River geochemistry, chemical weathering, and atmospheric CO₂ consumption rates in the Virunga Volcanic Province (East Africa)

Charles M. Balagizi¹,²,³, François Darchambeau², Steven Bouillon⁴, Mathieu M. Yalire¹, Thibault Lambert², and Alberto V. Borges²

¹Geochemistry and Environmental Department, Goma Volcano Observatory, Goma, RD Congo, ²Chemical Oceanography Unit, Université de Liège, Liège, Belgium, ³Department of Environmental, Biological and Pharmaceutical Sciences and Technologies, Second University of Naples, Caserta, Italy, ⁴Department of Earth and Environmental Sciences, Katholieke Universiteit Leuven, Leuven-Heverlee, Belgium

Abstract We report a water chemistry data set from 13 rivers of the Virunga Volcanic Province (VVP) (Democratic Republic of Congo), sampled between December 2010 and February 2013. Most parameters showed no pronounced seasonal variation, whereas their spatial variation suggests a strong control by lithology, soil type, slope, and vegetation. High total suspended matter (289–1467 mg L⁻¹) was recorded in rivers in the Lake Kivu catchment, indicating high soil erodibility, partly as a consequence of deforestation and farming activities. Dissolved and particulate organic carbon (DOC and POC) were lower in rivers from lava fields, and higher in nonvolcanic subcatchments. Stable carbon isotope signatures (δ¹³C) of POC and DOC mean δ¹³C of −22.5‰ and −23.5‰, respectively, are the first data to be reported for the highland of the Congo River basin and showed a much higher C4 contribution than in lowland areas. Rivers of the VVP were net sources of CH₄ to the atmosphere (4–5052 nmol L⁻¹) was recorded in rivers in the Lake Kivu catchment, indicating high soil erodibility, partly as a consequence of deforestation and farming activities. Dissolved and particulate organic carbon (DOC and POC) were lower in rivers from lava fields, and higher in nonvolcanic subcatchments. Stable carbon isotope signatures (δ¹³C) of POC and DOC mean δ¹³C of −22.5‰ and −23.5‰, respectively, are the first data to be reported for the highland of the Congo River basin and showed a much higher C4 contribution than in lowland areas. Rivers of the VVP were net sources of CH₄ to the atmosphere (4–5052 nmol L⁻¹). Most rivers show N₂O concentrations close to equilibrium, but some rivers showed high N₂O concentrations related to denitrification in groundwaters. δ¹³C signatures of dissolved inorganic carbon suggested magmatic CO₂ inputs to aquifers/soil, which could have contributed to increase basalt weathering rates. This magmatic CO₂-mediated basalt weathering strongly contributed to the high major cation concentrations and total alkalinity. Thus, chemical weathering (39.0–2779.9 t km⁻² yr⁻¹) and atmospheric CO₂ consumption (0.4–37.0 × 10⁶ mol km⁻² yr⁻¹) rates were higher than previously reported in the literature for basaltic terrains.

1. Introduction

Rivers transport dissolved and particulate matter from land to the oceans. Part of the solutes transported by rivers are derived from chemical weathering processes in the catchment that is a function of local lithology, climate, and topography [Ludwig et al., 1996; Gaillardet et al., 1999; Hartmann et al., 2014]. Part of the particulate load is derived from mechanical weathering. The terrestrial biosphere and in particular soils provide particulate (POC) and dissolved (DOC) organic carbon to rivers. Groundwaters carry the products of aerobic and anaerobic mineralization in soils toward the river network, and along with mineralization of POC and DOC within the river system, this typically leads to large emissions of greenhouse gases (GHGs) such as carbon dioxide (CO₂) [Raymond et al., 2013; Lauerwald et al., 2015; Borges et al., 2015] and methane (CH₄) [Bastviken et al., 2011; Borges et al., 2015]. Anthropogenic inputs of nitrogen from fertilizers or wastewater can lead to high N₂O emissions from rivers to the atmosphere that are commonly attributed to denitrification [Beaulieu et al., 2010a; Baulch et al., 2011; Marwick et al., 2014]. Nitrogen-poor rivers on the other hand have low N₂O levels [Baulch et al., 2011; Borges et al., 2015].

