ions. The former main diamond shape is subdivided into four elemental diamonds corresponding to a very specific type of water.

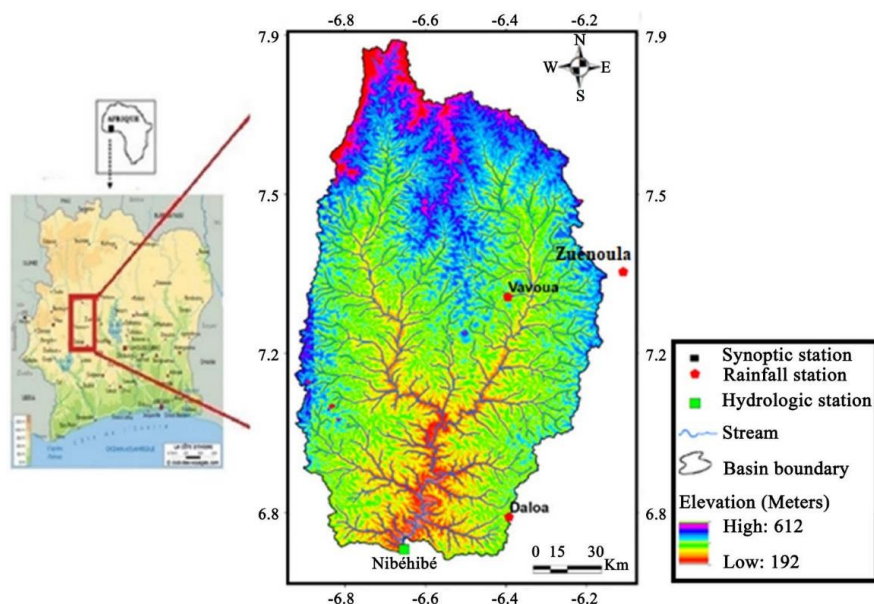


Figure 1. Study area.

Table 1. Method of determining parameters.

Parameter	Method of analysis	Standard
Nitrite	Molecular absorption spectrometry	NF T 90 013
Nitrate	Molecular absorption spectrometry	NF T 90 012
Ammonium	Molecular absorption spectrometry	NF T 90 015
Orthophosphate	Molecular absorption spectrometry with aluminium molybdate	NF T 90 023
Sodium	Atomic emission spectrometric assay	NF T 90 020
Sulfate	Nephelometry	NF T 90 040
Potassium	Atomic absorption	NF T 90 020
Chloride	Titrimetric method	NF T 90 014
Calcium/Magnesium	Atomic absorption	NF T 90 036
Hydrogen carbonate	Titrimetric method	NF T 90 036

Statistical analyses of data

Statistical data analyses were undertaken using artificial neural networks (ANN) whose goal is to highlight the phenomena at the origin of water mineralization. For this, 19 physical-chemical parameters (T, pH, EC, O₂, Eh, Mg²⁺, Ca²⁺, Na⁺, K⁺, HCO₃⁻, Cl⁻, NO₃⁻, SO₄²⁻, NO₂⁻, PO₄³⁻, NH₄⁺, Mn²⁺, Zn²⁺ and Fe²⁺) measured in well water (alterite aquifers) and borehole water (basement aquifers) constitute the input parameters of the model whose "weights" in the different samples were estimated at the output from of Kohonen's map.

The architecture of the ANN was defined to make a suitable selection of the input vector, the size of the network (or the total number of layers and neurons), the structure of the network, that is, type of interconnection between layers of neurons and transfer functions, without running after a standard procedure. Learning is performed with different map sizes and the optimal size is selected

by minimizing a so-called quantization error (QE) and topography error (TE), respectively (Park et al., 2003; Konan et al., 2006).

Technically, learning relates the entry space to the map; it aims at adapting the weights (W) so that close examples in the input space are associated with the same neuron or with nearby neurons in the map. The different stages of this learning algorithm are as follows: (a) virtual objects are initialized by objects taken randomly from the data set; (b) a real object is selected randomly and presented at the input layer; (c) the distance between that selected object and each virtual object is calculated; (d) the closest virtual object is believed to be "Best Matching Unit (BMU)", then the surrounding neurons of the BMU are modified (adjustment order).

The resulted neurons from the map are grouped using an ascending hierarchical classification procedure whose grouping principle is based on Ward's criterion. It consists in grouping together as well as possible the samples having a similar behaviour on a set of variables to give a more global vision to the map (Figure

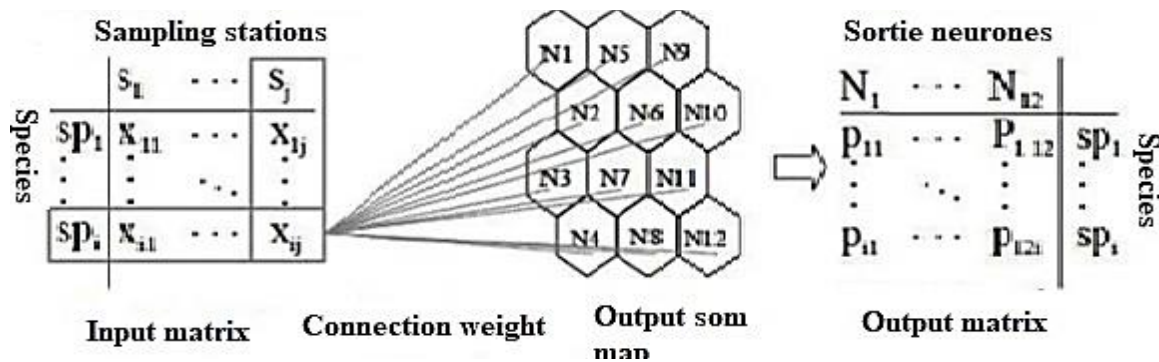


Figure 2. Simplified representation of the self-organizing map (SOM).
Source: Aguilar-Ibarra (2004).

2).

RESULTS AND DISCUSSION

Results of physico-chemical analyses of water

In this study, the set of parameters analyzed has been compared to existing standards. Tables 2 and 3 disclose the test results of physical-chemical parameters from the Lobo watershed. As shown, the recorded water temperature varied from 24.40 to 30.50°C for both dry and rainy seasons, respectively. For alterite sheets, the temperatures ranged between 26.10 and 29.10°C and between 27.50 and 30.50°C, respectively, for the rainy season and dry season. For both seasons an average thermal value was recorded and equals to 27.80 and 28.50°C. Also, the temperature of the cracked basement layers varies from 25.70 to 29.90°C with an average value of 27.64°C for the rainy season and from 24.40 to 30.20°C for the dry season with an average of 28.00°C (Tables 2 and 3). The mean water temperatures are the same in both types of water (above 25.00°C). For pH, the reported tests pointed out values between 4.29 and 7.06 pH units, with an average of 5.62 for alterites layers against 6.23, for the cracked basement layers during the rainy season and 5, 48 for the alterite layers against 6.20 for the basement layers during the dry season (Tables 2 and 3). The average pH of the waters in the investigated area is less than 7. Overall, the pH values are those of acidic water. The electrical conductivity which reflects the level of mineralization of the water varies from one water matrix to another. However, the layers of alterites have average electrical conductivities (239.97 and 240.73 $\mu\text{S}/\text{cm}$) lower than those of the layers of cracks (359.94 and 398.4 $\mu\text{S}/\text{cm}$), respectively for the rainy and dry seasons. The waters of the region are generally characterized by a low conductivity ranging from 74.5 to 1294 $\mu\text{S}/\text{cm}$. Parameters such as NO_2^- , Ca^{2+} , K^+ , Mg^{2+} ,

Na^+ , NO_3^- , SO_4^{2-} , and Cl^- meet the standards set by WHO. However, concerning PO_4^{3-} , the average values vary from 0.39 to 0.82 mg/L for the two types of groundwater in the rainy season and are 0.35 mg/L in the dry season. These values exceed the WHO potability standard of 0.20 mg/L.

Water chemical facies evaluation

The analysis of the Piper diagram (Figure 3) relating to the chemical compositions revealed that the groundwater of the Lobo watershed is dominated by chlorinated and sulphated calco-magnesian water. They are followed by chlorinated sodi-potassium waters for alterites and hydrogen carbonate calco-magnesian for waters of the cracked rocks. In these waters, the Cl^- ions constituting the most important among the anions.

Kohonen map size

The data obtained regrouping the 19 physico-chemical parameters (T (°C), pH, Eh, EC, O_2 , Mg^{2+} , Ca^{2+} , Na^+ , K^+ , HCO_3^- , Cl^- , NO_3^- , SO_4^{2-} , NH_4^+ , NO_2^- , NH_4^+ , PO_4^{3-} , Zn^{2+} , Fe^{2+} , Mn^{2+}) were analyzed using the statistical approach of Kohonen neural networks. Based on the quantization (QE) and topography errors (TE), the two minimum error types (Table 4), a Kohonen map of 45 cells (5 rows \times 9 columns) is chosen to project the 80 groundwater samples from the two major seasons (30 wells and 50 boreholes) (Figure 4). This map was obtained after several iterations during the learning phase.

Ascending hierarchical classification of the Kohonen map

The dendrogram resulting from the classification made it

Table 2. Physical and chemical characteristic of waters sampled in the rain season.

Type of water	Drilling water			Well water			WHO Standards (2011)
	Min.	Moy $\pm \alpha$	Max.	Min.	Moy $\pm \alpha$	Max.	
T (°C)	25.7	27.64 \pm 1.03	29.9	26.1	27.79 \pm 0.85	29.1	25
pH	4.99	6.23 \pm 0.55	7.06	4.29	5.62 \pm 0.70	6.61	6.5 - 9.5
Eh (mV)	14.6	259.26 \pm 107.80	361.2	262.9	322.8 \pm 42.78	413.3	-
Cond (μ S/cm)	74.5	359.94 \pm 304.04	1627	45	239.97 \pm 187.09	797	400
O ₂ (mg/L)	1.39	4.32 \pm 1.54	6.95	1.66	4.06 \pm 1.27	5.7	5
Ca ²⁺ (mg/L)	4.8	43.16 \pm 34.87	147	2.02	18.69 \pm 17.54	56.4	100
Mg ²⁺ (mg/L)	2.76	21.05 \pm 18.38	56.87	0	8.73 \pm 8.37	32.01	50
K ⁺ (mg/L)	2.6	9.65 \pm 11.60	46	1.03	9.66 \pm 7.93	25.6	12
Na ⁺ (mg/L)	2.94	20.67 \pm 8.72	33.7	2.24	19.64 \pm 9.72	36.2	200
Cl ⁻ (mg/L)	2	35.77 \pm 29.26	115	5	30.88 \pm 21.67	73	200
HCO ₃ ⁻ (mg/L)	1.2	45.72 \pm 29.98	90.4	0	48.66 \pm 55.92	234.8	65 - 160
SO ₄ ²⁻ (mg/L)	0	23.96 \pm 48.07	224.8	0	7.58 \pm 10.33	38.73	250
NO ₃ ⁻ (mg/L)	1.2	21.48 \pm 21.16	99	3.9	24.23 \pm 21.25	81	50
PO ₄ ³⁻ (mg/L)	0	0.82 \pm 0.67	2.43	0	0.39 \pm 0.43	1.61	0.2
NO ₂ ⁻ (mg/L)	0	0.08 \pm 0.19	0.72	0	0.03 \pm 0.03	0.1	3
NH ₄ ⁺ (mg/L)	0	0.22 \pm 0.31	1.45	0	0.33 \pm 0.41	1.5	0.5
Fe ²⁺ (mg/L)	0	0.97 \pm 2.44	12.8	0	0.47 \pm 0.76	2.6	0.3
Mn ²⁺ (mg/L)	0	0.1 \pm 0.12	0.41	0	0.11 \pm 0.17	0.66	0.05
Zn ²⁺ (mg/L)	0	0.03 \pm 0.06	0.24	0	0.03 \pm 0.07	0.29	3

Table 3. Physical and chemical characteristics of waters sampled in the dry season.

