External Nutrient Inputs into Lake Kivu: Rivers and Atmospheric Depositions Measured in Kibuye

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Abstract

Quantifying the external nutrients inputs is a key factor for understanding the formation of methane in Lake Kivu. This tectonic lake located between Rwanda and DRC contains a big quantity of dissolved gases predominated by carbon dioxide, methane and sulphide. The CH_4 is most probably produced in the lake, mainly in the sediments, from decomposing organic material and by reduction of CO_2. The sediments are carried out into the Lake Kivu which consequently may leads to the high production of methane from the decomposition of organic matter contained in sediments and biomass. For quantifying the external nutrient inputs into Lake Kivu, rivers in Kibuye catchment and atmospheric deposition were analyzed for phosphorus, nitrogen and Silica.

The results found show that a total budget of 276 $tN.yr^{-1}$ or an areal specific load of 401 $kgN.km^{-2}.yr^{-1}$of DIN (ammonia nitrogen and nitrate nitrogen), 5 $tP.yr^{-1}$ or 11 $kgP.km^{-2}.yr^{-1}$ of SRP, 59 $tP.yr^{-1}$ or 87 $kgP.km^{-2}.yr^{-1}$ of TP, 1122 $tSi.yr^{-1}$ or 2570 $kgSi.km^{-2}.yr^{-1}$ and 31620 t $TSS.yr^{-1}$ or 41 $tTSS.km^{-2}.yr^{-1}$ are deposited into Lake Kivu through rivers in Kibuye Catchment. The contributions of atmospheric deposition are considerable where about 2176 $tN.yr^{-1}$ and 1638 $tN.yr^{-1}$ of DIN respectively for wet deposition and dry deposition are deposited in Lake Kivu.

It was observed that nitrite nitrogen is negligible in atmospheric deposition and riverine inputs. DSi predominates in riverine inputs and is negligible in atmospheric deposition. Ammonia nitrogen comes from atmospheric deposition while nitrate nitrogen comes from riverine nutrient inputs. Considering the molar ration DSI: DIN: SRP of 10:20:1, the limiting nutrient for the primary productivity in external riverine inputs is phosphorus. Since the lake-internal nutrient recycling is about an order of magnitude larger than the external sources, the recent increase of dissolved methane in Lake Kivu is not generated only by external nutrient inputs.

Key words: *nutrients, atmospheric deposition, riverine inputs, internal cycling, Lake Kivu*

1. Introduction

Lake Kivu is an East African Rift Valley lake between the Republic of Rwanda and the Democratic Republic of Congo. The lake is situated immediately adjacent to the active volcano Nyiragongo. The catchment area is estimated to be about 7000 km^2, surface area of 2400km^2, altitude 1462-1463m, maximum depth 485m, volume $500x10^9m^3$, depth of thermocline in wet season is between 20-30m and in dry season 40-50m, oxygen maximum depth limit 50-70m with a discharge rate of $3.2x10^9m^3.yr^{-1}$ (Schmid et *al*., 2004, Degens et *al*., 1973, Tietze 1978 and Halbwach et *al*., 2002).

The lake contains $65x10^9$ m^3 of dissolved methane and about five times as much dissolved carbon dioxide (Tietze 1978, Tietze et *al.,* 1980).

The Lake Kivu is fed by several rivers taking source in Congo Nil Crest, from the North West to the South West of Rwanda and several rivers in DRC part. The only outlet of the Lake Kivu is Rusizi River flowing in Lake Tanganyika at an altitude of 772 m above sea level and thus 690 m lower than Lake Kivu.

The lake consists of one large main basin and four smaller separate basins: the Ishungu, the Kalehe, the Bukavu Basins and the Kabuno Bay (Botz et *al*., 1978). All basins except Bukavu basin contain high amounts of dissolved gases, which are associated with anaerobic conditions (Tietze et *al.,* 1980).

The high gas concentrations have different sources: the CO_2 is mainly of magmatic origin and is introduced into the lake most probably with groundwater flows. The CH_4 is most probably produced in the lake, mainly in the sediments, from decomposing organic material and by reduction of CO_2. The reason for the unusually high concentrations is the very stable stratification which prevents the exchange of gases between the deep water and the surface waters and finally the loss to the atmosphere (Tietze, 1980 and Halbwachs et *al.,* 2002).

The catchment area of Lake Kivu is densely populated with an average density of about 400 inhabitants per km^2 (Muvundja et *al.*, 2009). Intensive agricultural land use within the catchment increases the nutrients inputs into the lake (Müller et *al*., 1998).

Forest harvesting, erosion, sands and minerals exploitations increase the sediment concentrations in the surrounding rivers. The sediments are carried out into the Lake Kivu which consequently lead to the high production of methane from the decomposition of organic matter contained in sediments and biomass (Schoell *et al.,* 1988). Thus, quantifying the external nutrients inputs through measurement of rivers and atmospheric deposition is a key factor for understanding the formation of methane in Lake Kivu.

The methane can serve as one solution for energy problems that Rwanda is facing. The Lake Kivu contains five times higher amount of CO_2 than methane. Even though the methane concentration is five times less than that of CO_2, CH_4 contributes to 80% of the total pressure because of its lower solubility. However, with the estimated current methane production, the gas concentrations could approach saturation within this century (Schmid et *al*., 2005). Therefore a gas eruption will be triggered by CH_4 saturation, but CO_2 would constitute most of the erupted gas volume. When the pressure of dissolved gases exceeds the saturation it can outburst and kill several people as happened to the Lake Nyos in Cameroun in 1986 where a mass of dense carbon dioxide asphyxiated around 1800 persons in surrounding valley of the lake (Halbwachs et *al*., 2002).

This study is a contribution to the existing nutrients and silica data base that will help to understanding of methane gas production in Lake Kivu among other benefits such as drinking water supply, recreation and irrigation regulations.

The main objective of this study is to estimate the annually load of nitrogen, phosphorus and silica transported by rivers into Lake Kivu and the contribution of dry and wet atmospheric depositions..

2. Materials and methods

The study has been undertaken from October 2006 to June 2008 covering eight sampling sites of rivers and one sampling site of dry and wet deposition. In total, 20 or more flowrates and total suspended solids (TSS) measurements per river were performed, 7 to 14 samples of each river have been collected and analysed for nutrients and dissolved silica, 4 to 5 samples of wet depositions and 7 to 15 of dry depositions were taken. When it rained dry deposition was not taken into account only wet deposition was considered.

2.1. Description of the study area

Lake Kivu is the western and most elevated of the string of rift lakes which curves through east central Africa (Deuser et *al.,* 1973). The lake hydrochemistry was first studied by Damas who discovered large quantities of dissolved gas in deep water (Damas, 1937). The study area is composed of eight rivers in west of Rwanda inflowing into Lake Kivu precisely in Kibuye catchment. Those rivers are divided into two groups: the first group of 4 rivers in south of Kibuye and another group of four rivers in north of Kibuye. The atmospheric deposition was settled at site located on shore of Lake Kivu. Figure 1 shows the loacalisation of the Lake Kivu.