The annual global CH₄ emissions to the atmosphere between 2000 and 2009 have been estimated at ~548 Tg CH₄ yr⁻¹; of which 218 Tg CH₄ yr⁻¹ were from natural sources and 335 Tg CH₄ yr⁻¹ from anthropogenic sources [Kirschke et al., 2013]. Of the fluxes from natural sources, 175 Tg CH₄ yr⁻¹ were from natural wetlands and 43 Tg CH₄ yr⁻¹ from other natural sources, i.e., freshwater, geological processes, oceans, wild animals, wildfire, and termites [Pison et al., 2009; Bousquet et al., 2011; Beck et al., 2012; Fraser et al., 2013]. Approximately 49% of the global CH₄ emissions from freshwater ecosystems is thought to occur in the tropics [Bastviken et al., 2011].

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Raymond et al. [2013] provided global CO₂ evasion rates of 1.8 Pg C yr⁻¹ from streams and rivers, and 0.3 Pg C yr⁻¹ from lakes and reservoirs which is highly significant when compared to the land biosphere and oceanic carbon sink of 2.0 Pg C yr⁻¹, respectively [Le Quéré et al., 2014]. The emission from rivers and streams has been recently revised downward to <0.7 Pg C yr⁻¹ by Lauerwald et al. [2015]. Yet in both these studies, the CO₂ data distribution in rivers and streams is skewed toward temperate and boreal systems in the Northern Hemisphere, while little data are available at tropical latitudes. There has been a growing number of studies of GHG fluxes in African rivers [Koné et al., 2010; Bouillon et al., 2009; 2012, 2014; Mann et al., 2014; Marwick et al., 2014; Teodoru et al., 2015], that combined with new data have contributed to evaluate for the first time the emissions of GHGs from inland water at the African continental scale [Borges et al., 2015]. The CO₂ and CH₄ emissions from African inland waters were found to be significant at both regional and global scales, totaling 0.4 Pg C yr⁻¹ for river channels alone, and 0.9 Pg C yr⁻¹ for river channels and wetlands of the Congo [Borges et al., 2015].

Volcanic fields are characterized by dry gas emissions which dissolve in the near-surface groundwaters and could thus contribute to the regional aquatic C pool. Despite this distinctive feature, streams and rivers of volcanic zones are still under-investigated for GHG evasion estimates. Volcanic terrains also act as an atmospheric C sink through chemical weathering. Thus, chemical and physical weathering is an important part of many elements cycles. On a global scale, atmospheric CO₂ consumption by chemical weathering leads to the storage of 237–288 Mt C yr⁻¹ in surface waters and the oceans [Amiotte-Suchet and Probst, 1995; Amiotte-Suchet et al., 2003; Gaillardet et al., 1999; Munhoven, 2002; Hartmann et al., 2009; Moon et al., 2014]. About 63% of this global estimate is due to silicate weathering [Hartmann et al., 2009]. Basalt weathering represents 30–35% of CO₂ sequestered by silicate weathering [Gaillardet et al., 1999; Dessert et al., 2003], although basalts correspond to only 4–6% of the global continent area [Meybeck, 1987; Amiotte-Suchet et al., 2003; Hartmann et al., 2009]. Given the large quantity of sequestrated C and the subsequently significant role on climate regulation, more studies are needed to improve the quantification of chemical weathering and CO₂ consumption in basaltic formations. Investigating weathering rates in basaltic terrains at the regional scale contributes to reduce uncertainties in the modeling of the global atmospheric CO₂ consumption rate.