Type of water	Drilling Water			Well Water			WHO Standards (2011)
	Min.	Moy $\pm \alpha$	Max.	Min.	Moy $\pm \alpha$	Max.	
T (°C)	24.4	28 \pm 1.29	30.2	27.5	28.52 \pm 0.84	30.5	25
pH	4.91	6.2 \pm 0.58	7.05	4.3	5.48 \pm 0.7	6.53	6.5 - 9.5
Eh (mV)	-4.4	233.8 \pm 106.01	369.6	263.1	313.87 \pm 45.19	424.3	-
Cond (μ S/cm)	92.1	398.4 \pm 265.80	1294	37.9	240.73 \pm 180.98	725	400
O ₂ (mg/L)	1.83	3.8 \pm 1.21	6.08	2.89	3.9 \pm 0.8	5.61	5
Ca ²⁺ (mg/L)	0.8	50.83 \pm 40.62	158.4	0.8	17.96 \pm 12.30	41	100
Mg ²⁺ (mg/L)	0.24	16.9 \pm 17.52	58.32	0.24	6.46 \pm 6.88	19.2	50
K ⁺ (mg/L)	1.5	8 \pm 10.46	56.3	1.2	8.47 \pm 9.25	28.6	12
Cl ⁻ (mg/L)	5.1	33.3 \pm 32.55	137.4	3.3	34.84 \pm 46.7	193.1	200
Na ⁺ (mg/L)	5.1	21.73 \pm 8.38	34.9	3.8	16.99 \pm 11.47	38.8	200
HCO ₃ ⁻ (mg/L)	5.6	95.9 \pm 98.96	339.1	0.2	30.30 \pm 58.47	234.8	65 - 160
SO ₄ ²⁻ (mg/L)	1	13.8 \pm 21.79	79	1	3.4 \pm 2.5	11	250
NO ₃ ⁻ (mg/L)	3.2	35.2 \pm 40.57	152	0	27.43 \pm 27.6	88.1	50
PO ₄ ³⁻ (mg/L)	0.03	0.35 \pm 0.32	1.05	0.03	0.35 \pm 0.34	1.09	0.2
NO ₂ ⁻ (mg/L)	0.01	0.1 \pm 0.15	0.8	0.02	0.03 \pm 0.01	0.07	3
NH ₄ ⁺ (mg/L)	0	0.09 \pm 0.08	0.26	0	0.09 \pm 0.1	0.33	0.5
Fe ²⁺ (mg/L)	0.01	0.73 \pm 0.93	3.35	0.05	0.9 \pm 1.05	3.82	0.3
Mn ²⁺ (mg/L)	0	0.4 \pm 0.84	4.2	0	0.5 \pm 0.9	3.8	0.05
Zn ²⁺ (mg/L)	0	0.1 \pm 0.07	0.37	0	0.06 \pm 0.08	0.36	3

possible to group all the groundwater samples into four groups over a Euclidean distance of 1 (Figure 5). This

distance makes it possible to bring together the cells in pairs of groups having the same ancestors, therefore a

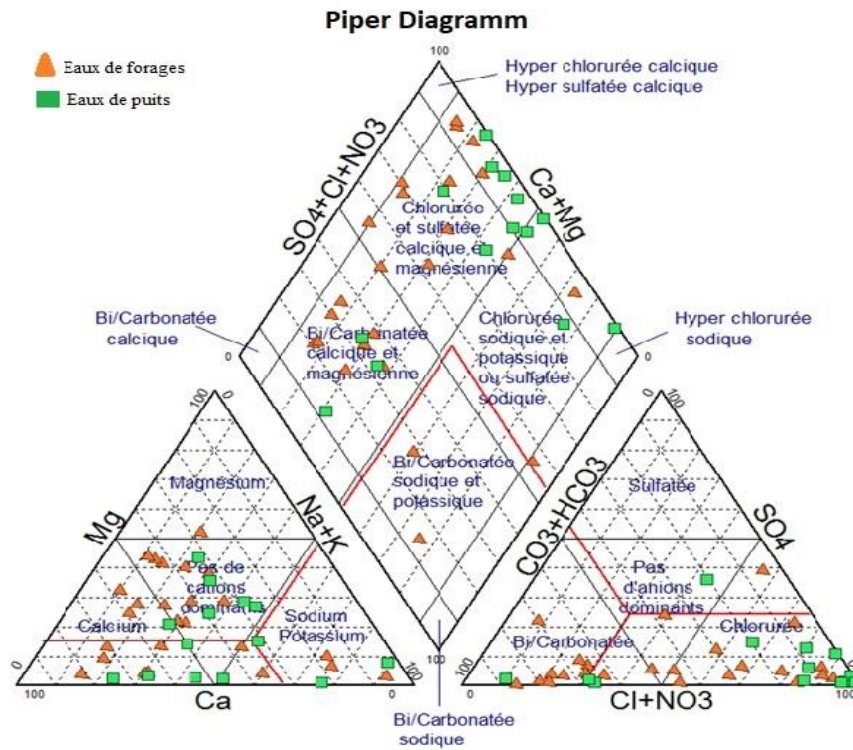


Figure 3. Diagram of piper.

Table 4. Estimation of the quantification errors and topology of the different sizes of Kohonen maps (the selected matrix is in bold) of the two seasons.

	EQ	ET
9x5	0.560	0.000
5x9	0.554	0.000
8x6	0.549	0.013

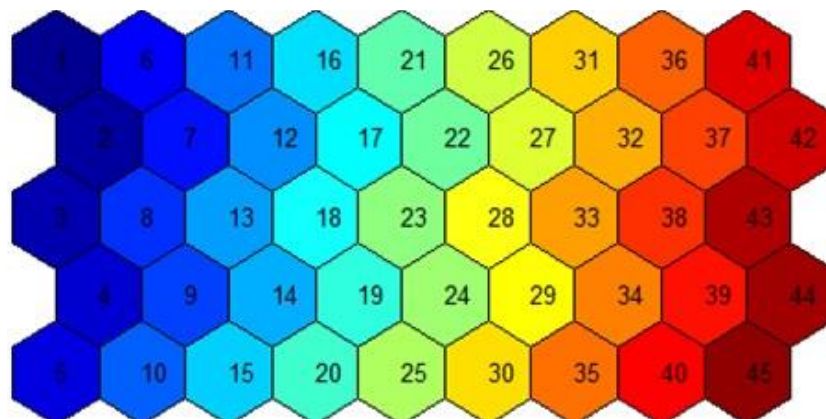


Figure 4. Water samples groups distribution on the Kohonen's map.

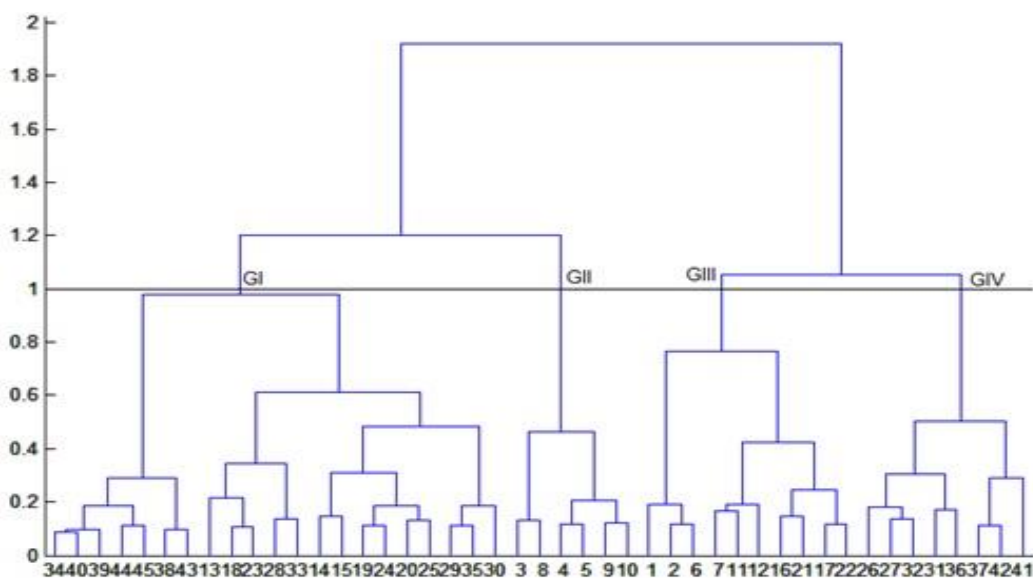


Figure 5. Ascending hierarchical classification dendrogram of the Kohonen map cells on water physico-chemical parameters basis.

strong relationship.

Distribution and count of water samples on the Kohonen map

The distribution maps, taken from the Kohonen map, make it possible to visualize the distribution of the samples of the different groups generated from the dendrograms at a Euclidean distance of 1 according to the physicochemical parameters of groundwater (Figure 6). The groups GIV appear homogeneous and are characterized by the pooling of drilling water. The other groups (GI, GII and GIII) are heterogeneous because they are made up of both samples from wells and from boreholes, the proportions of which vary from one group to another.

Differentiation and physicochemical particularities of water

Table 5 presents the importance of the physico-chemical parameters in the classification of sampling points and shows the water groups with high pollution parameters and weathering elements. Through this table, we can say that groups II and III are distinguished by high concentrations of the parameters (Na^+ , PO_4^{3-} , Mn^{2+} , NO_3^-). As for groups I and IV, they are characterized by high values of the parameters (Mg^{2+} , Ca^{2+} , Na^+ , K^+ , HCO_3^- , Cl^- , NO_3^- and SO_4^{2-} , PO_4^{3-} , SO_4^{2-} , and Fe^{2+}).

DISCUSSION

Lobo watershed groundwater has an average pH that varies from 5.48 to 6.20 for the two seasons. These waters are slightly acidic. This acidity could come from the decomposition of plant organic matter, with CO_2 production in the surface layers of the soil under biological activities. This is the characteristic of crystalline and crystallophyllian waters media, as evaluated by Kamagaté et al. (2011) on the Bandama watershed, Tampo et al. (2014) in Togo, Alassane et al. (2015) in Benin and Heriarivony et al. (2015) in Madagascar. The waters studied have an average electrical conductivity ranging from 240.73 to 398.4 $\mu\text{S}/\text{cm}$ for the two seasons. This result confers low mineralization of most of the groundwater in the study area. In agreement with Kamagaté et al. (2011), this weak mineralization is to be compared with the silicate nature of the rocky matrices crossed; the alteration and dissolution of chemical elements in ionic form are particularly slow. The average phosphate values range from 0.35 to 0.82 $\text{mg}\cdot\text{L}^{-1}$. According to Matini et al. (2009), the concentration of phosphate ion in groundwater should not exceed 0.2 $\text{mg}\cdot\text{L}^{-1}$. The high levels of phosphate ions could be due not only to human actions such as the discharge of wastewater (human excreta, polyphosphates in lye) but also to the dissolution of essentially schistose crystalline rocks (metasiltstones and metaarenites) Birimian and granite formations (metagranites, granitoids and granodiorites) (Kouakou, 2018) of the study area. The Piper diagram shows that most of the fodder and wells

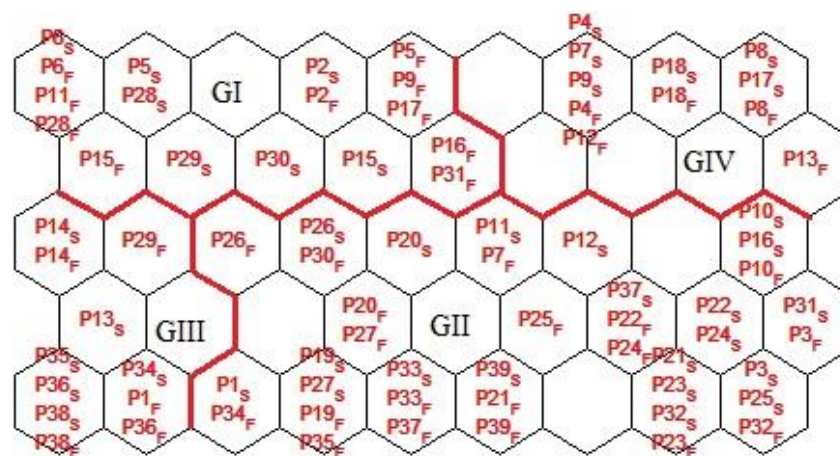


Figure 6. Water samples groups' distribution on the Kohonen's map.

Table 5. Physicochemical differentiation of water groups.