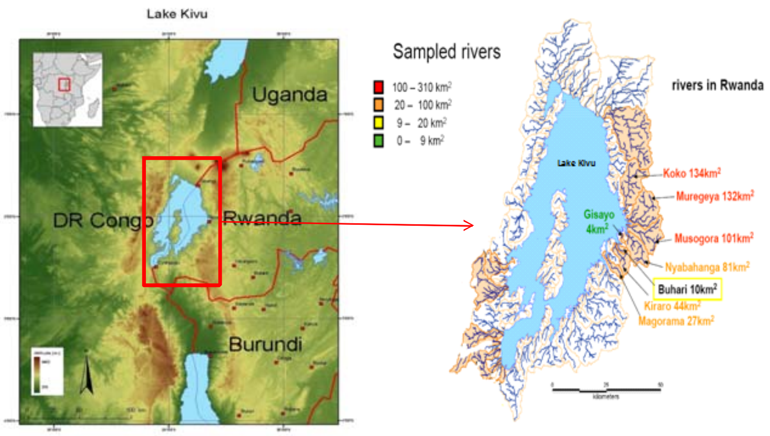

Figure 1: Central Africa Map showing the Lake Kivu and the sampling site with river basin catchment area

The geology of the catchment is characterized by volcanic rocks and magmatic rocks. In the study area granites, pegmatite and gneiss can be found. The south west is predominated by basalts stones. The stones on shores of Lake Kivu are yellow white colored due to the presence of sulfide products into waters (Nsengimana et *al*., 2001).

The study area (Figure 1) concerned eight rivers in Kibuye catchment of Lake Kivu; those rivers are Koko (4N), Muregeya (3N), Musogoro (2N) and Nyabahanga (1N) in North of Kibuye and Gisayo (1S), Buhari (2S), Kiraro (3S) and Magarama (4S) in south of Kibuye. The rivers Gisayo, Buhari, Kiraro, Magarama, Nyabahanga and Musogora cross Karongi district, Muregeya frontier between Rutsiro district and Karongi while Koko is between Rubavu district and Karongi.

The choice of river was based on the catchment size (Figure 1) and the sample was taken at a distance less than 150 m from the river outflow in the lake except where the site was not accessible.

2.2. Sampling and analyses methods

Sample collection

The sample of river water was collected twice a month, using polyethylene sampling bottles were cleaned using chlorhydric acid, and rinsed afterward with distilled water. Prior to water collection, sampling bottles were cleaned with the river water, then filled and labelled. The sample was taken in the middle of river. At every sampling site, two samples or more of 250-1000 ml were collected. The number of samples was dictated by the suspended material content. On one hand, more than 2 samples were collected in order to get enough suspended material after sample filtration; on the other hand 2 samples were collected for water with high turbidity. The collected samples were immediately stored in a cooler box containing ice for maintaining sample at 4°C.

Sample filtration

After sampling the filtration was done for samples in which soluble reactive phosphorus, nitrates, nitrites, silica and ammonium would be measured. Unfiltered sample were conserved for total phosphorus analysis. The whatman GF/C filters 0.45 µm of diameter were used and weighted before filtration and after, then dried at 40^0 C during 12 hours for solid particles weighing.

Discharge measurement method

Discharge was measured on sampling site by determining the velocity of a float and the total cross-sectional area of the river following the Float Method Procedure adapted from the orange method (Harrelson et *al*., 1994).

The measurement of cross section area was performed by dividing the cross section of a river into equal reach and determines the depth of the river at every vertical. The area of each section is then calculated and the total cross sectional area is determined by summing up individual areas. Figure 2 shows the presentation of cross section area on paper.

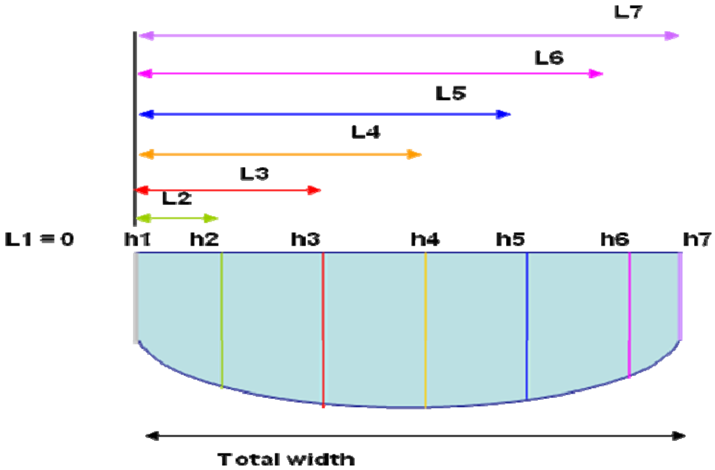

Figure 2: Diagramme of cross section survey (Author, 2009)

Where: Li: cross sectional width, hi: heigh

For calculating the cross section area the below formula is applied:

$$A = A_1 + A_2 + ... + A_n = 1/2h_1 * L_1 + [\frac{h_1 + h_2}{2}] * L_2 + ... + \frac{1}{2}h_n * L_n$$

Where A_i: area of the section i

The flow velocity was measured using non standard flow by plastic water bottle. For obtaining the river flow, the average velocity was multiplied by the cross section area.

$$Q = A * V$$

$$V = \frac{l}{t},$$

$$t = \frac{t_1 + t_2 + ... + t_n}{n}$$

with Q: river flow in m^3/sec, V: average velocity in m/sec, l: length for velocity measurement in m, t_i: time in seconde and t: mean time in sec.

Atmospheric deposition settlement and collection

Atmospheric deposition was collected at site settled at the shore of Lake Kivu in Kibuye. Dry deposition was measured using two plastic trays of 1200 cm^2 rinsed with detergent without phosphorus, the trays were placed at 1-1.5 m above the ground, 1liter of distilled water was added and trays were exposed 24 hours at open air and after this time interval, the remaining water is collected for chemicals analyses. Concerning wet deposition, similar trays were used except that no distilled water was added.

Chemical analyses

The nutrients were analyzed in the laboratory of the faculty of agriculture and in the laboratory of chemistry department (National University of Rwanda) as soon as possible after sampling using standards methods of UV-Visible spectrophotometer (CECIL CE-2041, 2000 series, England).

Prior to the analysis, the samples were filtered except TP samples which have been analyzed after digestion in an autoclave (Wolf sanoclave KL12-2, Germany) by potassium persulphate for 2 hours at 120 °C.

Data collection and treatments

The sampling scheduler was bimonthly and laboratory results are treated using appropriate software like MS Excel and descriptive statistics. From float flow measurement and water quality analysis we estimated the annual nutrient fluxes.

