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Relationship between Atmospheric Deposition of Nutrient (N and P) Concentration and Wind Direction in Lake Kivu Watershed, DR Congo Side

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Abstract

Original Research Article

Recent researches have suggested that atmospheric depositions are a major source of nutrients to aquatic ecosystems. It is important to identify and quantify nutrients deposited into surface water and the relationship with wind direction and wind speed to understand the contributing sources of nutrient deposition to Lake Kivu. This study analyzed the relationship of the contribution of TP and TN from the atmospheric deposition with wind direction and wind speed during the period 2017-2019 using regression analysis. Atmospheric deposition of nutrients (TP and TN) and lake water were analyzed in the laboratory for TP and TN using standard analytical methods. Wind speed (m/s) and wind direction (^{o}) were collected at Lwiro station using automatic sensor and gaps were filled by data downloaded from NASA/POWER SRB/FLASHFlux/MERRA2/GEOS website. Temporal variation of TN and TP atmospheric deposition rates is significantly different over time ($p<0.000$) at Lwiro station. Natural and anthropogenic activities in the watershed such as volcanic activities, biomass burning, and soil erosion introduce particles in the atmosphere following meteorological conditions and surface lake water becomes nutrients rich due to increasing nutrients input. It was observed that the average high rates of nutrients were coming more from the north part of the Lake (Goma) than other points. Volcanic and traffic activities were identified as being the main sources of nutrients in the north part of the watershed and appear to play an important role in the Lake eutrophication. The results can serve as a baseline as far as atmospheric nutrient loading sources in Lake Kivu watershed are concerned and suggest strategies for future assessment.

Key words: Atmospheric deposition, nutrient loading, wind speed and direction, Lake Kivu, Pearson correlation model.

1. INTRODUCTION

Nutrient transfer through the atmosphere is a significant part of the biogeochemical cycle of these elements (Bootsma *et al.*, 1996). Two processes which increase nutrient concentrations in the atmosphere are known as natural and anthropogenic processes (D'Almeida *et al.*, 1991). Natural processes include mainly from soil, volcanic dusts and gases. Anthropogenic emissions cover industrial gases, aerosols, fossil fuel combustion, incineration of waste and biomass burning and were identified as major atmospheric sources of nutrients (Sullivan and Woods, 2000; Andreae, 1993). Nutrients may be transported over long distances by very small particles (Koutrakis, 1984). These particles when aggregated or washed out by rain are called atmospheric deposition, respectively, dry and wet. Dry deposition of particles occur by direct impact and gravitational settling on land or water surfaces. In wet deposition, aerosols and gases are dissolved or suspended in water droplets. Besides such long-range transport processes, significant dry and wet depositions occur locally, and atmospheric sources in urban area may play an important role in the nutrient contamination of dry and wet depositions (Person *et al.*, 1993).

Wet and dry atmospheric depositions are the major scavenging processes but at the same time are responsible for the imbalance of many chemical species' biogeochemical cycles. The causes of atmospheric deposition depend on various factors including emissions, local and synoptic scale meteorological conditions, topography, and atmospheric chemical processes. In most cases, atmospheric deposition of nutrient in ecosystems is often a major problem (Kassomenos *et al.* 2003). Studies indicate that atmospheric deposition of nutrient demonstrate seasonal cycles around Great African Lakes (Bootsma *et al.*, 1996; Tamatamaha *et al.*, 2005). Certain weather situations provide the prerequisite meteorological conditions for atmospheric deposition loading.

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Many monitoring programs and researches have been applied to study wet deposition of pollutants in relation to meteorology, regional emission sources and other parameters (Lovett and Lindberg, 1984; Lindberg *et al.*, 1986; Hicks *et al.*, 1991; Zeller *et al.*, 2000; Peters *et al.*, 2002; Witz and Moore, 1981; Katsoulis, 1996; Turalıoglu *et al.*, 2005). Results showed good relationship between the meteorological parameters and concentration of different pollutants in the atmosphere. But little studies concerning atmospheric nutrients deposited in African Great Lakes and their effect on eutrophication aspect exist.