Group	T	pH	Eh	Cond	O ₂	O ₂ (%)	Na ⁺	K ⁺	Mg ²⁺	Ca ²⁺	Cl ⁻	NO ₃ ⁻	SO ₄ ²⁻	HCO ₃ ⁻	NO ₂ ⁻	PO ₄ ³⁻	NH ₄ ⁺	Mn ²⁺	Fe ²⁺	Zn ²⁺
I	++++	+++	++	+++	+	+	++++	+++	++	+++	+++	+++	+++	++	+	+	+	+	+++	+
II	+++	++	+++	+	++	++	+++	+	+	+	+	+	+	+	+	+++	+	+++	+	++
III	+	+	++++	+	+	+	+++	+++	+	+	+	+++	+	+	+	++	++	+	+	+
IV	++	++++	+	++	+	+	++++	+	+++	+++	+	+	+	+	++	+++	+	+	+	+

Intensity of physicochemical parameters ((+) = low, (++) = medium, (+++) = high and (++++) = very high).

studied have chlorinated sulphated Calco-magnesian and chlorinated sodi-potassium waters. This could be explained by the fact that the geology of the area is dominated by metamorphic rocks. Concerning the individuals of the four groups of the Kohonen's maps, the grouping of variables composed by the majority of physicochemical parameters such as Mg²⁺, Na⁺, Ca²⁺, K⁺, Cl⁻, PO₄²⁻, SO₄²⁻, Fe²⁺, Mn²⁺, NH₄⁺ and NO₃⁻ could indicate several phenomena of dissolution of ions such as oxidation-reduction

reactions then contributions linked to anthropogenic activities and especially acid hydrolysis of rock minerals. The fundamental elements (Ca²⁺, Mg²⁺, Na⁺ and K⁺) present a development comparable to those observed in the regions of Bongouanou, Dimbokro, Toumodi, Bouaké and Man (Mangoua et al., 2015). These results are similar to those of Savané and Soro (2001) and Jaunat (2012) who worked respectively in the north-west of Côte d'Ivoire and on the Ursuya massif in France. The observation of

these minerals in water indicates the phenomena of rock dissolution by the mechanism of acid hydrolysis of silicate minerals. The work of Lasm et al. (2011) and Mangoua et al. (2015) carried out in the regions of M'bahiakro, San Pedro and Bondoukou, respectively produced similar results.

The high contents of parameters such as Cl⁻, NO₃⁻, and SO₄²⁻ could also indicate the contribution of human activities in the process of water mineralization. The same observations were made in groundwater in Ghana by Yidana (2010). In fact,

according to these authors, the nitrate, sodium and chloride ions contained in groundwater, supply surface horizons washed away by seepage water. The labelling of groups (I and II) by Mn^{2+} and Fe^{2+} ions shows that the mineralization of these waters is not only linked to the phenomena of hydrolysis of rock minerals and anthropogenic but also to the phenomenon of oxidation-reduction (Mangoua et al., 2015). These high levels of iron and manganese in the waters have also been observed at Yamoussoukro (Soro et al., 2019). It could also be attributed to the crystalline geological formations rich in biotite (biotite granite) in the region as reported by Ahoussi et al. (2013) in the mountainous west of Côte d'Ivoire. The high levels of iron and manganese in groundwater lead to the deficit of dissolved O_2 in these aquifers by oxidation. Indeed, these two elements give water an unpleasant taste, a reddish-brown and black-brown appearance and colour. This situation forces rural populations to turn to other sources of supply whose bacteriological and parasitological qualities are questionable, which can have serious consequences on the health of populations

Conclusion

The physical and chemical characteristics of groundwater from the boreholes and wells in the Lobo watershed show that the water is slightly acidic with pH values between 4.29 and 7.06. Concerning the alterites layers, the average value of this pH is 5.62 against 6.23 for the basement layers cracked during the rainy season. For the dry season, the pH values are 5.48 for the layers of alterites against 6.20 for the basement layers. Overall, these waters are weakly mineralized with values varying from 239.97 to 240.73 $\mu S/cm$ for the alterite sheets and from 359.94 to 398.40 $\mu S/cm$ for the sheets of cracks, respectively during the rainy season and dry season. Parameters such as NO_2^- , Ca^{2+} , K^+ , Mg^{2+} , Na^+ , NO_3^- , SO_4^{2-} , and Cl^- meet the standards set by WHO. However, concerning PO_4^{3-} , the average values vary from 0.40 to 0.82 mg/L or the two types of groundwater in the rainy season and are 0.35 mg/L in the dry season. These values exceed the WHO potability standard of 0.20 mg/L. The chemical facies of these waters are mainly chlorinated and sulphated calco-magnesian. The results of the statistical analysis show that the mineralization of water is acquired by the dissolution of the rock by acid hydrolysis and oxidation-reduction reactions. They could also come from superficial input caused by anthropogenic activities.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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Full Length Research Paper

Mining the past for a better future of African waters: Historical changes in the fish and fishery of Lake Bam (Burkina Faso) before rehabilitation

Raymond OUEDRAOGO¹, Komandan MANO^{2,3*} and Adama OUEDA²

¹Institut de l'Environnement et de Recherches Agricoles (INERA), Ouagadougou, Burkina Faso.

²Laboratoire de Biologie et Ecologie Animales (LBEA), Université Joseph KI-ZERBO, Ouagadougou, Burkina Faso.

³Université de Dédougou, Burkina Faso, BP 176 Dédougou, Burkina Faso.

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Terrestrial waters provide multiple goods and services to human kind, but they have been severely diminished by increasing human exploitation of water and the landscapes surrounding aquatic communities. This research illuminates such dynamics in the recent history of exploitation of the Lake Bam fishery in Burkina Faso. To do so, from 2009 to 2015 we collected data on the ecology, exploitation and governance of the Lake Bam fishery. Direct sampling of fish documented the erosion of fish diversity and the reduction of fish size and the number of landings. Interviews with leaders of riverside community suggest a halting and uncertain transition in the governance of natural aquatic resources from the traditional (pre-colonial) approach to a republican (European democratic) one. The number of fishermen exceeds the fishery's carrying capacity, but the number of fishermen continues to rise, driven by the low level of opportunities in alternative livelihoods. National and international awareness regarding the lake's ecological and socio-economic importance has driven restoration projects that can benefit from these findings.

Key words: Water, fishery, sahel, ecological awareness, exploitation, governance.

INTRODUCTION

Aquatic ecosystems provide many services that contribute to human well-being and poverty alleviation. In developing countries, inland fisheries are extremely important since they are sources of animal protein, employment and income for rural populations (Millennium Ecosystem Assessment, 2005). Worldwide the settlement

of large cities along river courses over the past millennia indicates that human life has long been strongly linked to aquatic ecosystem services (Baron et al., 2002). While the deficient management of freshwaters has led to their overexploitation and disturbance (Malmqvist and Rundle, 2002; Humphries and Winemiller, 2009), there is an

*Corresponding author. E-mail: manokomandan@yahoo.fr. Tel: 00226 70172422.

increasing awareness to promote their conservation. The conservation of freshwaters requires their monitoring and assessment of the extent to which they are impacted. To Karr (1981) fish are commonly used to assess the overall health of aquatic ecosystems and their fisheries. Thus, determining the current status of fish communities gives information on the status of the body of water the communities occupy.

This bio-metric approach was adapted and applied in many areas in the world: Guinea (Hugueny et al., 1996), South Africa (Kleynhans, 1999; Rashleigh et al., 2009), Argentina (Crettaz-Minaglia and Juarez, 2020), Brazil (Gonino et al., 2020), Nigeria (Ali et al., 2017), Europe (Schmutz et al., 2007; Blabolil et al., 2017; Ergönül et al., 2018; Specziár and Erős, 2020), Côte d'Ivoire (Aboua et al., 2012), India (Basavaraja et al., 2014). It relies on the principle that fish respond to stress on aquatic ecosystems, and that these responses (Table 1) are sustained for a relatively long period of time, e.g. a time period long enough to suggest impacts and potential responses relevant to management policy. A range of relevant research (Table 1) has documented how indicators, such as the level of catch, the species mean adult length, the number of species, the type of species, the number of diseased and deformed fishes are used to assess the quality of a freshwater and the fishery that it offers. However, the lack of reliable data and information on fish and fisheries is a reality in Burkina Faso (Ouedraogo, 2010). For example, the main reliable document available on the lake Bam fishery that is Coenen (1988) is so old that it is likely not so relevant to policy. In and of itself it is not scientific research, but more of a collation of information summarized in a report as part of preparation for a fishery development project undertaken by the FAO. The other available documents are some reports that were prepared in 2005 as part of a lake rehabilitation project. To address this lack of data based on rigorous sampling and analysis, the present work aims to describe the historical changes in Lake Bam fishery in terms of fish community assemblage, commercial total landings and aquatic habitat quality. For the first time it documents the fish species in the lake and the fishing community.

MATERIALS AND METHODS

The study area

Lake Bam is located in the northern part of the country next to Kongoussi, the capital city of the Province of Bam (Figure 1). This largest natural water body in Burkina Faso is included in the catchment of the Nakanbé River, the second most important tributary of the Volta River. Because the lake is fed exclusively by runoff during the rainy season, its size varies from 600 ha during the dry season to 2600 ha during the rainy one. Currently the lake volume is said to be depleted as a result of mismanagement of its resources (Ouedraogo, 2010), and a project for its rehabilitation was officially launched in March 2017 (APPEAR, 2018) and is currently being implemented.

Data collection

Three methods were used to gather all available information about the Lake Bam. A survey of literature was conducted for historical data to itemise the above-mentioned indicators concerning Lake Bam. Then, selected stakeholders and experts were interviewed. Using a variety of fishing gears (cast nets, electric fishing, gillnets and long lines), fish were sampled to provide an overview on the fish community. The sampling of fish and the interviews were implemented from June to August 2009. This initial round of research was followed by the collection of complementary data from the fishermen and local community leaders.

The interviews

Interviews provided a survey of data based on the experience and knowledge of local fishermen. To do so, a workshop was held with 25 fishermen whose age ranged from 25 to 60 years. As aged people often are better informed by their long experience than youths (Leopold et al., 2008), we interviewed a retired fisherman, approximately 85 years-old, with some 60 years fishing experience on Lake Bam. The objective was to collect historical data on the use of fishing gear, the fishing community, fish landings and species composition. When sampling for fish in Lake Bam, these questions were also raised in discussion with local, currently active fishermen who were part of the sampling team.

The management of the lake continues to shift from traditional to republican regimes. The original, historical regime was established and run by the traditional communities that are led by the Naba and the Tengsoba. Its authority is based on customary beliefs and animist religion. The second regime was introduced by the colonizing power from Europe and is supposed to be supported by the evidence derived from scientific analysis of natural resources and the communities that exploit those resources. To gather information about lake management under the traditional regime, we interviewed two villagers who represent the traditional authority of their villages:

- (i) Naba Tigré: living in the village of Zimtanga, he is the Chief of the Canton of Datinga, an administrative area that is supposed to regroup more than 100 villages and that includes about 90 % of the lake water area and the surrounding upland catchment.
- (ii) Tengsoba Yaalé: the Tengsoba is the person traditionally responsible for natural resources management in the Mossi ethnic group, including the area of Bam. According to the local fishermen we interviewed, Tengsoba Yaalé represents the traditional authority in the management of Lake Bam. He is living in Bam Village, which is located about 10 km away from Zimtanga.