Nutrients specific load of rivers ($mg.d^{-1}$): The daily Nutrients specific load has been calculated by multiplying the concentration in $mg.m^{-3}$ by the daily discharge in $m^3.d^{-1}$.

$$NSL[mg.d^{-1}] = C[mg.m^{-3}] \times Q[m^3.d^{-1}]$$

Where: NSL: Nutrients specific load, C: concentration and Q: daily discharge

River annual nutrient load (mg.yr^{-1}): For every river, the annual nutrient load was calculated by multiplying the average concentration with annual discharge:

$$ANL(mg.yr^{-1}) = MeanC\left[mg.m^{-3}\right] \times Q\left[m^3.yr^{-1}\right]$$

With ANL: Annual nutrient load,

From the annually riverine nutrient load the specific load for every river was deduced by dividing the nutrient load by the catchment area for each river.

Nutrients load for dry and wet depositions: For estimating the nutrients load from dry deposition we apply the formula

$$NLDD\left[\mu g.yr^{-1}\right] = \frac{C\left[\mu g.m^{-3}\right] \times V_f\left[m^3\right] \times D[d.yr^{-1}] \times LA[m^2]}{A\left[m^2\right] \times \Delta t\left[d\right]}$$

Where: NLDD Nutrient loads of dry deposition, C: nutrient concentration in the bowl, V_f: the final water volume in the bowl, A: bowl surface, Δt: time interval for exposition, D: number of dry days per year assumed to be about 201d.yr^{-1} (Muvundja et *al.*, 2009) and LA: Lake area which is 2370 km^2.

Concerning the wet deposition it has been calculated by multiplying the mean rainfall concentration in the bowl with the annual precipitation which is 1404 mm.yr^{-1} (Muvundja et *al.*, 2009) and the lake area.

$$NLWD[\mu g/yr] = mean\ conc[\mu g/m3] \times mean\ AR[m/yr] \times LA[m2]$$

Where NLWD: annual nutrient load in wet deposition, AR: annual rainfall, LA: lake area.

3. Results

The following section presents the results obtained by measurements of discharge, nitrogen, phosphorus, silica and total suspended matter.

3.1. Discharge measurement

Table 1 presents the mean discharge in dry season, rainy season and the annual average. The rainy season comprises the great rainy season from March to May and the short rainy season from September to December. The dry season comprises the remaining months.

Table 1: Discharge variation in m^3.S^{-1}

	Average in Rainy season			Average in Dry season			Annual Average		
Rivers	**Mean**	**Std**	**N**	**Mean**	**Std**	**N**	**Mean**	**Std**	**N**
Nyabahanga	0.594	0.236	13	0.600	0.180	8	0.596	0.211	21

Musogora	0.939	0.432	13	0.710	0.223	8	0.852	0.378	21
Muregeya	2.350	2.739	12	1.259	0.792	8	1.914	2.208	20
Koko	2.469	2.186	12	1.422	0.519	8	2.051	1.773	20
Gisayo	0.034	0.046	12	0.030	0.014	8	0.033	0.036	20
Buhari	0.136	0.091	12	0.124	0.022	8	0.131	0.071	20
Kiraro	0.606	0.271	12	0.416	0.165	8	0.530	0.249	20
Magarama	0.465	0.311	12	0.364	0.172	8	0.425	0.264	20

N: Number of samples, Std: standard deviation

The discharge measurements of rivers in Kibuye showed a high fluctuation in rainy season as shown by standard deviations. The high flow is found in Koko River with an annual average flow of 2.051 $m^3.s^{-1}$ and the minimum flow is found in Gisayo River with an annual average flow of 0.033 $m^3.s^{-1}$. Considering season the highest water levels are found in rainy season and the lowest in dry season as shown in table 1.

3.2. Variation of nitrogen

Ammonia Nitrogen specific load in $kg.km^{-2}.month^{-1}$

Figure 3 (a) presents the average ammonia-nitrogen monthly specific load per km^2 of river catchment area in dry season and in rainy season in $kg.km^{-2}.month^{-1}$ of NH_4^+-N. The highest ammonia loads are found in the North sub-catchment Kibuye Rivers (Koko, Muregeya, Musogoro and Nyabahanga) while the lowest loads are found in South sub-catchment Kibuye rivers (Magarama, Kiraro, Buhari and Gisayo). The variation with seasons shows that the highest loads are observed in rainy season with a monthly mean specific load of 2.4 $kgN.km^{-2}$, while in dry season is of 1.8 $kgN.km^{-2}$.

Nitrate-nitrogen specific load in $kgN.km^{-2}.month^{-1}$

Figure 3 (b) presents the average nitrate-nitrogen monthly specific load in dry season and in rainy season.

The highest values of monthly nitrate nitrogen flux are found in Muregeya River and Koko. The lowest values are found in Gisayo and Magarama. Considering the dry and rainy season, the highest fluxes are observed in rainy season with a monthly mean specific load of 35 $kgN.km^{-2}$, while in dry season it is of 20 $kgN.km^{-2}$. Annually, the highest load is observed in Muregeya and the lowest load in Gisayo rivers with respective loads of 120 $tN.yr^{-1}$ and 0.7 $tN.yr^{-1}$.

Nitrite-nitrogen load in $kgN.km^{-2}.month^{-1}$

Figure 3 (c) gives the mean monthly nitrite nitrogen specific load in dry season and in rainy season.

The nitrite-nitrogen load in river sampled is low compared to other parameters analysed. The rivers transporting more nitrite-nitrogen are Koko and Muregeya with annual load of 0.41 $t.yr^{-1}$ and 0.43 $t.yr^{-1}$ respectively. The rivers depositing less nitrite nitrogen are Gisayo and Magarama with 0.01 $t.yr^{-1}$ and 0.05 respectively.

The nitrite load variations within seasons show the high values in rainy season with an average of 0.273 $kgN.km^{-2}.month^{-1}$ whereas in dry season is 0.195 $kgN.km^{-2}.month^{-1}$. Except Koko River where the highest load is observed in dry season.