This study focuses on the geochemistry of rivers of the Virunga Volcanic Province (VVP) (Figure 1), characterized by high volcanic activity, located in a tropical climate zone, and with a dense hydrographic network, but which remains poorly studied from a geochemical point of view. We concentrated on the geochemical characterization of the major rivers of the VVP by: (1) quantifying concentrations of nutrients, major cations, organic and inorganic carbon and their stable carbon isotope composition (δ¹³C); (2) the quantification of riverine CH₄ and N₂O concentrations and (3) the estimation of spatial variations of these parameters. We additionally quantified solutes and suspended material fluxes, the chemical weathering rates and the associated atmospheric CO₂ consumption during basalt weathering. Finally, the dependence at regional scale of chemical weathering on climatic factors (temperature and runoff) was discussed.

2. Study Area

2.1. Geological and Hydrological Settings

The VVP is located in the western branch of the East African Rift and is bounded on the north by Lake Edward, on the south by Lake Kivu, the Rwandan dorsal on the east and the Mitumba Range on the west (Figure 1). Virunga volcanic activity started during the mid-Miocene [Pouclet, 1977] and consists of eight major volcanic edifices perpendicularly aligned to the position of the rift. Most edifices are dormant except Mount Nyiragongo (4370 m) and Mount Nyamulagira (3058 m), both located in the Democratic Republic of the Congo (DRC) and are the Africa’s most active volcanoes. The edges of the rift are difficult to detect due to intense erosion, important vegetation cover and frequent lava flows [Smet, 2007] especially in the east. Nearly all the Virunga lavas are of alkalic to highly alkalic composition (Table 1), the alkalic character varies from a relatively sodic pole [Na₂O > K₂O] to a potassic or hyperpotassic pole [K₂O ≫ Na₂O]. The VVP consists of plains, shelf, and mountain ranges with altitudes of 900 m in the basin of Lake Edward and 1460 m in the Lake Kivu basin. The highest point is the Mount Karisimbi summit at 4508 m (Figure 1). The alluvial plain extends over the south basin of Lake Edward (i.e., lacustrine of Figure 2b), and then steadily rises up toward the Nyamulagira and Nyiragongo lava flows (i.e., basalt/volcanic ash of Figure 2b). The boundary...
Figure 1. Map of the Virunga Volcanic Province (VVP) showing the sampling sites. Eight of the 13 sampled rivers drain into the Kabuno bay (a subbasin of Lake Kivu), i.e., Mubimbi (Mb), Kisheke (Kl), Renga (Re), Mukoni (Mk), Muzungu (Mz), Kihira (Kh), Kamutoni (Ka), and Chabiringa (Cha). The five others rivers drain into Lake Edward catchment, i.e., Rwankwi (Rk), Ndata (Nd), Rangira (Ra), Rwahambi (Rw), and Ngwenda (Ng). The blue lines represent the hydrographic network by BEGo (Synoptics, Keyobs, Royal Museum for Central Africa, Catholic University of Louvain) [2005]. The map also shows the six dormant volcanoes of the Virunga, i.e., Mikeno (Mi), Karisimbi (K), Visoke (V), Sabinyo (S), Gahinga (G), and Muhabura (Mu) while Nyiragongo and Nyamulagira are still active. The black lines in the inset map display the boundaries of the East African Rift System.
between the Lake Edward and Lake Kivu watersheds is located on the line connecting the Nyamulagira-Nyiragongo-Karisimbi volcanoes (W to E oriented line; Figure 1). This boundary also corresponds to the limit between the Congo River basin to the south and the Nile River in the North. The mountain climate that marks the region is controlled by the nearby equatorial forest of the Virunga National Park and the mountain range. Precipitation is estimated at 1400–1500 mm yr\(^{-1}\) \cite{Muvundja et al., 2009}, and the mean annual temperature at \(24.8^\circ\)C. The region experiences a long wet season (September–May) and a dry season (June–August), with a short occasional dry season from mid-January to February. Lake Kivu (1460 m) and the hundreds of tributaries dominate the hydrography in the south of Virunga. The center and the north consist of a river network that feeds the Rutshuru River which flows into Lake Edward.