The relationship between atmospheric nutrients deposition and meteorological parameters such as wind speed, wind direction, temperature and relative humidity can provide important information about nutrients loading. Several scientific papers have shown a strong relationship and the issue of the dispersion condition at several scales, and climatically related variables such as air pollutants (Hein *et al.*, 2001; Dastoor and Larocque, 2004; Dayan *et al.*, 2017). In the past decades, Davis and Kalkstein, (1990) and Dayan *et al.*, (2008) examined the relationship between atmospheric pollutant concentrations and atmospheric meteorological and found that wind speeds may transport nutrients pollutants from distant sources. They also, concluded that pollutants associated with traffic were at the highest concentration levels when wind speed was low (Elminir, 2005). Hargreaves *et al.* (2000) found that a weak negative association was observed between NO_2 concentration and wind speed.

Due to its unique physical environment (dense population around the lake with high anthropogenic activities and active volcanoes) and geographical position (high altitude lake), the Lake Kivu is influenced by atmospheric deposition of nutrients. Under the impact of nutrients deposition and increased human activities around the fragile environment, Lake Kivu has suffered fundamental changes in eutrophication these recent decades (Bagalwa, 2015). Amongst the consequences there have been: significant episodic eutrophication, fish dying, exacerbating degradation of water quality and shrinking of lake area. Lake Kivu watershed has faced changes in meteorological conditions this last few years and the increase of population has triggered increase in mobile and stationary fuel combustion emissions. Mobile sources e.g. motor vehicles, motor cycles, locomotives and boats account for a large part of total emissions in major cities (Gerardo and Maricruz, 1997; Holloway *et al.*, 2000; Makra *et al.*, 2010).

This study evaluated the relationship between nutrients (N and P) concentration and local meteorological conditions (wind direction, wind speed) to predict major sources and direction pathway of nutrient loading to Lake Kivu during the study period. It is hypothesized that high concentrations of nutrient emissions come from town than rural area and from natural sources than anthropogenic sources.

2. MATERIAL AND METHODS

Lake Kivu watershed located along the western branch of the East African rift (western rift) is characterized by a highest elevation, topographic doming and rift shoulder uplift of all the Great Lakes of East Africa. The study sites were located in the Kalehe basin (2^{o}14, 259' S, 28^{o}52, 726'E) of Lake Kivu. Therefore, during the 13 months (December 2017 – February 2019), samples were collected once a month from atmospheric deposition and lake samples profile were collected at the same location in the Kalehe basin using Van Dorn bottle from depth of 40, 30, 20, 10, and 1 m and mixing them in equal parts to produce a single integrated sample (Morales-Bequero *et al.*, 2006). Where, data of atmospheric deposition were collected at the station installed around Lake Kivu at Lwiro (2^{o}14.228'S, 28^{o}48.441'E). Dry atmospheric deposition was collected by filling 1500 to 2000 mL of deionized water before sampling for 24 h the day of sampling as described by Amadio *et al.*, (2014) and Bagalwa *et al.*, (2017). Dry deposition rates were calculated in terms of concentration (µmol m-2 per day) using equation 1:

$$D = \frac{24\,CV}{AH} \qquad \textbf{(1)}$$

Where:
D = nutrient deposition (µmol m-2 day-1)
C = nutrient concentration in sample (µmol /L)
V = total volume of sample at end of collection period (L) A = surface area of collection bucket (m2)
H = number of hours that sample basin was deployed

The water collected from lake and atmospheric deposition were analysed in the laboratory at Lwiro for total phosphorus and total nitrogen using standard method APHA (1989) and Wetzel and Likens (2000). Analyses of total phosphorus (unfiltered water) and total dissolved phosphorus (filtered water) were performed using potassium persulfate digestion followed by the colorimetric, ascorbic acid / molybdate method and Total nitrogen (unfiltered) was measured using potassium persulfate digestion followed by colorimetric indophenol blue method.

The study used meteorological data from Lwiro station and gaps in data were filled by data downloaded from NASA website. The meteorological data collected included wind speed and wind direction and were measured using an automatic gauge (Pribble and Janicki, 1999; Barmpadimos *et al.*, 2011). The missing daily data were downloaded from NASA/POWER SRB/FLASHFlux/MERRA2/GEOS. Wet and dry atmospheric deposition of nutrient TP and TN were analyzed to derive the amount of TN and TP being directly deposited to the lake surface using standard method (Bagalwa *et al.*, 2017). TN and TP from atmospheric wet and dry nutrient depositions were quantified by analyzing the collected dry and wet samples at Lwiro station and lake photic mixing water during the time period using validated laboratory techniques (APHA, 2005; Wetzel and Likens, 2000).