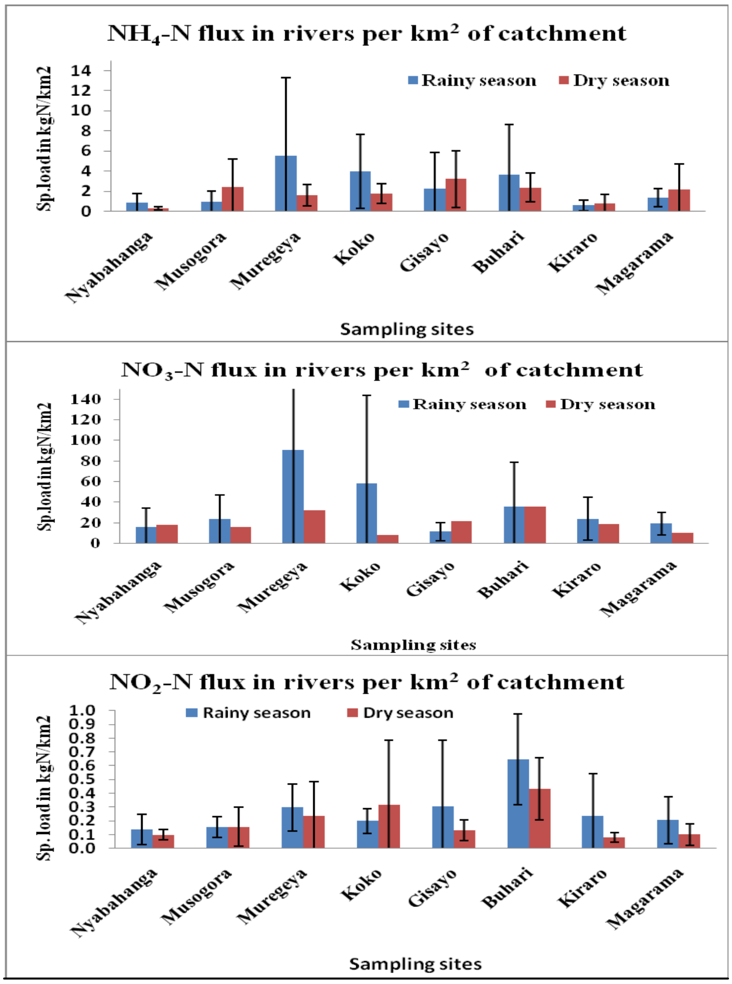

Figure 3:N-Ammonium(a), N-nitrate(b), N-nitrite(c) specific load in $kgN.km^{-2}.month^{-1}$

3.3. Variation of phosphorus loads in rivers

SRP specific load in kgP.km^{-2}month^{-1}

Figure 4 (a) presents the mean monthly SRP specific load in dry season and in rainy season.

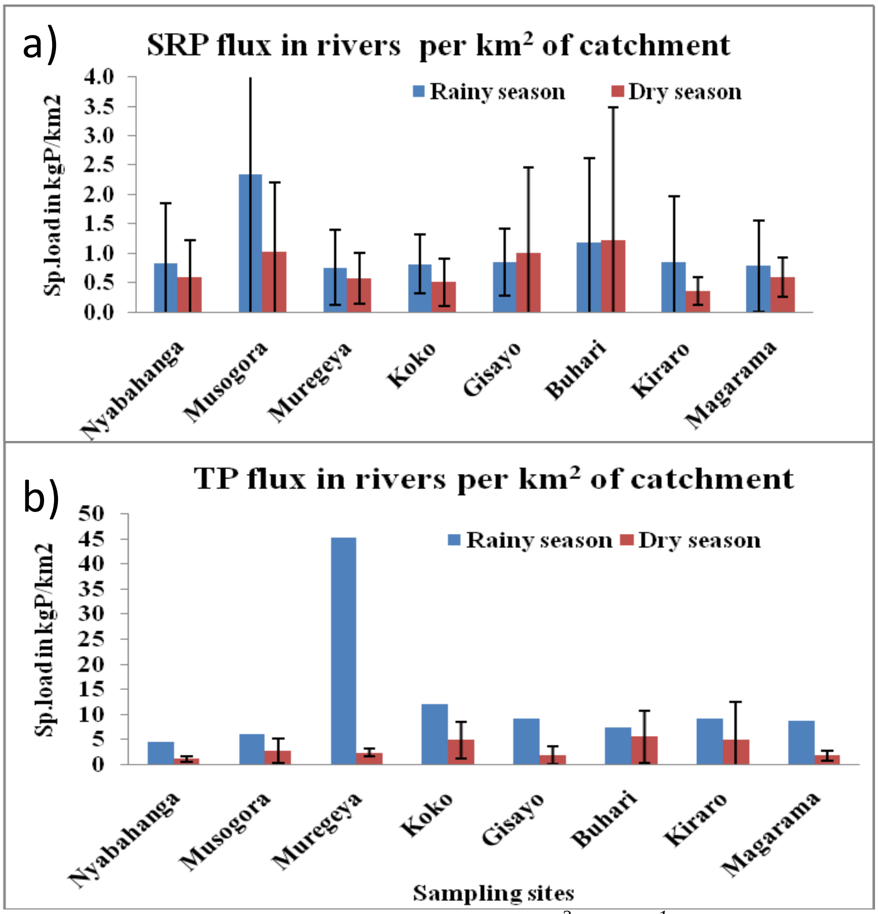

Figure 4: SRP(a), TP (b) specific load in kgP.km^{-2}.month^{-1}

SRP mean annual load varies in the range of 0.045 t.yr^{-1} for Gisayo to 2 t.yr^{-1} for Musogora river. In dry season, the SRP load ranges between 0.359 and 1.226 kg.km^{-2}.month^{-1} respectively in Kiraro and Buhari. In rainy season, SRP varies in the range of 0.757 kg.km^{-2}month^{-1} to 2.339 kg.km^{-2}.month^{-1} respectively in Muregeya and Musogora. Comparing two seasons, it was observed the highest SRP loads in rainy season with a monthly mean specific load 1.05 kg.km^{-2} whereas in dry season is of 0.735 kg.km^{-2}.

TP specific load in kgP.km^{-2}.month^{-1}

Figure 4 (b) presents the mean monthly TP specific load per river catchment area in dry season and in rainy season.

TP annual load varies in the range of 0.24 t.yr^{-1} (Gisayo River) to 33t.yr^{-1} (Muregeya River). In dry season, TP load ranges from 1.1 kg.km^{-2}month^{-1} (Nyabahanga) to 5.5 kg.km^{-2}.month^{-1} (Buhari) while in rainy season it is in the range of 5 kg.km^{-2}.month^{-1} to 45 kg.km^{-2}.month^{-1} respectively in Nyabahanga and Muregeya. Comparing the seasons the highest values are found in rainy season. The mean specific load of 13 kgP.km^{-2}.month^{-1} was observed in rainy season whilst 3.2 kgP.km^{-2}.month^{-1} are observed in dry season.