The sampling of fish

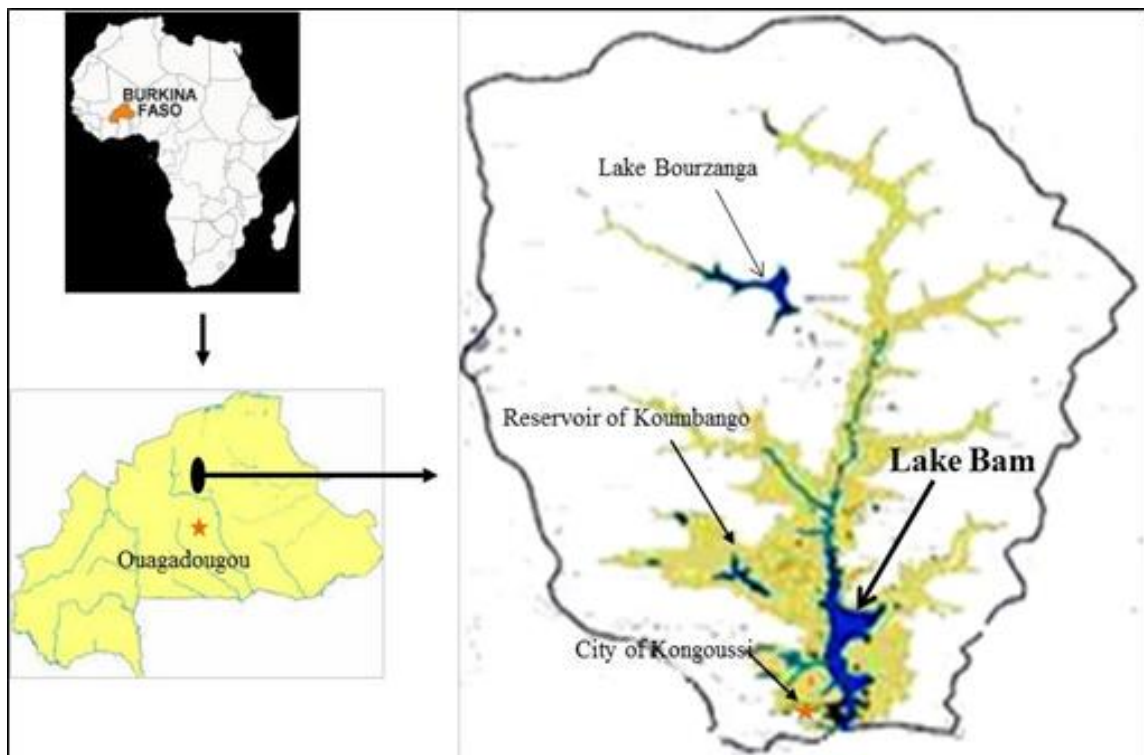
In early July 2009, we sampled fish with long lines, gillnets, cast nets and electric fishing. The specimens were classified into species according to Lévêque et al. (1990, 1992); their total length (TL) and body weight (*W*) were measured. Fish were sampled in the lake itself, as well as in the main and secondary tributaries a few hours after it had rained. The rain aided our sampling since fish often become concentrated at the brook mouths and migrates upstream as soon it rains (Bénech and Quensièrre, 1987).

Data analysis

To highlight the historical changes in the fishery, we organized the data into the following categories: climatic and hydro-morphologic features, the governance of the lake and its resources, fishing

Table 1. Effects of environmental stresses on fish and fishery.

Indicators	Trends	Sources	Remarks
Level of catch	Falling level of total catches	Welcomme, 2001; Allan et al. 2005	If the number of fishermen does not decrease.
	Falling level of catches per unit of fishing effort	Welcomme, 2001; Albaret and Laë, 2003; Rice and Rochet, 2005 ; Ruangrai, 2006; Sheaves et al., 2012	
Mean length	Disappearance of large size species	Welcomme, 2001; Albaret and Laë, 2003 ; Allan et al., 2005	At community level. Example of large size specie: <i>Heterobranchus</i> sp.)
	Falling mean size or weight	Welcomme, 2001; Albaret and Laë, 2003; Piet and Jennings, 2005; Allan et al., 2005	At species level
Number of species	Declining number of species	Welcomme, 2001; Albaret and Laë, 2003; Allan et al., 2005; Sheaves et al., 2012	
Type of species	Decline and disappearance of higher trophic levels	Welcomme, 2001; Albaret and Laë, 2003	The highest trophic levels species are predators (Ex: <i>Lates niloticus</i> , <i>Hydrocinus forskahalli</i>)
	Increase of lower trophic levels	Murawski, 2000; Welcomme, 2001	Ex: phyto-planktophagous species like <i>Oreochromis niloticus</i>
	Decrease of intolerant species and increase of tolerant species	Welcomme, 2001	Tolerance means ability to withstand harsh conditions
Diseases and deformed fishes	Increasing proportion with disease, tumours, fin damage, and other anomalies	Karr, 1981	May lead to mortality of fishes

**Figure 1.** The study area: Lake Bam catchment is shown on the right-hand map.

pressure and the fishery production, changes in the fish community, restoration actions. We then analysed the dynamic trends of these entities over time.

RESULTS

Climatic and hydro-morphologic features

The lake relies exclusively on rain to be filled, but the annual rainfall shows a general decreasing trend over the past century. From 878 mm in 1927 it dropped to 572.6 mm in 2008. Figure 2 illustrates a clear 35% decrease of the rainfall trend from 1927 to 2015 despite the missing of data from 1980 to 1989.

Rainfall in the Sahel region is usually scarce and patchily distributed. According to Ouedraogo (2010), the sparse, upland vegetation and the patchy, intense patterns of precipitation contribute to strong soil erosion, and these results in the transportation of significant quantities of sediments to the lake. With about 500,000 m³ of sediments deposited every year, the lake lost one third of its water volume, as measured by depth, between 1963 and 2006. If this trend continues, lake water storage capacity will vanish, and the lake will disappear in a quarter of century. The elderly villagers who participated in this survey said that, the lake is increasing in area as it becomes shallower and shallower. They illustrated this by showing areas that formerly surrounded the lake where they were farming maize, sorghum and millet some 3-5 decades ago. But the pieces of land on which they used to farm are now flooded by August, the middle of the rainy period that lasts from June to September. Furthermore, the lake loses large quantities of water due to (i) the heat that resulted in high evaporation (ii) abstraction of large quantities of water for irrigation. The surface water temperature ranges from 18 to 42°C, and the evaporation rate is about 7 mm/day (Pouyaud, 1986). As a result, the lake water surface declines by 1.5 m over the course of the year, a significant decrease for a lake that is 2-3 m deep during the rainy season.

Water management within Lake Bam catchment

In arid regions like the Sahel, people have historically dug small size ponds to store water to be used during the dry season. Today, larger reservoirs are created and many others are under construction as the demand for water increases year-by-year. According to a national list of water bodies developed a decade ago, the lake catchment currently hosts 45 reservoirs; all sizes included (Figure 3).

The dams are not supplied with migratory devices, e.g. fish ladders, the absence of which, in all probability impedes the migration of fish. Furthermore, upstream reservoirs have to be filled before the water flows into the lake, which delays the filling of the lake as compared to

what it was in the past.

Pollution and degradation of habitat

According to the fishermen, fish mortality is gradually increasing as water levels increasingly decline during the fish community's most vulnerable period, from April to June, the variable and unpredictable end of the dry season before the rainy season starts. Firstly, this may be due to increasing pollution concentrations in the water column as pollution rates in runoff increase at the same time that the lake's volume decreases. Observations on the river banks during the dry season, confirmed by Google maps, show the presence of large, irrigated, vegetable farms in the immediate surroundings of Lake Bam. The same irrigated lands used to grow vegetables during the dry season are rain-fed farms of sorghum and of other cereals during the rainy season from July to October. Local experts of agriculture explain that the farmers use large quantities of fertilisers and pesticides. Inadequate government oversight or control results in overuse of these chemicals, and the excess is washed into the streams and the lake during the rainy season. Secondly, the area surrounding Bam is grazed by a significant population of livestock, estimated at more than 100 000 animals, all types included (Ouedraogo, 2010). Animal nutrient deposition across the landscape is washed by runoff to Lake Bam, thereby increasing the nutrient input (Derlet et al., 2010). The fishermen observed that, in entering the lake to drink water, the cattle stir up bottom sediments, making the water more turbid, and defecate, increasing the organic loading of the water column, the decomposition of which increases oxygen demand. The resultant hypoxia during the period of lowest water levels may increase stress and mortalities in fish.

Changes in the fishery governance

The traditional management approaches

Elderly and traditional authority leaders explained that before colonisation in the early 20th century, riverside people managed the lake according to their own rules, values, and understandings. That traditional belief system is consecrated by more than 12 holy sites existing in and around the lake along the shore area. From time to time, sacrifices were offered to prevent harm to the community, such as drowning, floods and diseases, and to ensure fruitful usages of the resources (such as fish and water), and for the wealth of people in general. The offerings can include one or many of the following items: traditional beer, sesame, bean cakes, black bullock, black goat, black hen, donkey, dog and horse. The dog and the horse replace human being which was formerly used as a sacrifice. Additional items may be required depending on

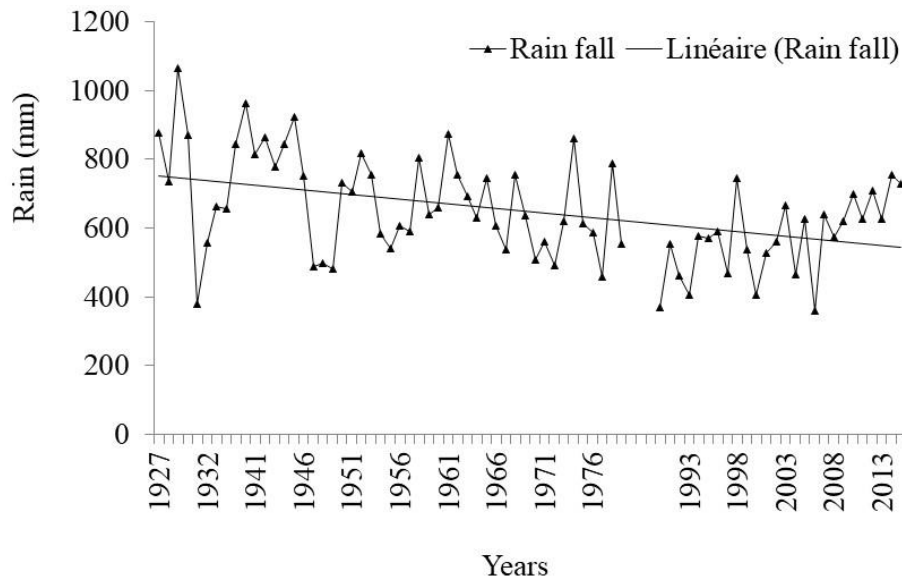


Figure 2. Annual Rainfall trend from 1927 to 2015 in Bam area.

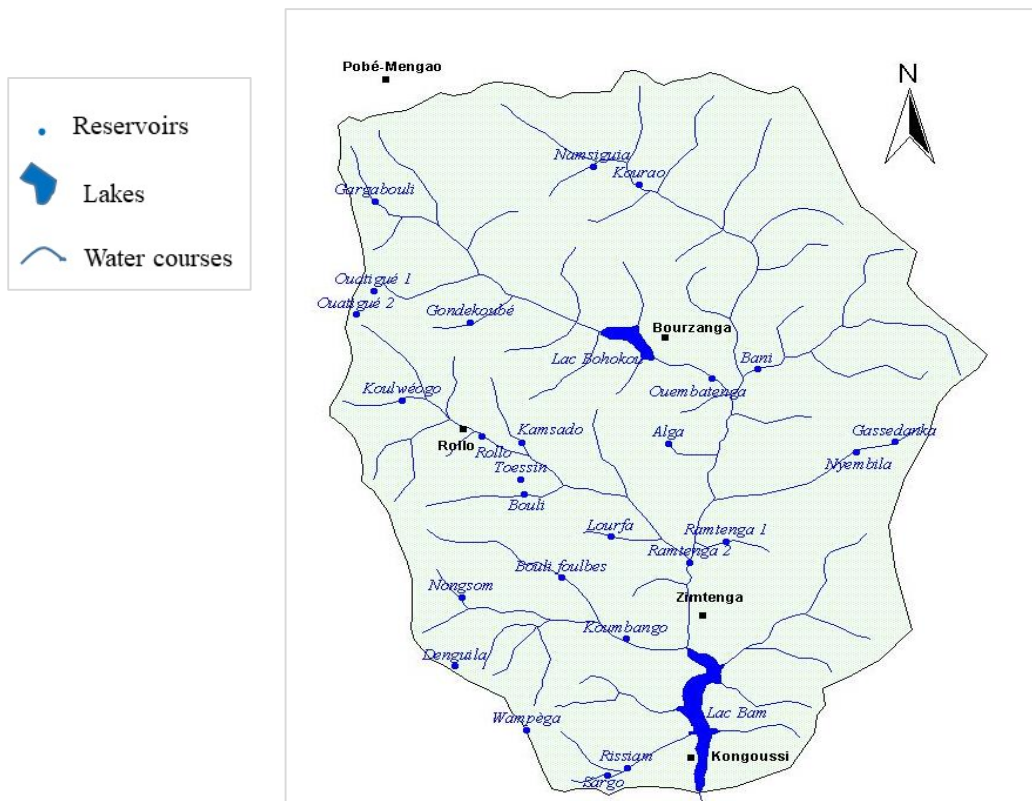


Figure 3. Spatial distribution of reservoirs, lakes and water courses in Lake Bam catchment area (Source: Government of Burkina Faso, 2009).

the circumstances of the sacrifice. Sacrifices for the benefit of the entire community were ordered by a group

of wise people, and the Chief of the Canton had to provide the ingredients. To do so, he used to send people



Figure 4. The fishermen association asked the Tengsoba Yaallé of Bam village for sacrifice for fruitful and peaceful fishery (Photos R. OUEDRAOGO, 23 May 2013).

to walk around and to catch any animal that roams freely. On 23rd May 2013, we witnessed a sacrifice event that the fishermen of Lake Bam asked Yaalé to proceed for fishing to be productive (Figure 4).