The relationship between atmospheric concentration of nitrogen and phosphorus and wind direction were assessed using meteorological data and daily atmospheric nutrient concentration from the station of Lwiro located around the lake. The data were analyzed using correlation method as proposed by Monteith *et al.*, (2016).To determine if any relationship exists between atmospheric concentrations of TN and TP and possible sources of atmospheric nutrient, wind directions and wind speed were examined over the sampling period. Wind directions obtained from NASA in degrees were constrained to fall into one of four quadrants, with each quadrant containing 90° of the compass, and atmospheric nutrient concentrations as determined before were assigned to quadrants based on wind direction over the period of time for which the concentrations were applied (Pribble and Janicki, 1999). Mean TP and TN concentrations were computing between the same winds directions in the Lake Kivu basin. A Pearson correlation analysis approaches were used to compare wind direction and wind speed data with concentration of TP and TN obtained from atmospheric deposition and Lake Kivu water (Monteith *et al.*, 2016; Camarero and Catalan, 2012). TN:TP ratio were calculated in samples of atmospheric deposition and lake profile samples and compared with the standard Redfield ratio (Zheng *et al.*, 2019).

3. RESULT

Daily dry TP and TN atmospheric deposition rates and lake samples profile concentration are present in table 1 (Table 1).

Table-1: Daily dry TP and TN atmospheric deposition rates and lake samples profile concentration for different days

Date	Atmospheric deposition		Lake samples profile	
	TP (μmol/m^2/day)	TN (μmol/m^2/day)	TP (μmole/L)	TN (μmole/L)
19-Dec-17	1.535	10.07	0.301	2.204
27-Jan-18	2.280	9.410	0.526	2.662
23-Feb-18	1.292	6.106	0.536	10.596
21-Mar-18	1.281	5.670	0.178	3.288
28-Apr-18	1.326	9.702	0.095	2.088
25-May-18	1.416	8.170	0.478	4.590
20-Jun-18	0.347	5.129	0.313	5.190
28-Jul-18	1.253	8.134	0.334	7.692
24-Aug-18	1.271	3.803	0.167	6.309
19-Sep-18	0.601	11.123	0.394	6.516
27-Oct-18	1.202	17.508	0.473	5.814
23-Nov-18	0.794	31.134	0.116	5.160
31-Dec-18	0.676	9.583	0.281	10.103
26-Jan-19	1.181	9.583	0.109	6.349

Table 1 show that TP and TN atmospheric deposition rates and concentration of lake profile water samples varied from date to date of sampling. High values of aggregate atmospheric deposition rates of TP and November for TN were record in atmospheric deposition and February and December for lake samples. Whereas, low TP were recorded in June and low TN in August in atmospheric deposition and in April in lake samples profile. Significant difference was observed between atmospheric deposition rates and lake samples concentration of TP (t=7.215, $p<0.005$) and fairly significative difference within TN (t=2.362, p=0.03) following the paired test Wilcoxon method.

Temporal variations of TN/TP ratios of atmospheric deposition rates and lake samples profile during the study compared to standard Redfield ratio are presented in figure 1.

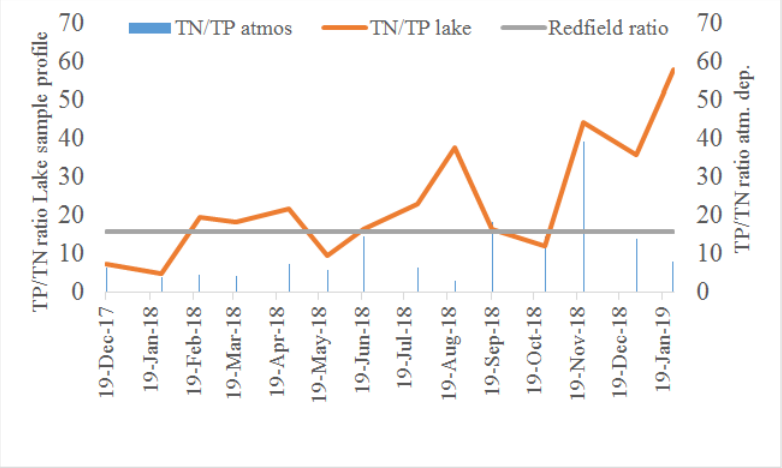

Fig-1: Temporal variation of TN/TP ratio of atmospheric deposition rates and lake samples profile

Temporal variation of TN/TP ratio of atmospheric deposition and lake samples profile shows that high TN/TP ratio occurred from August and November to January 2019 in lake samples and June, September and November for atmospheric deposition rates. During this period the TN/TP ratios were higher than the Redfield ratio (< 16). Low Redfield ratio were recorded between December 2017 to April 2018 in atmospheric deposition while low TN to Redfield ratio were recorded in December-January 2018, May and October 2018 in lake samples. The different ratios were significantly different over time ($p<0.000$) at Iko station.