3.4. Variation of Silica loads in rivers

Figure 5 shows the variation of dissolved silica specific load in sampled rivers within seasons in kgSi.km^{-2}.month^{-1}

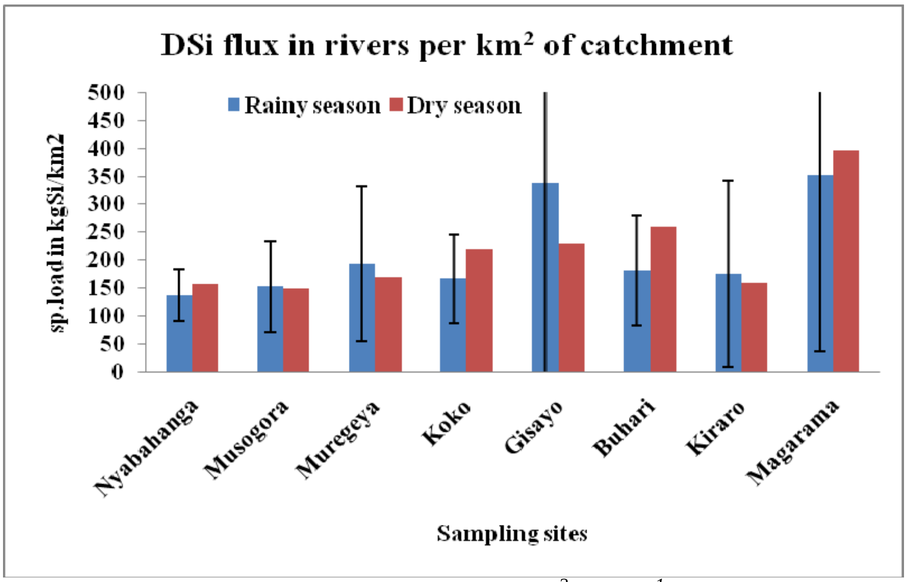

Figure 5: DSi monthly specific load in kgSi.km^{-2}.month^{-1}

The minimum annual load of 16 tSi.yr^{-1} was found in Gisayo River and the maximum annual Silica load of 298 tSi.yr^{-1} was found in Koko (table 5). In dry season the maximum monthly specific load of 398 kg.km^{-2} is found in Magarama River and the minimum value of 148 kgSi.km^{-2} in Musogora River. In rainy season, the maximum Dsi load of 353 kgSi.km^{-2}.month^{-1} and the minimum Dsi load of 137 kg.km^{-2}.month^{-1} are found respectively in Magarama and Nyabahanga Rivers. In general, the monthly mean highest areal catchment specific load is observed in dry season (217 $kg.km^{-2}.month^{-1}$) compared to rainy season (212 $kgSi.km^{-2}.month^{-1}$).

3.5. Variation of total suspended solids loads in rivers

Figure 6 gives the variation of TSS and presents monthly TSS specific load in rainy season and in dry season for each river

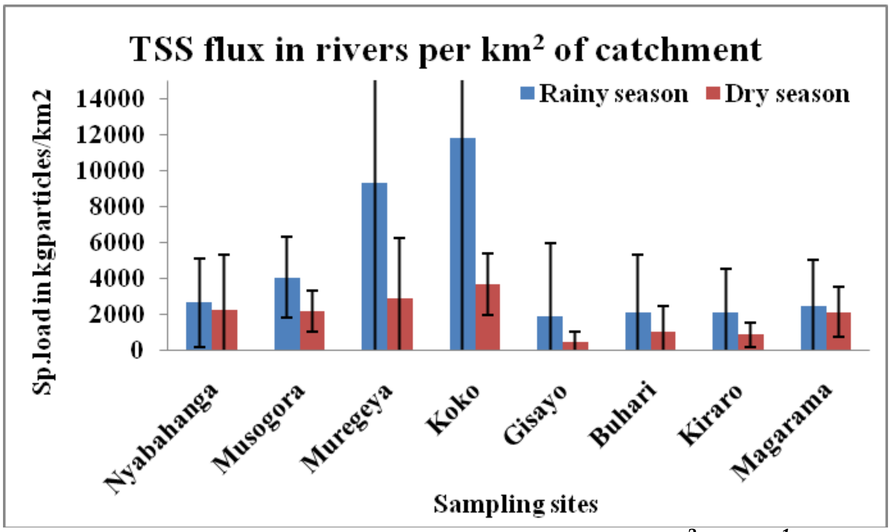

Figure 6: TSS monthly specific load variations in $kg.km^{-2}month^{-1}$

The flux variation with seasons shows the highest fluxes in rainy season and the lowest in dry season. The most discharging river in rainy season is Koko with 1580 $t.month^{-1}$ to areal catchment specific load 11793 $kg.km^{-2}.month^{-1}$ of particles and the less discharging is Gisayo river with 8 $t.month^{-1}$ of particles with an areal specific load of 510 $kg.km^{-2}.month^{-1}$. In dry season the fluxes of 490 $t.month^{-1}$ (3685 $kg.km^{-2}.month^{-1}$) and 2 $t.month^{-1}$ (510 $kg.km^{-2}.month^{-1}$) are observed respectively in Koko and Gisayo rivers. Annually, In all rivers sampled it is noticed the maximum loads of TSS in Koko rivers with an annual flux of 13053 $t.yr^{-1}$.

3.3. Nutrients loads from atmospheric depositions

Nutrients load in wet deposition

Table 2 presents the mean nutrient loads in wet deposition. According to the results shown in table 2; the wet deposition on Lake Kivu surface area brings about 1988 $t.yr^{-1}$ of NH_4-N, 180$t.yr^{-1}$ of NO_3-N, 129$t.yr^{-1}$ of SRP, 51 $t.yr^{-1}$ of DSi and 8 $t.yr^{-1}$ of NO_2-N.

Table 2: Average nutrients concentration in wet deposition and annual nutrient load

Parameter	Std	Concentration Mean (($\mu g.l^{-1}$)	Min-max ($\mu g.l^{-1}$)	N	Annual Load ($t.yr^{-1}$)
NH_4-N	522	597	(102-1181)	5	1988
NO_3-N	60	54	(1-124)	4	180
NO_2-N	2	3	(0-6)	5	8
PO_4-P	52	39	(2-115)	4	129
Si	22	15	(2-54)	5	51

Nutrients loads in dry deposition

Table 3 shows the concentration of nitrogen, phosphorus and Dsi analysed in dry deposition and their respective annual loads in $t.yr^{-1}$

Table 3: Mean nutrient concentrations and annual loads in dry deposition

Parameter	Std	Mean concentration $\mu g.m^{-2}d^{-1}$	Min-max $\mu g.m^{-2}d^{-1}$	N	Nutrient load $t.yr^{-1}$
NO_3-N	283	277	(0-748)	8	132
	470				
NH_4-N	0	3133	(566-14330)	12	1492
NO_2-N	15	29	(0-50)	15	14
PO_4-P	110	104	(21-417)	13	50
TP- PO_4-P	439	327	(26-1307)	7	156
Si	1	1	(0-3)	5	0.3

The results are almost the same as in wet deposition; the rainy fall on Lake Kivu contains much NH_4-N with annual load of NH_4-N of 1492 $t.yr^{-1}$ of NH_4-N, 132 $t.yr^{-1}$ of NO_3-N, 156 $t.yr^{-1}$ of TP, 50 $t.yr^{-1}$ of SRP, 14 $t.yr^{-1}$ of NO_2-N and 0.3 $t.yr^{-1}$ of Dissolved silica.