In former times, the rules were legitimized and enforced by a group of wise people led by the Tengsoba and acknowledged and followed by the community in general. By this approach the Lake and the other natural resources were managed. For instance, when declining water levels broke the lake into separate pools, some pools were designated to be open to domestic animals, some for domestic needs, but all were managed for fish conservation. During this period fishing and hunting for crocodiles were strictly forbidden, a ban that generally protected aquatic biodiversity. Clearing large areas of land cover of vegetation was subject to the approval of the Tengsoba. Medicinal trees, trees producing edible fruits and holy forests were always strictly protected. Hunting and cutting trees were seasonally restricted. During the protection period, no wildlife animal could be killed, because they were thought to be pregnant. But

killing wildlife such as snakes for human protection was allowed and even encouraged.

Anyone who witnesses a violation event was expected to report to the authority. A range of punishments were applied for different offences, but a person who repeatedly violates the rules was gradually marginalised. For instance, this person was not properly greeted by anybody in the community. The ultimate sentence was the drowning of the guilty person in the lake. Not only was finding the dead body extremely difficult, but the person was then qualified as donkey; and as animal and could not benefit from a proper funeral. This extreme condemnation was greatly detested in the community.

The republican management approaches

In the early to mid-20th century, the French colonial administration introduced new rules governing natural resources. The elderly respondents in our interviews reported some republican management policies that they

could not understand, nor accept:

(i) Overnight, local people lost the ownership of the lake, which was now allocated to the State. But the new owner was not present to implement their rules.

(ii) For leisure purposes the French colonisers cleaned the lake banks from vegetation. Then they used to cross the lake with a motorised boat, to swim and to fish.

(iii) No foreign fisherman was allowed to catch fish in the lake, and rules for foreigners willing to undertake any activity other than fishing existed. But the coloniser invited professional fishermen from the neighboring Republic of Mali to fish in the lake without seeking the agreement of the indigenous people.

(iv) Six to seven decades ago the colonial administration introduced a fishing tax or licence of 6000 FCFA/year/fisherman, the equivalent of 9.15 Euro or the price of two 4-year old bulls or two new bicycles. This was much higher than what the average, indigenous citizen could afford. For comparison, at that time, the colonial administration introduced a national Head tax for all citizens. The entire city of Kongoussi, the biggest agglomeration next to the lake had to pay only 15 FCFA/year (that is, 0.02 €). But this amount was seldom met by the city, meaning that the fishing tax was unreasonably high.

Today the Naba Tigre, Chief of the Canton of Datinga, and the Tengsoba are both calling for a reorientation of the lake management to better accommodate and integrate traditional authorities within what is, ostensibly, a republican regime. To explain previous failures to accomplish this, the Naba, points out that the republican system tries to involve the traditional authority but from a wrong perspective. He is frequently invited for meetings regarding the lake, which regrettably he has no strong authority to manage, because he manages people but not natural resources. In addition to his invitation, he has suggested that the Tengsoba also be solicited, because he is the most appropriate for managing natural resources following the traditional approach. According to the Tengsoba, the government or any other governing body has to provide them with the ingredients for sacrifice for the community's benefit. This is necessary because the Naba can no longer order the free catching of animals for sacrifices. People still respect and believe in the Tengsoba power as they often come to him for assistance.

The exploitation of fish resources

Historically, riverside people were fishing for subsistence using elementary gear. Commercial fishing was introduced in Bam in 1953 by the French colonial administrator, who invited some professional fishermen from the River Niger in the Republic of Mali to fish the lake. With a much longer fishing tradition than what

existed at that time in Burkina Faso, they brought more efficient gear, such as cast nets, gill nets, long lines and canoes. Their number reached 30 some years later, but they left the lake more than a quarter of a century ago. In addition to their role as trainers for local people with little previous history of fishing, these fishers were providing fish products to local markets and to Ouagadougou the main city of the country that is 110 km far in the South. Half a century ago about 100 persons were fishing in the lake. Today there are about 650-700 fishermen inhabiting the 36 riverside villages.

The fishermen mentioned a remarkable decrease of catches over the past 70 years. From about 50 kg of fish per day in 1950 the landings of a fisherman dropped to 2.3 kg in 1987 and to 0.5 kg in 2009. The total landing of the lake was estimated at 175 t in 1990, 150 t in 2000 and about 80 t in 2009 (Ouédraogo, 2010).

Historical changes in the fish community

The fishermen described the historical changes in the fish community as they witnessed or heard from elder people. Six decades ago, the fish community was dominated at about 60% by two species: *Clarias gariepinus* and *Heterotis niloticus*. They were followed by *Polypterus* sp., *Synodontis* sp., *Auchenoglanis occidentalis*, *Protopterus annectens* and the tilapia group which together contribute at 35 % to the fish community. *Alestes* species and *Brycinus* specie were rare, as together they contributed to about 5% to the fish community. *Barbus* sp. appeared during that period.

Three decades ago, *C. gariepinus* and *H. niloticus* were still dominant, *Polypterus* specie, *Synodontis* specie, *P. annectens* and the tilapias frequent, *Alestes* specie and *Brycinus* specie were relatively frequent as compared to *Barbus* specie which was rare. The mormyrid family, *Hydrocynus* specie, *Heterobranchus* specie and *Malapterurus electricus* appeared at that time. *Heterobranchus* specie was somehow frequent, and very large specimens were often caught. *Lates niloticus* was twice introduced but never established. The only written document about the Lake Bam fish community Coenen (1988) mentioned 21 species in the commercial landings but estimated that the lake was hosting 30 species regrouped in 11 families. *Sarotherodon galilaeus* was dominant (39.1%), followed by *Oreochromis niloticus* (16.3%), *Brycinus nurse* (9.9%), *Marcusenius senegalensis* (9.1%), *Schilbe intermedius* (8.9%), *Auchenoglanis occidentalis* (5.6%) and *Synodontis schall* (4.2%); the other species contributed 6.9%.

In 2009, some fifty-two sampling events yielded 2533 fish, regrouped in 20 species and 9 families. Two species strongly dominated: *Sarotherodon galilaeus* (30.2 %) and *Enteromius ablabe* (26.3%). They were followed by *Chelaethiops bibie* (6.5%) and *Enteromius macrops* (5.9%). *Oreochromis niloticus*, *Clarias gariepinus*,

Coptodon zillii and *Hemichromis letourneauxi* contributed at 4% each. Together the 11 remaining species contributed a total of 15%. The fishermen pointed out that nowadays *Heterotis niloticus* and *Heterobranchus* sp. still exist, but they are extremely rare and seasonal (Table 1).

In 2009 the maximum total length (TL in mm) was 119 for *S. galilaeus*, 85 for *E. ablabes*, 310 for *C. gariepinus* and 160 for *O. niloticus*. Table 2 shows the species list, the relative frequencies and the size of fish in Lake Bam. A comparison of data in Coenen (1988) and ours shows that a likely loss of 8 species and a decrease in fish mean weight over 20 years (Table 3).

Social impacts of the lake and its resources

Today, there are 650-700 fishermen inhabiting the 36 riverside villages. But only 3-5 of them rely more or less exclusively on fishing for their daily livelihood. It means that most fishermen are also involved in other economic activities, such as rain-fed agriculture, irrigated agriculture, livestock breeding, selling of goods, artisanal mining of gold, etc, and only take up fishing as an additional income source. Such occasional fishermen often lack the experience or knowledge to fish sustainably. In contrast to former times, forbidden fishing methods are currently commonly used. They include nets of small mesh size, unsuitable long lines, beach seine, poisoning, etc.

In addition, about 600 women are involved in the post-harvest segment of the fishery. They sell fresh fish, smoke fish that they later sell, fry and cook fish in small restaurants. Seasonality is observed in the fishery. During the rainy season, the fishers are all involved in rain-fed agriculture that is labor-intensive. Therefore, they allocate the least time to fishing by tending to use passive gear, such as gillnets and long lines. The fishermen also indicated that by this time, as there is much water in the lake, fishing is rather less productive. During the dry season, as water levels decline and concentrate the fish the fishing becomes more intensive. The fishermen tend to fish more when money-demanding social events are planned: festivals (e.g. Christmas), funerals, when children return to school in October after the long holidays, etc. The fishermen affirmed that without fishing, they would have to sell their crops or domestic animals to meet the cash needs of these occasions.

Previously, the fish production of Lake Bam was collected by fishmongers coming from Ouagadougou and sold in that city. Today, it is exclusively sold in local markets and even has to meet the competition from fish imported from Asia, Côte d'Ivoire and other countries and sold in the areas surrounding the lake. This means that the lake fishery is less and less competitive, and perhaps is so depleted that it has to be completely rehabilitated through significantly higher levels of investment and effort.

The restoration actions undertaken in Lake Bam

To support rehabilitation of Lake Bam, significant attention is given to lake conservation. In 2009 the lake was allocated the status of a Ramsar site - a recognition of its international ecological importance (Government du Burkina Faso, 2009). To protect the lake, trees are being planted on the banks and stony walls (bunds) built on the brooks to slow down the transportation of sediment into the lake (Figure 5). The first stony walls were built by a Germany-funded project dedicated to restore the soils of the areas to improve agriculture. Today, many NGOs and associations now pursue projects that prioritize the lake's protection. Some brooks whose 2.5 m deep accelerated runoff rates and erosion are now filled of sand and used for agriculture.

The lake is currently being rehabilitated under a project that was launched 03 March 2017 (APPEAR, 2018). The restoration project has two phases. The first step consists mainly, in erecting a 25 cm high wall at the downstream edge of the lake, in intensifying the irrigated farming of vegetables, protecting the lake resources, studying the possibility of dredging and enhancing the fishery. As for fish, the project planned to farm fish for restocking, and to provide the fishing community with equipment for fishing and processing fish. But noticeably no fish related research activity is planned (MAH, 2012). The second step will consist in dredging the lake, if feasible, to increase the lake's depth and water storage capacity.

DISCUSSION

The present study does not intend to make an extensive or detailed description of the fishery of the lake or to conduct solid statistical analysis but to address general trends that serve as a warning on the lake's status. This study confirms the need for reform of natural resource management in Burkina Faso. The replacement of the traditional management system by the republican one is not effective (Yelkouni, 2012), and in the intervening limbo the lack of clear governing responsibility and accountability has only exacerbated the misuse and decline of the Lake Bam resources. As concluded by GTZ (2002), two legitimised approaches to the management of the lake, and its resources exist in the area and should be sensibly integrated.

The fish of Bam exhibit typical features of a degraded and depleted fish community. We found that the lake exhibits an erosion of fish diversity, confirming what many authors believe (Horrigan et al., 2002; Albaret and Laë, 2003; Freeman and Marcinek, 2006). Vulnerable, large size and intolerant species such as *H. niloticus*, *Heterobranchus* sp. and *Lates niloticus* (Froese and Pauly, 2019) gradually declined significantly and have been replaced by pygmy ones; e.g. *E. ablabes*, *E. macrops* and *C. bibie* as well as tolerant, resilient and

Table 2. Lake Bam fish species list, relative frequencies (%) and size in 2009.