Person correlation of TP and TN atmospheric deposition rates (µmol/m^2/day) and TP and TN concentration in lake water is presented in figure 2.

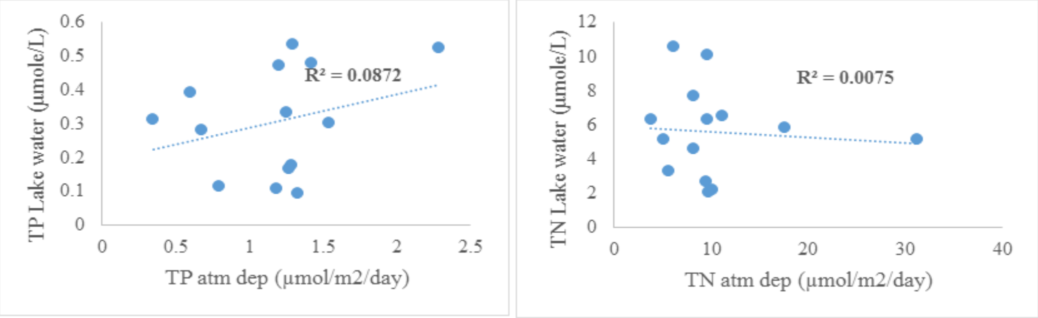

Fig-2: Pearson correlation between TP and TN atmospheric deposition rates and TP and TN concentration of lake samples

Pearson correlation between atmospheric deposition rates of nutrient and lake samples nutrient shows a weak positive linear correlation for TP (R^2=0.0872) and negative linear correlation for TN (R^2= 0.0075). The increased rates of TP in atmospheric deposition are followed by the increased concentration of TP but the increased of rates of TN in atmospheric deposition result for a decreased of TN in the lake.

Wind speed is an important factor influencing atmospheric deposition of nutrient to ecosystem. This factor varied from one location to another in term of intensity. Pearson correlation between TP and TN atmospheric deposition at Lwiro station and wind speed shows a weak positive correlation with TP (R^2=0.0064) and TN (R^2=0.0073) as presented in figure 3.

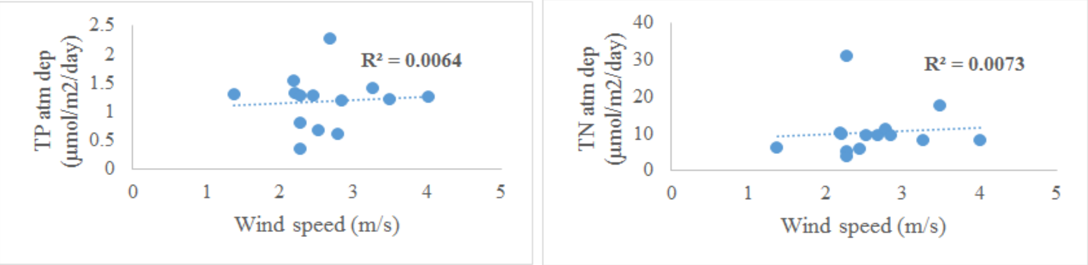

Fig-3: Pearson correlation between TP and TN rates (µmol/m^2/day) from atmospheric deposition and wind speed at Lwiro station

The increased wind speed has a tendency to increase atmospheric deposition rates of TP and TN during the period of the study. For lake profile samples analysis, Pearson correlation between TP and TN concentration (µmole/L) from Lake Kivu water and wind speed (m/s) is presented in figure 4.