3.4. Annual nutrient deposits in Lake Kivu through rivers

Tables 4 and 5 present the annual nutrients deposits and annual specific load for all rivers sampled in Kibuye. As shown in table 4 a total budget of 16 $t.yr^{-1}$ of NH_4^+-N are deposited into Lake Kivu by rivers in Kibuye catchment with a specific load 27 $kgN.km^{-2}.yr^{-1}$. The same, a total budget of 259 t of nitrate nitrogen are deposited into Lake Kivu annually with a specific load of 374$kgN.km^{-2}.yr^{-1.}$ The annual deposit of nitrite nitrogen is of 1 $tN.yr^{-1}$ to a specific load of 2$kgN.km^{-2}.yr^{-1}$.

Table 4: Annual nitrogen deposits in Lake Kivu

	NH_4-N		NO_3-N		NO_2-N	
	Load	Spec load	Load	Spec load	Load	Spec load
Site	$t.yr^{-1}$	$kg.km^{-2}.yr^{-1}$	$t.yr^{-1}$	$kg.km^{-2}.yr^{-1}$	t.yr-1	$kg.km^{-2}.yr^{-1}$
Nyabahanga	0.70	9	16.1	199	0.116	1.4
Musogora	1.65	16	26.5	263	0.189	2.3
Muregeya	7.05	53	120.6	914	0.427	5.3
Koko	5.44	41	73.4	548	0.409	5.1
Gisayo	0.12	31	0.7	167	0.011	0.1
Buhari	0.39	39	4.3	430	0.066	0.8
Kiraro	0.38	9	12.0	272	0.087	1.1
Magarama	0.51	19	5.5	202	0.051	0.6
Total	**16**		**259**		**1.357**	
Average		**27**		**374**		**2.1**

Table 5 gives the annual nutrient deposits and specific load for SRP, TP, DSi and TSS.

Table 5: Annual phosphorus, DSi, TSS loads and specific loads

	SRP in PO_4-P		TP in PO_4-P		DSi		TSS	
	Load	Spec load	Load	Spec load	Load	Spec load	load	spec load
Site	$t.yr^{-1}$	$kg.km^{-2}.yr^{-1}$	$t.yr^{-1}$	$kg.km^{-2}yr^{-1}$	$t.yr^{-1}$	$Kg.km^{-2}yr^{-1}$	$t.yr^{-1}$	$Kg.km^{-2}yr^{-1}$
Nyabahanga	0.68	8	2.49	31	138	1710	2429	29992
Musogora	2.08	21	5.09	50	184	1820	3905	38661
Muregeya	1.04	8	32.87	249	245	1855	10403	78809
Koko	1.02	8	12.75	95	298	2223	13053	97413
Gisayo	0.05	11	0.24	59	16	3889	61	15174
Buhari	0.14	14	0.76	76	24	2434	194	19351
Kiraro	0.31	7	3.60	82	99	2239	819	18605
Magarama	0.24	9	1.55	57	118	4388	758	28065
Total	**5.56**		**59.34**		**1122**		**31621**	
Average		**11**		**87**		**2570**		**40759**

By estimation 5 $tP.yr^{-1}$ of SRP are transported into Lake Kivu through rivers in Kibuye with an areal specific load of 11 $kgP.km^{-2}.yr^{-1}$. The same, 59 $tP.yr^{-1}$ with a specific load of 87 $kgP.km^{-2}.yr^{-1}$, 1122 $tSi.yr^{-1}$ with a specific load of 2570 $kgSi.km^{-2}.yr^{-1}$ and 31621 t $particles.yr^{-1}$ with a specific load of 40759 kg $particles.km^{-2}.yr^{-1}$ respectively of TP, DSi and TSS are deposited annually into Lake Kivu across rivers in Kibuye catchment.

3.5. Nutrients mean concentrations in rivers

Table 6 presents the mean annual nutrient concentrations DIN, SRP, TP, DSi and TSS concentrations for eight rivers analysed in Kibuye catchment of Lake Kivu.

Table 6: Mean annual concentrations of nitrogen, phosphorus, dissolved silica and Total suspended solids in rivers

	DIN in µg.l^{-1}			SRP in µg.l^{-1} of P			TP in µg.l^{-1} P			DSi in mgl^{-1}			TSS g.l^{-1}		
Sites	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**
Nyabahanga	18.1	2024	718	0.6	112	30	39	570	144	3.49	9.5	7.2	0.01	1.00	0.17
Musogora	26.8	1575	729	6.0	308	68	61	663	213	2.19	10.0	6.6	0.04	0.27	0.14
Muregeya	57.7	2067	911	7.6	66	22	93	5384	863	1.58	8.1	4.9	0.02	0.33	0.13
Koko	83.1	1549	675	1.9	53	22	86	971	341	0.30	11.9	6.1	0.04	0.41	0.18
Gisayo	134.1	1675	912	1.9	247	47	36	1694	392	1.76	16.7	11.0	0.01	0.16	0.05
Buhari	135.7	1575	873	0.4	194	41	15	555	224	0.89	10.8	6.3	0.00	0.20	0.04
Kiraro	118.8	1445	670	1.9	158	27	25	563	203	0.40	11.8	6.1	0.01	0.12	0.04
Magarama	75.1	622	380	4.8	152	36	39	971	190	0.58	14.0	8.4	0.01	0.16	0.06
Average			**734**			**36**			**321**			**7.1**			**0.10**

Used abbreviations: Dissolved Inorganic Nitrogen (DIN as ammonium, nitrite and as nitrate), Soluble Reactive Phosphorus (SRP), Dissolved Silica (DSi), Total Phosphorus (TP) and Total Suspended Solids (TSS).

As shown on the table 7, the mean annual concentration of DIN is of 734 µgN.l^{-1}. The mean concentration of SRP is of 36 µg.l^{-1}, mean total phosphorus concentration of 321 µgP.l^{-1}, mean DSi concentration of 7.1 mgSi.l^{-1} and 0.1 g.l^{-1}of TSS.

4. Discussions of Results

4.1. River flow

The flow varies with time, season and catchment area. The high values are found in rainy season and the low water levels are found in dry season. All sampled rivers take source in Congo Nile crest which divides Rwanda water body in two parts. The rainy season in the region starts with March and ends in May. As shown on table 1 the highest discharging river is Koko and the lowest is Gisayo that is explained by their catchment areas.

From the flow measurements we may say that flow is directly proportional to the catchment area.
According to the classification of rivers based on discharge characteristics, rivers Gisayo is a brook, Buhari, Kiraro, Magarama, Nyabahanga and Musogora are considered as small streams while Muregeya and Koko are streams (Chapman, 1996). As shown by the standard deviation, it should be noted that there is a high variation of the flow throughout the year.