Species	Frequencies	TL (mm)			Weight (g)			Remarks
		Mean	Maxi	Mini	Mean	Maxi	Mini	
<i>Alestes baremoze</i>	1.31	80.88	120.00	40.00	5.67	18.20	1.70	
<i>Auchenoglanis occidentalis</i>	0.36	184.78	230.00	163.00	65.50	113.50	48.30	
<i>Brycinus nurse</i>	0.36	68.11	90.00	50.00	3.86	7.60	2.00	
<i>Chelaethiops bibie</i>	6.50	38.49	49.00	15.00	0.51	0.90	0.10	
<i>Clarias gariepinus</i>	4.00	184.15	310.00	120.00	47.84	250.00	8.10	
<i>Coptodon zillii</i>	4.00	72.39	125.00	40.00	9.94	30.20	1.20	
<i>Enteromius ablabes</i>	26.35	37.46	85.00	17.00	0.62	11.00	0.10	
<i>Enteromius macrops</i>	5.90	49.19	75.00	30.00	1.32	4.00	0.20	
<i>Hemichromis fasciatus</i>	3.45	38.22	50.00	31.00	1.14	2.20	0.50	
<i>Hemichromis letourneauxi</i>	4.00	42.79	65.00	30.00	1.48	4.30	0.50	Seen in our catches in 2009
<i>Hippopotamyrus pictus</i>	0.04	59.00	59.00	59.00	1.90	1.90	1.90	
<i>Marcusenius senegalensis</i>	0.87	94.00	120.00	70.00	6.84	13.60	2.00	
<i>Oreochromis niloticus</i>	4.00	82.93	160.00	14.00	15.67	75.40	0.50	
<i>Petrocephalus bovei</i>	2.65	53.81	70.00	38.00	1.57	3.70	0.50	
<i>Polypterus senegalus</i>	0.08	143.50	152.00	135.00	16.90	18.70	15.10	
<i>Sarotherodon galilaeus</i>	30.2	51.13	119.00	30.00	3.28	36.90	0.60	
<i>Schilbe intermedius</i>	0.44	69.82	90.00	50.00	3.27	7.40	0.90	
<i>Siluranodon auritus</i>	3.41	82.35	111.00	49.00	4.32	9.60	0.70	
<i>Synodontis punctifer</i>	0.52	66.08	111.00	45.00	3.95	13.50	1.20	
<i>Synodontis schall</i>	1.51	65.66	110.00	45.00	4.20	16.00	1.10	
<i>Heterotis niloticus</i>								Seldom seen by the fishermen
<i>Heterobranchus</i> sp.								

Table 3. Lake Bam fish community evolution from 1987 to 2009.

Criteria of comparison	Species	1987 ± 30	2009 ± 22
Number of species			
Species composition (%)	<i>Sarotherodon galilaeus</i>	39.1	30.2
	<i>Oreochromis niloticus</i>	16.3	4.00
	<i>Brycinus nurse</i>	9.9	0.4
	<i>Marcusenius senegalensis</i>	9.1	0.9
	<i>Schilbe intermedius</i>	8.9	0.44
	<i>Auchnoglanis occidentalis</i>	5.6	0.4
	<i>Synodontis schall</i>	4.2	1.5
	Other species	6.9	62.3
Mean weight (g) of major species	<i>Sarotherodon galilaeus</i>	23	3.3
	<i>Oreochromis niloticus</i>	16.3	14.8
	<i>Schilbe intermedius</i>	9.9	3.9

less vulnerable ones like *S. galilaeus* (Ouédraogo, 2010). Also, the small length of species characterises the degradation of the carrying capacity of the Lake Bam fishery (van Zwieten et al., 2011). Bam fishes are much smaller than those of many other areas of Burkina Faso (Ouédraogo, 2010) (Table 3).

As for the fishing community, the lake now hosts about

14 times more fishermen than what the FAO would have recommended, e.g. 2 fishermen/km². According to van Zwieten et al. (2011) a fisherman daily lands 7 to 28.8 kg of fish in Lake Volta (Ghana) depending on the gear used; in Bam he currently lands only half a kilogramme. Such a low production level cannot sustain the involvement of foreign, professional fishermen and



Figure 5. A stony wall built by the fishermen on a small tributary of the lake in 2015 in the area of Song-N-Med-Beenga, close to Bam village) (Photo R. Ouedraogo, 25 Oct. 2015).

scarcely supports the part-time fishermen currently fishing in Lake Bam. In Bam the number of local fishers may have increased over time as the perceived profitability of fishing outweighed other factors, such as other economic activities, policy measures and the existence of restrictions (Charles, 2000). As they no longer catch much fish, the emigration of foreign, professional fishermen was expected, just as it happened in other bodies like Lake Higa (Ouedraogo et al., 2015). Actually, in Burkina waters, fishing efforts are not really regulated and limited. This is in line with one of the objectives of the fishery policy, that is, to provide employment to rural people (MAHRH, 2010). But this might not be in line with sustainability.

Fish can die as a result of a wide variety of natural and unnatural causes. In Nigeria, Solomon-Wisdom and Olatunde (2014) found a strong and positive correlation between fluctuation in physicochemical parameters and fish mortality. The level of Lake Bam water seasonally fluctuates substantially as a result of natural and human factors, which may affect greatly the fish and fishery (Baijot et al., 1994; Kabré and Illé, 2000; Patrick, 2016.) Lake Bam's location at the headwaters of a river catchment makes it naturally vulnerable to such threats. As posited by the River Continuum Concept (Vannote et al., 1980) and demonstrated by Meyer et al. (2007) and Konan et al. (2013) fish diversity is lower in upstream river and reaches and increases as one moves downstream. This is also consistent with the suggestions of Haigh and Krecek (1991) and Neiland and Béné

(2008). As with other aquatic ecosystems (Carpenter and Brock (2004) and Solomon-Wisdom and Olatunde (2014) increasing trends of yearly fish mortality is convincing evidence that the lake is in an advanced state of physical and biotic decline, requiring large-scale measures to rehabilitate it.

Conclusions

The fish community of Lake Bam exhibits signs of collapse. Declining trends in species number, in species tolerance, in fish size and in fish landings as well as the hydro-morphological alterations of the lake confirm significant degradation of the aquatic ecosystem. These trends are linked to a history of poorly regulated fishing and land-use in the surrounding catchment, and such abuse of natural resources is only exacerbated by unchecked increases in the number of fishermen and the general use of unsuitable fishing methods, neither of which have reversed the decline in fish landings.

Part of the basis for such mis-management of the lake can be attributed to the failure to establish a unified system of governance with clear and unquestioned responsibility and authority for natural resource management. This confusion arises from the unresolved tension between a waning traditional system and a republican approach that so far has failed to establish strong links between the national and local governments. For the moment, it appears best to seek better ways to

improve both traditional and republican institutions, with perhaps more effort given to integrating their operations. This follows the suggestions of two leaders of the tradition authority and should be the basis for further testing ways to decentralisation governance in Burkina Faso.

While this research establishes a recent foundation of data, much research is needed to continue to build on this foundation and provide policy makers with rigorous data in planning and adapting efforts to rehabilitate the lake and its fishery. The history of failures in management to date stems in part from the absence of useful information or reliance on deficient and fragmentary data. Such an ambitious research-based development approach will require strong cooperation between 'developers' and researchers in the implementation of the rehabilitation project.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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Full Length Research Paper

Residents' perception of the effects of soot pollution in Rivers State, Nigeria

Mina Whyte¹, Tamuno-Wari Numbere² and Kabari Sam^{3,4*}

¹Department of Planning, Research and Statistics, Rivers State Primary Health Care Management Board, Rivers State, Nigeria.

²Department of Public Health, Rivers State Ministry of Health, Rivers State, Nigeria.

³Environment and Conservation Unit, Centre for Environment, Human Rights and Development, Rivers State, Nigeria.

⁴Department of Marine Environment and Pollution Control, Faculty of Marine Environmental Management, Nigeria Maritime University, Delta State, Nigeria.

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Air pollution is a growing cause of morbidity and mortality globally. Nigeria is confronted with rising air pollution concerns due to activities of extractives, industrialisation and high population growth rate. Many areas of Rivers State, which provide 60% of Nigeria's crude oil output, have recently been experiencing visible fallout of soot. To assess the perception of residents of Rivers State on the current soot pollution, a cross-sectional study was undertaken via an online survey among people residing in the state who were literate and had access to internet-enabled devices. Results indicated that most respondents (81.5%) were aware of the soot pollution and perceived the main causes of soot to be from artisanal refining of crude oil (87.8%) and burning of confiscated crude oil and its products (76.5%). Majority also perceived that the soot had caused them chronic cough (69.9%) and irritation to eyes, nose and throat (64.2%). Female respondents were significantly more likely (AOR=1.38 CI = 1.02, 1.86) to complain of a health effect from soot pollution. There is a critical need to investigate identified sources of soot and mitigate possible impact. Public health campaigns should be launched for adequate risk communication on the adverse effects of soot, with attention given to gender-sensitive messages. Relevant authorities should develop stringent policies to prevent soot pollution and improve access to appropriate services to address the health effects.

Key words: Air pollution, soot, health effects, chronic cough, artisanal refining.

INTRODUCTION

The onset of global industrialisation in the 18 and 19th centuries brought about peculiar socio-economic issues, many of which resulted in attendant environmental and health challenges (Kirby, 2013; Godish and Davis, 2015).

Air pollution in particular has been a growing cause of morbidity and mortality, dating back to the Great London Smog of 1952 (Kirby, 2013). Air pollution occurs when air contains harmful substances different from its natural

*Corresponding author. E-mail: k.sam@cehrd.org.ng.

constituents, which are detrimental to human health and the environment (Natural Resources Defense Council, 2018). These substances can be in the form of gases, particulate matter (PM) or even energy such as heat or noise (Godish and Davis, 2015). Air pollution is arguably more prevalent in countries where natural resources mining, at the artisanal and regulated levels, are conducted devoid of best practice or acceptable standards (Efobi et al., 2019). In such countries, like Nigeria, human health is exposed to disproportionate and avoidable levels of air pollution which poses significant health risks to local populations.

Nigeria is battling with rising air pollution concerns. The vast oil exploration and production activities and high population growth rate are major contributors to this problem (Olowoporoku et al., 2012; Yakubu, 2018). As a result of more than 50 years of oil and gas exploration and production, Nigeria suffers extensive environmental degradation occasioned by gas flaring (Brandt, 2020) and oil spills (UNEP, 2011a; Zabbey et al., 2017). Despite Nigeria's commitment to climate action, the country is primarily dependent on fossil fuels, a major source of flared gas (Brandt, 2020). In the Niger Delta region, the hub of Nigeria's oil and gas production, air pollution has been attributed to use of biomass fuel like firewood, indiscriminate burning of vegetation and refuse, traffic and industrial emissions, and gas flaring (Adejoh et al., 2015; Fagbeja et al., 2008; Godson, 2011). Artisanal refining (small scale and unregulated burning of hydrocarbons to derive petrol, diesel and kerosene) of crude oil in Rivers State has also been shown to have detrimental effects on the atmosphere through the release of carbon dioxide, methane and other gases (UNEP, 2011b; Ogele and Egobueze, 2020).

The World Health Organisation (WHO) estimated that in 2016, 4.2 million deaths were attributed to diseases linked to ambient air pollution, with 91% occurring in low- and middle-income countries like Nigeria (WHO, 2016; WHO and International Programme on Chemical Safety, 1996). Particulate matter is the common proxy indicator for air quality and the WHO guideline values are $50 \mu\text{g}/\text{m}^3$ 24-h mean for particles with a diameter of 10μ or less ($\leq \text{PM}_{10}$) and $25 \mu\text{g}/\text{m}^3$ 24-h mean for particles with a diameter of 2.5μ or less ($\leq \text{PM}_{2.5}$) (WHO, 2016). Environmental monitoring data from the World Bank showed that by 2015, 94% of Nigerians were exposed to air pollution levels above the WHO guidelines (World Bank, 2015). By 2016, all Nigerians were exposed to high air pollutant levels exceeding WHO guidelines (World Bank Group, 2016). Rivers State, one of the nine states in the crude oil rich Niger Delta region of Nigeria (Figure 1), is the hub of oil and gas exploration in the region, and thus faces increasing air pollution problems. Studies have documented various effects of air pollution in Rivers State, notably acid rain and more recently, soot pollution (Chuks, 2015; Nduka and Orisakwe, 2010; Yakubu, 2018).