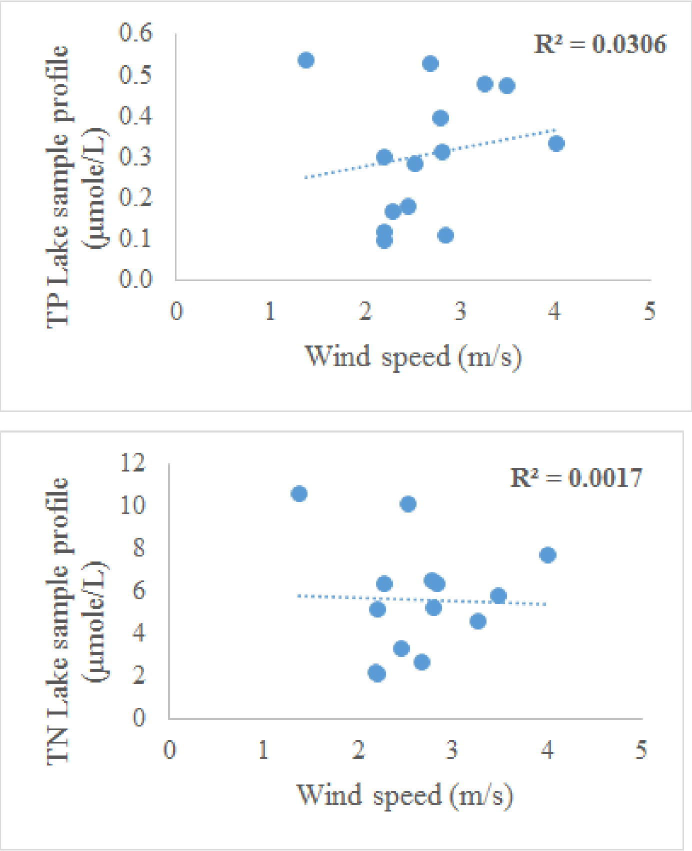

Fig-4: Pearson correlation between TP and TN concentration (µmole/L) and wind speed from lake profile samples

Pearson correlations of TP and TN have different trends. An increased wind speed is followed by an increase of TP concentration in lake profile samples. But, contrary to TP, increase of wind speed resulted in decrease of TN in lake profile samples. This was due to the natural form of different composed (P and N). Wind direction as a factor of atmospheric deposition, the results are presented in figure 5 bellow.

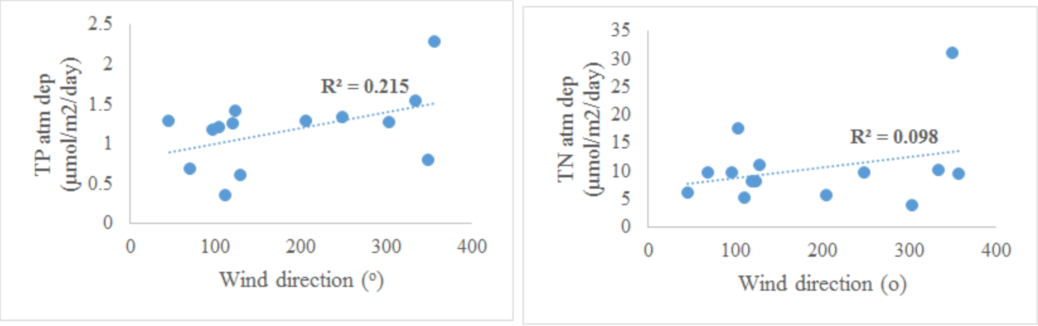

Fig-5: Pearson correlation between TP and TN atmospheric deposition rate (µmol/m2/day) and wind direction (^{o})

TP and TN atmospheric deposition rates exhibited weak negative correlations with respect to wind direction, and the coefficients of determination were 0.215 and 0.098, respectively. However, the coefficient of determination for TP and TN in Lake water were only 0.0937 and 0.4855 for Lake water with wind direction (Figure 6).

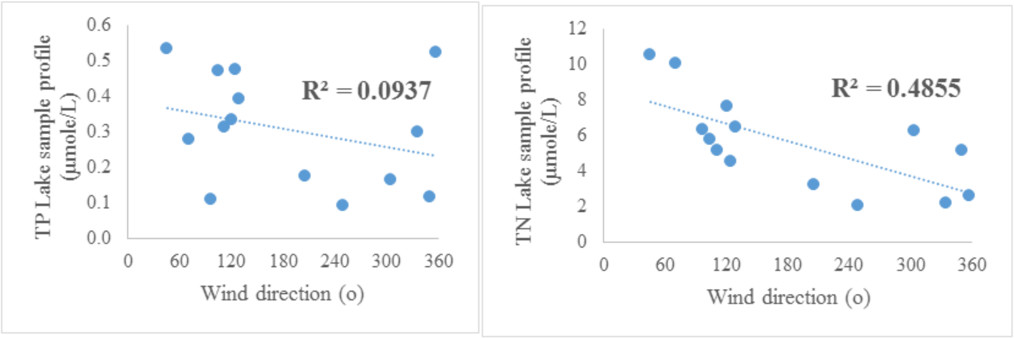

Fig-6: Pearson correlation between TP and TN concentration (µmole/L) from lake samples profile and wind direction (^{o})