4.2. Nutrients loads

Ammonia nitrogen : As shown on figure 3 (a), the river discharging more ammonia nitrogen is Muregeya located in North of Kibuye. In total about 16 $tN.yr^{-1}$ of ammonia nitrogen are deposited into Lake Kivu across rivers corresponding to the areal specific load of 27 $kgN.km^{-2}.yr^{-1}$ (Table 4). Comparing seasons, the high quantity of ammonia nitrogen is found in rainy season in which about 1.5 $tN.month^{-1}$ are deposited into Lake Kivu to areal specific load of 2.4 $kgN.km^{-2}.month^{-1}$ while in dry season it is estimated the deposit of about 0.8 $tN.month^{-1}$ to areal specific load 1.8 kg $N.km^{-2}.month^{-1}$.

Moreover the seasonal ammonia nitrogen variations in some rivers showed high specific load in dry season probably due to high atmospheric inputs as observed in Lake Tanganyika riverine inputs (Nahimana et *al*., 2000**)**.

The average concentration in ammonia nitrogen within rivers fluctuates between 17 $\mu g.l^{-1}$ for Kiraro and 91 $\mu g.l^{-1}$ for Gisayo the remaining rivers are in this interval of concentration. Gisayo collect situated near Kibuye City, may be polluted by waste water discharge as its catchment is densely populated (Muvundja et *al*., 2009 and WHO, 2003).

Ammonia nitrogen arises in water body from the breakdown of organic and inorganic matter in soil and water, excretion by biota, reduction of nitrogen gas in water by microorganisms and from gas exchange with the atmosphere, it can come also from municipal or community waste. It has been reported that ammonia is toxic to fresh water organisms at concentrations ranging from 0.53 to 22.8 $mg.l^{-1}$ (Chapman, 1996).

Considering the monthly specific load of river it is observed that the river in Kibuye catchment have almost the similarities except Muregeya and Koko (figure 3(a)).

Nitrate and nitrite nitrogen loads: As shown in figure 3(b) in the rivers, nitrate-nitrogen is the most important nitrogen flux. The river in north of Kibuye transport more nitrate compared to south rivers of Kibuye; this is explained by their catchment area as shown on table 1. The land cover dominated by intensive agricultural activities with inorganic nitrogen fertilizers use should be the main source of nitrate nitrogen into river. The mean annual nitrate nitrogen load of 259 $tN.yr^{-1}$ or a specific load of 374 $kgN.km^{-2}.yr^{-1}$ is deposited into Lake Kivu through rivers in Kibuye catchment (table 4).

The variation of nitrate monthly specific load with seasons is also notable, the highest loads are observed in rainy season (figure 3(b)). This shows that nitrate specific loads are linked to different intensity of agricultural land use and are transported by surface runoff.
The nitrite nitrogen load is less than 1% of DIN load (sum of NH_4^+-N and NO_3-N)

The concentration in NO_2-N is very low compared NH_4^+ and NO_3^- and ranges between 4 to 19$\mu g.l^{-1}$. It is explained by the fact that nitrite is an intermediate oxidation state and readily oxidizes to nitrate in natural waters (US Geological survey, 2000). Therefore, we can remove nitrite nitrogen load in calculations of nutrients external inputs into Lake Kivu.

With an annual average concentration of 50 $\mu g.l^{-1}$ of NH_4-N, ammonia nitrogen contributes to about 5.9% nutrient inputs into Lake Kivu while the remaining percentage of 94% is due to NO_3-N. The mean annual NO_3-N concentration of 675 $\mu g.l^{-1}$ is high and tends to stimulate algal growth and indicate possible eutrophic conditions as this concentration exceeds 200 $\mu g.l^{-1}$ NO_3-N (Chapman et *al*., 1996).

Phosphorus loads in rivers: The results of SRP and TP show that the mean annual concentrations are respectively 36 $\mu.l^{-1}$ PO_4-P and 321 $\mu g.l^{-1}$ PO_4-P (table 5). The ratio TP: SRP of about 9:1 shows that a big quantity of phosphorus is in form of particulate phosphorus while organic phosphorus is low (Muvundja et *al*., 2009). Phosphorus is an essential nutrient for living organisms in water body. It is also generally the limiting nutrient for algal growth and, therefore controls the primary productivity of a water body.

As shown in the figure 4 (a) comparing seasons, the highest SRP load is observed in the dry season and should due to the biomass burning and intensive agricultural activities in river wetlands (Langenberg et *al*., 2003, Bootsma et *al*., 1996). For TP the high load is observed in rainy season the dilution does not affect the P load (figure 4(b)). The relatively high load of TP observed in rainy season (9 t $P.km^{-2}.month^{-1}$) may be influenced by domestic sewage and ground water discharge. Domestic sewage is a very important source of phosphorus for shallow groundwater and surface water (Taminskas et *al*., 2007).

The rivers in North sub-catchment Kibuye contain more phosphorus as they are located in a catchment characterized by intensive agriculture activities. A total budget of 5.5 $tP.yr^{-1}$ or $11kgP.km^{-2}.yr^{-1}$ of SRP are deposited into Lake Kivu by rivers in Kibuye catchment whereas 59 t $P.yr^{-1}$ or 87 kg $P.km2.yr^{-1}$ of total phosphorus are set down into lake across rivers (table 5).

Considering the molar ratio of DIN and SRP (Table 6) it was observed for DIN: SRP a ratio 20:1, as a result phosphorus is limiting nutrient of primary production from external nutrient inputs across rivers in Kibuye catchment as found in Muvundja (2009).

Dissolved silica loads (DSi): The dissolved silica concentration ranged from approximately 5 $mg.l^{-1}$ to 11 $mg.l^{-1}$. Temporal trends in silica of river water showed seasonal dependence similar to other studies (Muylaert et *al.,* 2009). The silica is transported to rivers via groundwater. In both groundwater and rivers, the concentration of silica is controlled by the solubility and seasonal recharge. Silica solubility increases with increased water temperature.

As shown (table 5), it was observed an increase of DSi load with catchment area in North of Kibuye (from Nyabahanga to Koko) and in south from Gisayo to Magarama this is explained by the fact that the primary source of dissolved silica in natural waters is the chemical breakdown of silicate minerals in rock and sediments by chemical weathering processes (Muylaert et *al*., 2009). But considering the monthly specific load it is observed that all rivers have a specific load ranging between (148-398) $kgSi.km^{-2}.month^{-1}$ and (137-353) $kgSi.km^{-2}.month^{-1}$ respectively in dry season and in rain season. All rivers in Kibuye catchment of Lake Kivu have almost similar chemical properties.