The fine particles in soot ($\text{PM}_{2.5}$) pose peculiar health challenges. When inhaled, the size of these fine particles enables them to penetrate deep into bronchiolar tissue causing oxidative stress and pulmonary inflammation, and possible deoxyribonucleic acid damage (Niranjan and Thakur, 2017; Valavanidis et al., 2013). Short-term effects of these are irritation of the eyes, nose and throat, cough, chest tightness, wheezing, dyspnea and acute exacerbation of asthma, while long-term effects include arrhythmias and lung cancer among others (EPA, 2017; Niranjan and Thakur, 2017). A study in England reported that residents of an air polluted town perceived that the pollution had worsened allergies, asthma, bronchitis and lung cancer (Howel et al., 2003). Similarly, common health complaints related to air pollution as reported in the Niger Delta region are difficulty in breathing, cough, exacerbation of asthma, and skin disorders (Godson, 2011; Obafemi and Eludoyin, 2012). These documented adverse health effects from exposure to soot establishes it as a major environmental risk to human health.

Even with the existence of environmental laws and regulations like the Constitution of the Federal Republic of Nigeria, the National Oil Spill Detection and Response Agency (NOSDRA) Act (2006), Environmental Guidelines and Standards for the Petroleum Industry in Nigeria (EGASPIN) and National Environment Standards and Regulation Enforcement Agency (NESREA) Act of 2007, poor monitoring and regulatory control of the oil industry have contributed to an increase in environmental pollution (Sam et al., 2017). Recently, concerns over air pollution have heightened in Rivers State by the visible fallout of soot over many areas of the state (Onukwugha, 2018; Giles, 2018; Todo and Ehiri, 2018). Previous concerns over environmental pollution in the Niger Delta have led to agitations and conflict between the community members and industrial companies or authorities, as typified in Ogoniland, Rivers State (Richard et al., 2001; Lindén and Pålsson, 2013). Hence, it is pertinent that the recent air pollution be addressed on all fronts, considering public perceptions, to prevent an escalation of the situation.

In response to the soot pollution, the Rivers State Government set up a technical team to generate preliminary air quality data in Port Harcourt (Rivers State Government, 2019). However, the study was limited to only one local government area and did not assess the perceptions of the local residents, as well as the effect the pollution had on the daily activities of residents. The study, nonetheless, reported the possible causes of the soot to include artisanal refining, emissions from asphalt factories, indiscriminate burning of mixed waste, burning of tyres and vehicular emissions (Rivers State Government, 2019). Although industrial sources were identified (e.g. emissions from asphalt factories), most of the other sources mentioned were due to activities of residents (e.g. artisanal refining, indiscriminate burning of mixed waste, burning of tyres and vehicular emissions).

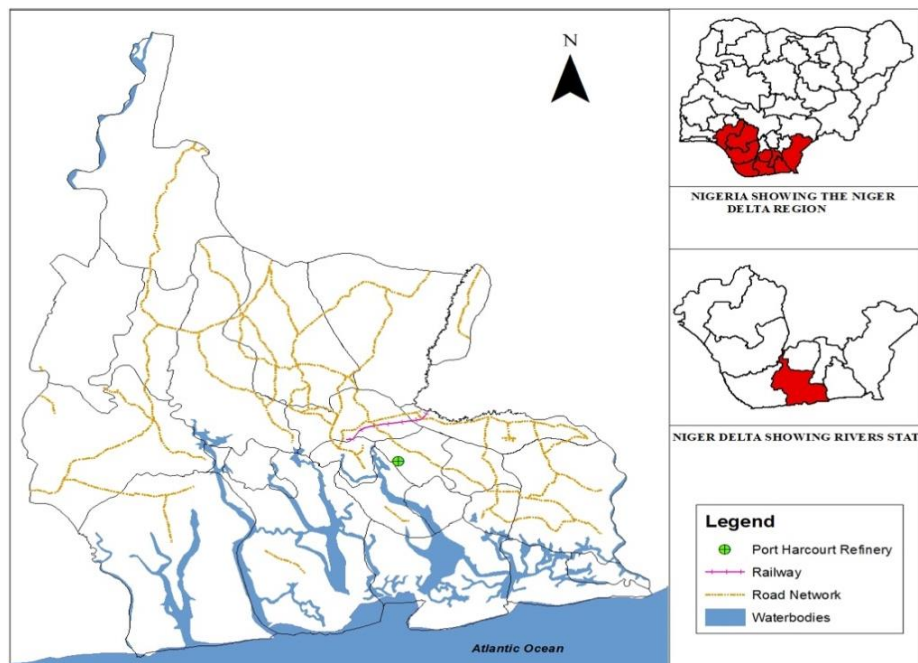


Figure 1. Map of Rivers State, and its location in the Niger Delta region of Nigeria.

A classic example is the stockpiling of expired tyres at the Abali park area of Port Harcourt which was set ablaze by unknown residents in 2017 resulting in the emission of pollutants, including soot, contributing to air pollution. Nevertheless, not much has been done since the report was published in terms of mitigating these causes, or creating awareness through public sensitization and behaviour change communication. Residents of Rivers State continue to inhale visible black particles (soot) in Rivers State with limited information on the socio-economic, environmental and public health effects it can cause to them. This study assessed the perception of residents of Rivers State on the current soot pollution, and its effect on their health and daily activities. The findings of this research will aid in informing relevant stakeholders (public and policy makers) as they undertake appropriate measures for minimising exposure to, and communicating risk associated with soot, while taking into consideration the perceptions of the residents.

METHODOLOGY

Study area

The survey was conducted in Rivers State, located in the Niger Delta region of Nigeria (Figure 1) with an estimated total population of 7,745,000 as at 2018 (Rivers State Government, 2016). It comprises 23 local government areas (LGAs) with diverse ethnic groups, and functions as the hub of oil and gas production in the Niger Delta region. The state is well known for its large crude oil and natural gas reserves, contributing more than 60% of Nigeria's crude oil output (Rivers State Government, 2016). The thriving oil

and gas sector has contributed to its growing population especially in the Port Harcourt metropolis (Port Harcourt and Obio/Akpor LGAs). It has a high literacy rate with 84% of women and 95% of men having completed at least secondary level of education and can read (NPC and ICF International, 2019).

Study population

Respondents were people living in Rivers State who were literate and had access to internet enabled devices, like smartphones and tablets. A compulsory first question was designed to exclude all respondents who did not live in Rivers State from participating in the study.

Sample size and sampling method

A minimum sample size of 597 was calculated using Taro Yamane's formula for known populations (Yamane, 1973), at a confidence level of 95%, a precision of 5%, and a response rate of 67% based on a similar study (Elliott et al., 1999). A 17-question survey was designed on the Survey Monkey website (www.surveymonkey.com) and divided into four parts: sociodemographic information, awareness of soot and its possible causes, perceived health impacts of soot and behavioural changes made due to soot pollution. The questionnaire was structured based on available literature from similar studies (Elliott et al., 1999; Howel et al., 2003). The questions ranged from single to multiple choice and some open-ended questions.

Data collection methods

A brief message with a link to the survey was posted selectively on social media group pages which had the majority of their members

residing in Rivers State. It was circulated via social media, and the link was active for two weeks before the survey closed in January 2018.

Ethical consideration

Ethical approval to carry out the study was obtained from the Rivers State Health Research Ethics Committee. Respondents were informed that their participation in the survey was voluntary and confidential and they signified consent by proceeding to fill the questionnaire. No personal identifiers, including Media Access Control addresses, were collected during the study. The dataset was downloaded from the site as an Excel spreadsheet and then exported to Stata version 15 (StataCorp, College Station, Texas, USA) for analysis. It will be stored for a period of three years on a password protected device accessible only to the authors.

RESULTS

Socio-demographic characteristics of respondents

A total of 1,001 responses were obtained while the survey was open, of which 98% were eligible as residents of Rivers State. Responses were obtained from people living in 22 out of 23 LGAs in the state, with most of them residing in Obio/Akpor LGA (50.8%). The mean age of respondents was 39.3 ± 10.3 years and majority of the respondents were male (58.5%). Half of the respondents had completed postgraduate level of education (50%), while a greater proportion were employed in the public or private sector (64%) and lived in urban LGAs (86.7%) (Table 1).

Awareness of soot pollution

Almost all respondents (96%) indicated they had observed the presence of soot in the state. Majority said they had first noticed it between October 2016 and March 2017 (Figure 2).

Perceived causes of soot pollution

The three major causes of the soot were perceived to be illegal or artisanal refining of crude oil ("kpofire") (87.8%), burning of confiscated crude oil and its by-products (76.5%) and industrial sources such as factories (53.9%) (Figure 3).

Perceptions on the health effects of soot pollution

Majority of the respondents thought that the soot had affected their health or the health of a member of their household. Cough (69.8%), irritation to the eyes, nose or throat (64.2%), and skin irritation (32.6%) were the most common health effects mentioned in relation to soot

pollution (Table 2).

Controlling for age, female respondents were significantly more likely to complain of a health effect (AOR = 1.38, CI = 1.02, 1.86) associated with soot pollution than males. Other factors showed no evidence of significant association with perceived health effects of soot pollution (Table 3).

Effect of the soot pollution on the daily life of residents

When asked to report how the soot pollution had affected their daily routine, majority of respondents reported that they were cleaning surfaces and floors more often (89.5%). Other reported effects were washing their hands and feet more often, worrying about their children's health, doing less outdoor activities such as recreation, exercise, farming, and fishing, and even planning to relocate to a less polluted area (Figure 4).

DISCUSSION

Sampled residents in Rivers State were aware of the soot pollution and first noticed the soot visibly between the last and first quarter of 2016 and 2017, respectively, with the highest level of awareness in January, which coincides with the peak of the dry season in Nigeria. Previous studies in some African cities, including Rivers State, have shown seasonal variations in particulate matter levels, with the highest values recorded in the dry season (Ugbebor et al., 2016; Ogele and Egobueze, 2020).

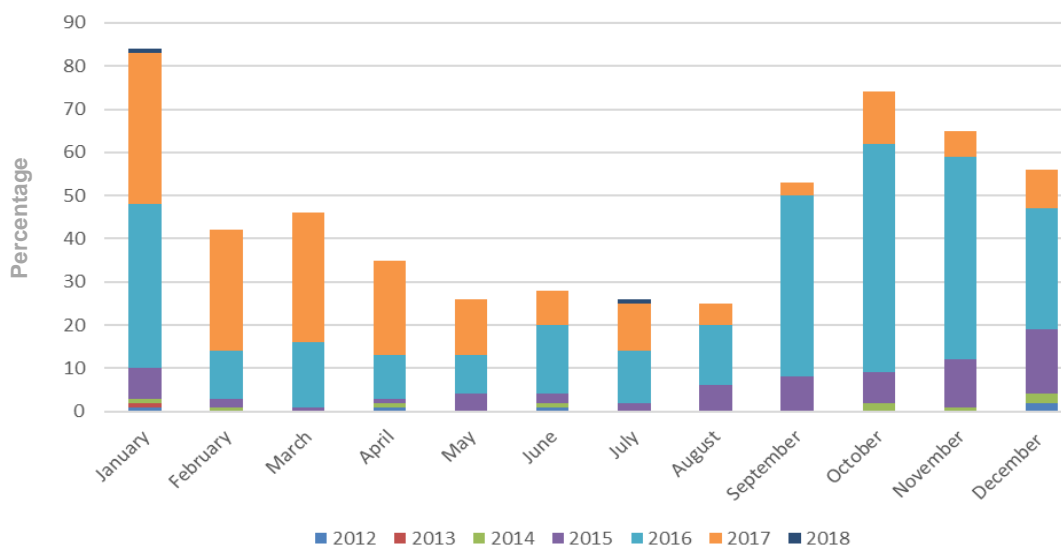
Artisanal or illegal refining of crude oil, in addition to burning of confiscated crude oil and its by-products, and emissions from industrial sources such as factories were perceived to be major causes of soot in Rivers State. This is consistent with findings from other studies carried out in Rivers State where the majority of participants agreed that illegal refining of crude oil was a major cause of air pollution (Kalu, 2018; Rivers State Government, 2016).

Majority of the respondents thought that the soot had affected their health or the health of a member of their household. Omanga et al. (2014) reported similar findings in a study conducted in rural Kenya where over 80% of study participants perceived that air pollution posed a serious risk to their health (Omanga et al., 2014). Another study carried out in Delta State, located in the Niger Delta region as our study site, also described that most respondents had strongly agreed that air pollution from gas flaring had negative, harmful effects on health (Edino et al., 2010).