These results indicated that the driving force of TP and TN deposition was source of nutrient in the basin. The most preferential wind direction in Lake Kivu basin were North –East, North-West, South-East and South-West. The mean TP and TN atmospheric concentrations for the days associated with wind direction is presented in table 2.

Table-2: Mean atmospheric deposition rates of TP and TN (µmol/m2/day) in relation to wind direction

Wind direction	TP (µmol/m2/day)	TN (µmol/m2/day)
North –East	1.47±0.62	13.604±12.02
North-West	0.98±0.436	7.845±2.458
South-West	1.304±0.03	7.686±2.85
South-East	1±0.423	9.941±4.2

TP and TN deposition rates shows a trend with preferential direction. The greatest deposition rate of TP was recorded in North-East and South-West. The lowest TP were recorded in North-West. For TN high mean atmospheric deposition rate were recorded in North-East and South –East while the lowest in South-West. TP is strongly correlated to wind direction (t= 9.996; p=0.002) while TN is correlated to wind direction (t=7.091, p= 0.005).

DISCUSSION

TP and TN atmospheric deposition rates in both atmospheric deposition samples and Lake Sample concentration profile have a similar trend for TP than for TN. High values of these nutrient were recorded at the same period of the sampling as also found by Vuai *et al.*, (2013) at Mwanza station in Tanzania in Lake Victoria. The high peak values for atmospheric deposition rates were obtained in February for TP and in November for TN during the sampling period. Generally, the atmospheric deposition over a region depends on both the pollutant emission quantity and the weather situations. Weather conditions (wind speed and direction, rainfall intensity and their frequency) can concentrate or disperse pollutants in a region or transport pollutants to regions distant from the emission sources (Cheng *et al.*, 2007a, b). Wind speed and direction are factors to disperse pollutant especially nutrient and major ions in aquatic ecosystem and are pointed as major meteorological factors of transport of nutrients in atmosphere (Sundarambal *et al.*, 2012).

During the first agricultural season (preparation period in June and beginning of planting period in September) high TN/TP ratio was recorded in atmospheric deposition (>16 Redfield ratio) that were suspected to cause eutrophication in the lake during this period. Redfield ratio N/P of 16:1 by moles in general indicates a roughly balanced supply of N and P, and algae assemblages (Zheng *et al.*, 2019). In November a high ratio TN/TP was recorded in the samples but it started in October. During this period, deposition can be dominated by local sources coming from biomass burning, primary biogenic particles, and particles emitted from local soils but during wet season, when emissions from local sources are reduced (e.g., soils are wet, wind speeds lower, reduced biomass burning), long-range transport of aerosols might become the dominant P source or volcanic emissions in the case of Lake Kivu basin (Gross *et al.*, 2016). Three factors (rainfall pattern, nutrient accumulation in the atmosphere and wind speed/direction) were probably the main causes of this trend recorded.

Rainfall pattern during the sampling period, January - February and June - August with low rainfall and other months with high rainfall are the cause of the trends recorded for nutrient concentration in atmospheric deposition and lake profile samples. Generally, frequent heavy precipitation causes low concentrations of nutrients and other particles at the end of the rain. Zhang *et al.*, (2008); Rastogi and Sarin, (2005) showed in their respective studies that during heavy precipitation low concentration of chemical species were obtained in atmospheric deposition.

The second factor is the accumulation of nutrients during dry period in the atmosphere which constitute dry deposition in atmospheric deposition or during the first rainfall the nutrients are deposit as wet atmospheric deposition. This phenomenon has also been reported by Langenberg *et al*., (2003) in their study of external source of nutrients for Lake Tanganyika. All these studies reveal that the dissolved inorganic nutrients were recorded in wet deposition than in dry atmospheric deposition.