2.2. Soil Type and Land Uses

Three classes of soil are distinguished in the VVP (Figure 2a). The first lies on the area of presently active volcanoes and is composed of umbric and mollic andosols; the second covers the area of extinct volcanoes and composed of mollic andosols. The third consist of soil of alluvial and metamorphic rocks parent materials, formed by luvic phaeozems, haplic acrosols, and mumic cambisols (Figure 2a). The soils of presently active volcanic areas contain a thin humus layer covering lava flows on which mosses and lichens grow. A thick and slightly compact and humus-rich soil has developed on old lava flows; while the soil of the alluvial plain derives from sedimentary deposits. Local people practice traditional agriculture and livestock but an important area of the Virunga area is part of the Virunga National Park. No chemical fertilizers are used in the region. The lack of agricultural management on lands with steep slopes and the significant deforestation have generated substantial soil movements. They mainly include soil erosion and landslides, particularly in the mountainous watershed of Lake Kivu. The region is experiencing significant urbanization due to rural exodus triggered by repeated wars, causing Goma and the other small cities to host 4.2% of the population of the North Kivu province \cite{Document stratégique de réduction de la pauvreté (DSRP), 2005}.

3. Materials and Methods

3.1. Sampling Techniques

We carried out monthly sampling on 13 rivers in the VVP (all located in the DRC) from December 2010 to February 2013; eight are located in the Kabuno bay basin (a subbasin of Lake Kivu) while the five others drain into Lake Edward (Figure 1). Temperature, specific conductivity, pH, and dissolved oxygen (%O\(_2\)) were measured in situ with a Hanna (Hi 9828) multiparameter probe between December 2010 and December 2011.
Figure 2. (a) Map of the major dominant soil groups, (b) lithology, (c) biomass, and (d) organic carbon distribution in the Virunga Volcanic Province.
and with an YSI ProPlus probe for the rest of the measurement period. The same calibration procedures were applied for both probes ensuring data continuity. Calibration of the pH electrode was carried out the evening prior to field measurements using pH 7.00 and pH 10.00 (25°C) standard buffers. The oxygen probes were calibrated with humidity-saturated ambient air in the field. Precision of conductivity, water temperature, pH, and \( \%O_2 \) was estimated to 1 \( \mu \)S/cm, 0.1°C, 0.01 pH units, and 0.5\%, respectively. Water for the analysis of dissolved gases (CH\(_4\) and N\(_2\)O) was collected in two glass serum bottles of 50 mL and poisoned with 200 \( \mu \)L of a saturated HgCl\(_2\) solution, and sealed with butyl stoppers and aluminum caps. Samples for the measurement of the carbon isotopic composition in the dissolved inorganic carbon (\( \delta^{13}C\)-DIC) were stored in 12 mL Extainer vials and preserved with 100 \( \mu \)L of saturated HgCl\(_2\) solution. Water for total alkalinity (TA), major elements, dissolved organic carbon (DOC), and its \( \delta^{13}C \) signature was filtered through a 0.2 \( \mu \)m pore size polysulfone syringe filters, after prefiltration on 0.7 \( \mu \)m glass fiber filters. TA samples were collected in 50 mL high-density polyethylene bottles, 20 mL scintillation vials were used for major ions and preserved with 50 \( \mu \)L of HNO\(_3\) 65\%, while samples for DOC and \( \delta^{13}C\)DOC were collected in 50 mL Supelco glass bottles with polytetrafluoroethylene-coated septa, and preserved with 50 \( \mu \)L concentrated H\(_2\)PO\(_4\). Samples for total suspended matter (TSM), particulate organic carbon (POC) and its \( \delta^{13}C \) signature, and for particulate nitrogen (PN) were obtained by filtering a known volume of water (between 700 and 1700 mL depending on the turbidity of the river) through Macherey-Nagel GF-5 precombusted (5 h at 500°C) glass fiber filters. Two 50 mL plastic bottles were filled with water from the Macherey-Nagel GF-5 filtration, preserved with 200 \( \mu \)L of H\(_2\)SO\(_4\), 4 \( \mu \)L for nitrites (NO\(_3^-\)), nitrites (NO\(_2^-\)), ammonium (NH\(_4^+\)), and soluble reactive phosphorus (SRP) determination. For total phosphorus (TP) determination, a 50 mL plastic bottle was filled with unfiltered water and preserved with 200 \( \mu \)L of 4 \( N \) H\(_2\)SO.