The total budgets of 1122 $tSi.yr^{-1}$ or 2570 $kgSi.km^{-2}.yr^{-1}$of DSi are deposited into Lake Kivu. The variation of DSi load with season shows the highest values in rainy season (figure 5) this shows that the dilution by rainy water does not affect the DSi load.

The DSi in Kibuye rivers should come from weathering of silicate minerals and the human activities in which small amount of metasilicate are used in detergents and fertilizers. The recent estimates have shown that anthropogenic Si inputs may amount to 6% of total Si inputs in a river (Muylaert et *al*., 2009).

Fluctuations in suspended solids: The concentration of total suspended solids in rivers of Kibuye ranged between 41 $mg.l^{-1}$ for Kiraro to 180 $mg.l^{-1}$ in Koko. The concentration in TSS increases as a function of river basin (figure 6). Particles are derived by sheet, bank and gully erosion in the watershed and by the resuspension of particles deposited in the river bed. Rates of erosion are associated with climate, particularly the amount and intensity of rainfall, and can be modified by vegetative cover. Deforestation or increased intensive agriculture results in large increases in erosion. On the overall characteristics of the watershed, the peak in suspended sediment may, or may not, occur at the same time as the peak discharge (Chapman, 1996).

A total budget of 31621 $t.yr^{-1}$ of TSS is estimated to enter the Lake Kivu through 8 rivers in Kibuye basin with a specific load of 40759 $kg.km^{-2}.yr^{-1}$ (table 5). This may due to deforestation, intensive agricultural activities within the catchment as 91% Rwandan active population earned their living directly or indirectly from agriculture (RADA, 2009). The brick making, mining and sand extraction activities in Koko, Magarama, Kiraro, Nyabahanga, Musogora and Muregeya rivers as observed on the ground, contribute to the increase of TSS.

In this study, the high TSS levels are reached in rainy season as shown on figure 6. This suggests that runoff water contributes a significant proportion of these constituents into the river systems.

TSS in lake lead to fish gills clogging, either killing them or reducing their growth rate. They also reduce light penetration. This reduces the ability of algae to produce food and oxygen. When the water slows down, as when it enters a reservoir, the suspended sediment settles out and drops to the bottom. This causes the water to clear, but as sediment settles it may change the bottom. The silt may smother bottom-dwelling organisms, cover breeding areas, and smother eggs (US Geological Survey, 2000).

Nutrients loads through atmospheric depositions: Nutrients in wet deposition are high compared to dry deposition this is on contrary to what was found in Lake Victoria (Tamatamah et *al.,* 2005). This should due to the geomorphology of Lake Kivu area and other parameters like wind direction and temperature. The average results for wet deposition are shown in table 2 and for dry deposition in table 3. The most predominant nutrient in wet deposition is ammonia nitrogen. Nitrate and SRP are in low concentration while silica and nitrite are negligible in wet deposition.

The nutrients load contributions from atmospheric deposition was estimated to all Lake Kivu surface area. As shown on table 2 and table 3 a total budget of 1492 $tN.yr^{-1}$ and 1988 $tN.yr^{-1}$ of ammonia nitrogen are deposited into Lake respectively by dry deposition and wet deposition. Ammonia is high compared to other nutrients in atmospheric deposition for unknown reasons. Dissolved silica load is negligible in dry deposition as normally it comes from weathering processes. The presence of DSi in wet deposition should come from dust transport by wind. The total phosphorus load in dry deposition was 156 $tP.yr^{-1}$; SRP load while in the dry deposition was estimated to 50 $tP.yr^{-1}$. The dry deposition input is composed by 30% of bio available phosphorus contrary to what found in Lake Victoria where 70-75 % of dry deposition inputs is bio available phosphorus (Tamatah et *al*., 2005).

It was noticed that nutrient loads in wet depositions are high in comparison to the dry deposition for nitrate nitrogen, dissolved silica, SRP and NH_4-N except for NO_2-N in which the inverse case occurred (table 2 and table 3). The TP was not measured in wet deposition. The NH_4-N load in atmospheric deposition is greater than NO_3-N load contrary to the findings in Lake Malawi where the inverse case occurred (Bootsma et *al*., 1999). This should be assessed in further studies.

5. Conclusions and Recommendations

This study deals with estimation of riverine and atmospheric nutrient inputs of nitrogen, phosphorus and silica into the Lake Kivu which would serve as a database and contribution to those researchers interested in studying the chemistry and production of the dissolved gases found into the Lake Kivu.

Considering the molar ratios of riverine nutrient inputs (Si:DIN:SRP=10:20:1) in this study, the limiting nutrient for the primary productivity in external riverine inputs of Kibuye catchment into Lake Kivu is phosphorus.

The most important nutrient in riverine inputs is NO_3-N and DSi whereas in atmospheric deposition is NH_4-N.

A total budget of 276 $tN.yr^{-1}$ of DIN (Ammonia-Nitrogen and Nitrate-Nitrogen) with a specific load of $404kgN.km^{-2}.yr^{-1}$, $5.5tP.yr^{-1}$ of SRP with a specific load of 11kg.km^{-2}.yr^{-1}, 59 tP.yr^{-1} of TP with a specific load of 87kgP.km^{-2}.yr^{-1}, 1122 tSi.yr^{-1} with a specific load of 2570 kgSi.km^{-2}.yr^{-1} and 31620 t particles.yr^{-1} or a specific load of 40759kgTSS.km^{-2}.yr^{-1} are deposited into Lake Kivu by rivers in Kibuye catchment.

The contributions of dry and wet deposition are respectively 1638tN.yr^{-1}and 2176tN.yr^{-1} of DIN (NH_4-N, NO_3-N and NO_2-N) to the whole lake surface area. It was observed that NO_2-N is negligible in atmospheric deposition and riverine inputs while DSi predominates in riverine inputs and negligible in atmospheric depositions. 99.6% of external NH_4-N inputs come from atmospheric depositions and 45% external NO_3-N inputs is crossing rivers sampled in Kibuye catchment of Lake Kivu. 100% of TSS (31621 t.yr^{-1} of particles) is fully supplied by riverine inputs in Kibuye catchment of Lake Kivu while TSS was negligible in atmospheric depositions.

For all nutrients analysed (in Kibuye Rivers and atmospheric deposition to the whole Lake Kivu area), external nutrients inputs contribute 100%, 16%, 9% and 8% respectively for NO_3-N, NH_4-N, SRP and DSi. The major part of nutrients is generated by internal loadings. In conclusion the recent increase of gas methane reported in last 30 years in Lake Kivu is not attributed to external nutrient inputs due to the growing human population as suggested (Schmid et *al*., 2004).

The extension of this study by covering the remaining rivers inflowing into the Lake Kivu (Rwanda and DRC side) and by settling sufficient centres for atmospheric deposition collection in south and north of Lake Kivu is necessary for obtaining an overview of all Lake Kivu catchment. A regular monitoring of flow discharge in order to have sufficient hydrological data is also recommended.

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