Multivariate logistic regression analysis in this study showed that being female was significantly associated with a perception that the soot had affected their health. A study conducted in the United States on the

Table 1. Socio-demographic characteristics of respondents.

Demographic variables	Frequency	Percentage
Age (years)		
Mean \pm SD	39.3 \pm 10.3	-
Place of residence		
	n=980	
Rural	130	13.3
Urban	850	86.7
Sex		
	n=820	
Male	480	58.5
Female	340	41.5
Education		
	n=833	
None	4	0.4
Primary	3	0.4
Secondary	20	2.4
Tertiary	390	46.8
Postgraduate	416	50.0
Occupation		
	n=833	
Student	26	3.1
Unemployed	71	8.5
Self-employed/Business owner	203	24.4
Employed (public/private sector)	533	64.0

**Figure 2.** Awareness of soot pollution by respondents.

association between $PM_{2.5}$ and all-cause and specific-cause mortality showed suggestive evidence of increased susceptibility of women to the effects of $PM_{2.5}$ compared to men (Franklin et al., 2007). Similarly, Ezzati and

Kammen (2001) showed that women were more likely to be near various sources of pollution for a longer duration leading to higher levels of exposure than men (Ezzati and Kammen, 2001).

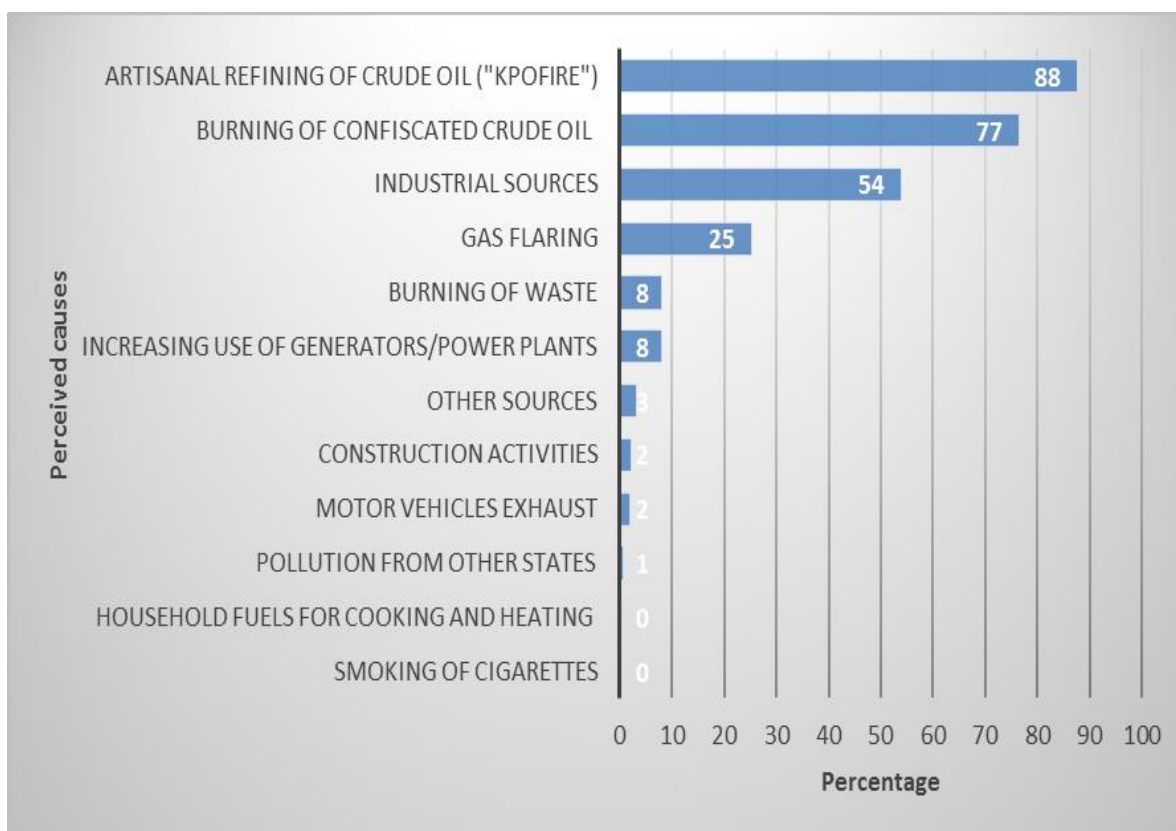


Figure 3. Perceived causes of air pollution among residents.

Table 2. Perceived health effects of soot pollution on respondents.

Perceived health effects	Frequency (n=534)	Percentage
Cough	373	69.8
Irritation to eyes/nose/throat	343	64.2
Skin irritation	174	32.6
Worsens already existing allergies	170	31.8
Breathlessness	156	29.2
Poor or blurry vision	126	23.6
Worsens symptoms of already existing asthma	121	22.7
Worsens already existing bronchitis	73	13.7
Worsens already existing lung cancer	15	2.8

Implications of the study

In general, the research identified the need for regulatory authorities to design preventive measures, and mechanisms for addressing the impacted population. It also provided evidence for relevant agencies to develop appropriate risk management approaches and enact relevant laws and policy that would prevent soot production in the region. Subsequently, the intricate implications of the research are outlined.

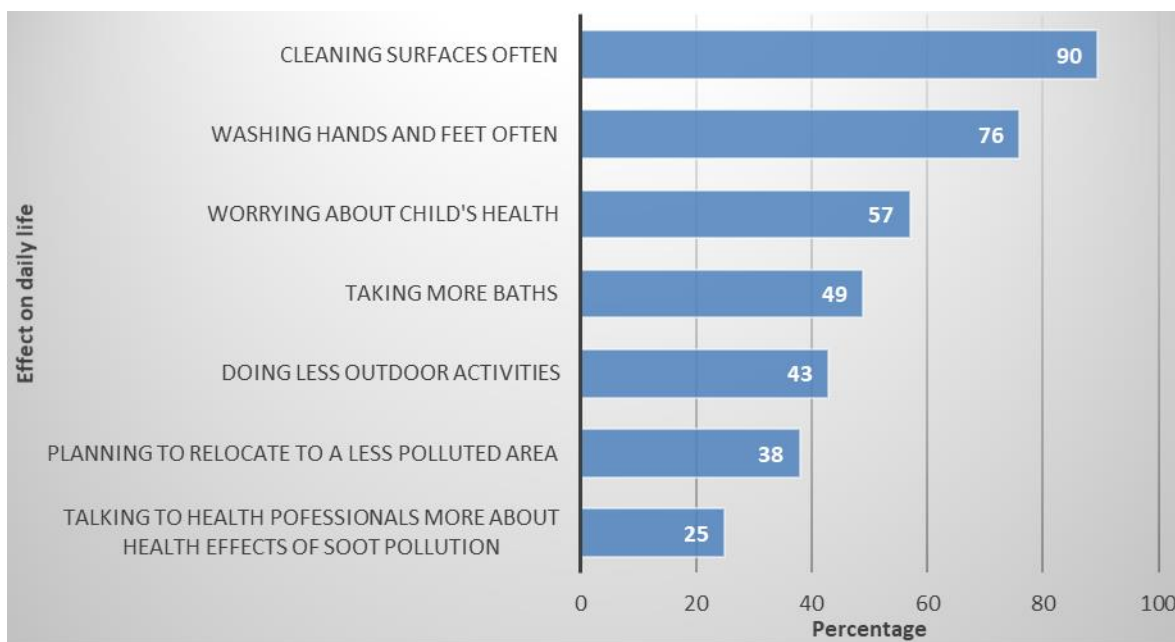
Socio-cultural impacts of soot

The presence of soot largely affects cultural activities and lifestyle of residents as people spend more time indoors making community members communicate and interact less with themselves. This is buttressed by the results that showed that residents tend to spend most of their time indoors rather than outdoors, with parents restricting their children from outdoor activities out of fear of the impact of soot on children's health. A proportion of

Table 3. Sociodemographic factors associated with perceived health effects of soot pollution on respondents.

Variable	Has experienced health effect of soot		Adjusted odds ratio (95% CI)	p-value
	Yes [n (%)]	No [n (%)]		
Sex				
Female	227 (44.8)	113 (36.1)	1.38 (1.02 - 1.86)*	0.027*
Male	280 (55.2)	200 (63.9)		
Level of education				
Post-graduate	269 (52.7)	147 (45.5)	4.86 (0.50 - 47.76)	0.130
Tertiary	233 (45.7)	157 (48.6)	3.98 (0.41 - 39.01)	0.188
Secondary	6 (1.2)	14 (4.3)	1.48 (0.13 - 17.52)	0.810
Primary	1 (0.2)	2 (0.6)	1.49 (0.05 - 40.91)	0.868
None	1 (0.2)	3 (0.9)		
Place of residence				
Urban	465 (90.5)	389 (82.4)	1.42(0.91 - 2.21)	0.125
Rural	49 (9.5)	83 (17.6)		
Occupation				
Employed (Public/Private)	343 (67.5)	190 (58.5)	1.14 (0.66 - 1.97)	0.420
Self-employed	114 (22.4)	89 (27.4)	0.82 (0.46 - 1.47)	0.603
Student	11 (2.2)	15 (4.6)	0.52 (0.19 - 1.39)	0.086
Unemployed	40 (7.9)	31 (9.5)		

*Factor is significant at $\alpha = 0.05$, C.I. $\neq 0$.

**Figure 4.** Effects of soot on daily life of residents.

respondents also indicated plans to relocate to other cities, thereby occasioning an economic imbalance on

the communities if there is a depletion in human resources in polluted cities (Allen, 2017).

Policy changes and agency strengthening

With the outcome of this study, factual arguments should be proposed to ensure a significant change in policies and implementation of existing ones. Extant laws on environmental pollution and the development of stringent air quality thresholds for the regulation of air quality should be strengthened. Industries and firms responsible for emitting soot should be sanctioned or shut down where necessary. Surveillance of artisanal refining camps, education and sensitization of security personnel involved in crude oil seizures, increase in monitoring of firms involved in discharging soot especially particulate matter by environmental agencies should be implemented.

Public awareness and sensitization

This study can serve as an informative tool for the development of risk communication and health awareness for residents in Rivers State. Information, education and communication materials developed should be used for advocacy to engage policy makers and environmental regulators, as well as awareness creation for the local population to take steps at reducing soot and attendant air pollution in Rivers State. Gender-sensitive messages targeted at women who seem to be more vulnerable to the effects of soot should be prioritised in campaigns.

Establish alternate livelihood for artisanal refiners

Reports indicate that youth involvement in artisanal refining is as a result of unemployment and a mindset that it is lucrative, thereby negating the acute, chronic and remote health, social, economic and environmental effects (Zeeuw et al., 2018). A subsequent improvement in the livelihood means of the youths will result in a decline in their artisanal refining involvement with an end result of improved air quality in Rivers state and the region at large.

Behaviour change communication

This research identified burning of confiscated crude oil as one of the primary sources of soot in Rivers State. Behaviour change communication through trainings and seminars would be useful in initiating a change in attitude and mode of operations of the security agents involved in crude oil seizures would likely reduce the prevalence of soot in the state. More environmentally friendly options to dispose of confiscated crude oil and its by-products can be deployed such as appropriate storage in designated warehouses or tank farms. Standard operating procedures (SOP) and protocols could be developed in

collaboration with the State's Ministry of Environment in this regard.

Conclusion

Soot pollution is a public health concern affecting the health and lives of residents of Rivers State, Nigeria. The perceived causes of the current soot problem should be investigated and mitigated by the relevant authorities. Public health campaigns should be launched for adequate risk communication on exposure limitation and access to health care. Relevant authorities should urgently develop stringent policies to prevent soot pollution, set baselines for air quality and further investigate the socio-economic impacts of soot on the local economy and residents. In addition, given the duration of exposure of residents in Rivers State to increasing levels of soot, there is need for an epidemiological study to underscore contextual health impacts and/or potential risks posed to the residents. Also, an extensive campaign and advocacy for behavioural changes, development of stringent air quality thresholds and strengthening of extant laws, regulatory agencies and development of alternate livelihood structures for artisanal refiners is recommended.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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