The third factor is wind speed and wind direction in the basin. Nutrient is transported from emission source to deposit to other places by wind. The removal of nutrient via wet deposition is considered as an important pathway in cleansing the atmosphere (Bourcier *et al*., 2012), and equally important as dry deposition in terms of the inputs of nutrients to the affected aquatic ecosystems (Pan and Wang, 2015). Natural and anthropogenic activities in the basin such as volcanoes activities, biomass burning, and soil erosion are introduced in the atmosphere by meteorological conditions and rich surface lake water in increasing nutrient. In addition, land preparation for cultivation is actively pursued during this dry period in the study area is also prevalent in changing rates of atmospheric deposition of nutrient. These data seem to support the hypothesis that Goma station located at the north part of the Lake Kivu is the major source of atmospheric nutrient. This suggests that the occurrence of atmospheric nutrient deposition depends mainly on meteorological conditions, sources of nutrients depositions and anthropogenic activities in the basin.

Thus, the results obtained in this study can serve as a baseline for assessing nutrient loading changes in Lake Kivu basin in the future. This revealed that if TP and TN rates in the atmosphere increases with natural or anthropogenic activities the concentration of these nutrients increases also in the Lake Kivu profile samples. This confirms that atmospheric deposition is a contributor of nutrient in Lake Kivu as also revealed by Bagalwa *et al*., (2017); Muvundja *et al*., (2009). The high atmospheric deposition rates recorded in November for TN are influencing high concentration of this nutrient in the next month (December 2018) in lake water. Deposit of nutrients depends on wind speed and wind direction as found also in Chine by Pan *et al*., (2017). Phosphorus has not gas form; it's only in particulate form and has high molecular mass, which does not allow transport for long distance in the atmosphere. Source of the phosphorus in the basin or behind the basin are one of the raison that TP in the atmospheric deposition has negative correlation with wind speed. Additionally, Ahn and James (2001) reported, that the high spatial variability of P atmospheric loads suggests that the atmospheric deposition of P mainly depends on local sources. In our study, TP deposition showed a weakly positively correlated with wind speed. However, it is now that the main components of phosphorus emitted to the atmosphere and deposited in freshwater, are dust from soils, primary biological aerosol particles (microorganisms, dispersal units, fragments and excretions), ash from volcanoes, biomass burning, the combustion of oil and coal, and emissions from phosphate manufacture as argue by Tipping *et al*., (2014).

But nitrogen is both particulate and gases form. The gases form, it can travel long distance before deposition in Lake Kivu water. The positive correlation in the atmospheric deposition confirms this hypothesis of distance of transport of gases pollutants. Karhu *et al*., (2010) found the same results when they presented the correlation between wind speed and chlorophyll a concentration (Chlorophyll-a), which showed patterns of coherence with either positive or negative correlations. But they found that the correlation between Chlorophyll-a and wind speed is generally negative in areas with deep mixed layers and positive in areas with shallow mixed layers in the Ocean. In Lake Kivu, the mixing layers are reduce and others layers are anoxic, that confirms the positive correlation tendency observed.

Wind direction is also weak negative correlations with TP and TN. These indicated that the driving force of TP and TN deposition was source of nutrient in the basin. The increase in TP and TN atmospheric deposition rates in wind direction at north part of the lake might be linked to a relatively significant contributor of volcanoes and traffic road. In conclusion, we found that volcanoes ash is a highly significant source of nutrients through atmospheric deposition to the Lake Kivu surface water. It becomes important to know the pattern of dispersal atmospheric deposition of nutrient from the original sources, the way in which chemical change may occur during its migration, and the efficiency of the sinks. That action may be of course direct, as in deposition on the surface of watercourses to which it penetrates and can cause eutrophication.

4. CONCLUSION

The present study was conducted to investigate the relationship between wind speed and direction on atmospheric TP and TN in dry and wet atmospheric depositions rates within the Lake Kivu basin. TP and TN in atmospheric deposition rates show weak positive correlated with wind speed. The high TP and TN rates in atmospheric deposition were recorded at the wind direction of North of the lake than in south. Atmospheric deposition is a significant source of nutrients (TN and TP) to aquatic ecosystems in tropical regions where biomass burning, traffic and volcanoes activity are intensely regular. Increased of these nutrient can accelerate eutrophication and its associated environmental consequences in freshwater ecosystems. This founding is an important basis for the qualitative prediction, control, and management of basin nutrient problems in Lake Kivu.

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