### 3.2. Analytical Techniques

Concentrations of CH\(_4\) and N\(_2\)O were determined by gas chromatography (GC) with flame ionization detection (FID) coupled to a Hayesep N column was used for CH\(_4\) measurements, while an Electron Capture Detector (ECD) coupled to a Hayesep D column was used for N\(_2\)O measurements. The two detectors were calibrated at the start and end of each series with certified gas mixtures of 1, 10, and 30 \( \mu \)atm of CH\(_4\) and 0.2, 2, and 6 \( \mu \)atm of N\(_2\)O (Air Liquide Belgium). The overall precision of measurements was \( \pm 3.9\% \) and \( \pm 3.2\% \) for CH\(_4\) and N\(_2\)O, respectively [Borges et al., 2015]. Concentrations of dissolved CH\(_4\) and N\(_2\)O were calculated based on the partial pressure of the gas, its volume in the headspace and the water volume according to standard procedures by Weiss [1981]. \( \delta^{13}C\)-DIC was analyzed using an elemental analyzer-isotope ratio mass spectrometer (EA-IRMS, Thermo Flash EA/HT and DeltaV Advantage). First, a 2 mL Helium headspace was created in the sample which was then acidified with H\(_2\)PO\(_4\) and equilibrated overnight. A subsample from the headspace was injected into the EA-IRMS, and data were corrected for isotopic fractionation between dissolved and gaseous CO\(_2\) as described by Gillikin and Bouillon [2007]. Measurements were calibrated with LSVEC and either NBS-19 or IAEA-CO-1 reference materials. The reproducibility of \( \delta^{13}C\)-DIC measurement was typically better than \( \pm 0.2\%_{\text{iso}} \). TA was determined by Gran titration method with 0.1 M HCl as titrant using an automated titrator (Metrohm 725 Dosimat) equipped with a pH probe (ORION 8102 SC). Data were quality checked with certified reference material obtained from Andrew Dickinson ( Scripps Institution of Oceanography, University of California, San Diego, USA). Typical reproducibility of TA measurements was better than \( \pm 3 \mu \)mol L\(^{-1}\). For DOC and \( \delta^{13}C\)DOC analysis, 9–15 mL of sample were analyzed using a wet oxidation DOC analyzer (Thermo Hiper TOC or Aurora 1030W) coupled to an IRMS (Delta +XL or Delta V Advantage), calibrated with IAEA-C6 and an internal sucrose standard (\( \delta^{13}C = -26.99 \pm 0.04\%_{\text{iso}} \)) calibrated against international reference materials. Reproducibility of \( \delta^{13}C\)-DOC was typically better than \( \pm 0.2\%_{\text{iso}} \) and relative standard deviation for DOC concentration measurement was always below \( \pm 5\% \). Major elements were measured with inductively coupled plasma mass spectrometry (ICP-MS; Agilent 7700x) calibrated with the following standards: SRM1640a from National Institute of Standards and Technology, TM-27.3 (lot 0412) and TMRain-04 (lot 0913) from Environment Canada, and SPS-SW2 Batch 130 from Spectrapure Standard. Limit of quantification was 0.5 \( \mu \)mol L\(^{-1}\) for Na\(^+\), Mg\(^{2+}\), and Ca\(^{2+}\), 1.0 \( \mu \)mol L\(^{-1}\) for K\(^+\) and 8 \( \mu \)mol L\(^{-1}\) for Si. TSM values were obtained as the ratio of sediment load to the filtered water volume, the sediment load being determined as the net weight of sediment collected on the precombusted GF-5 filters, after redrying, with a precision of \( \pm 0.2\% \). To measure the POC, \( \delta^{13}C\)-POC and particulate nitrogen (PN), a cutout of 11 mm diameter was made in the GF-5 filter, carbonates were removed by exposure to concentrated HCl.
fumes for at least 4 h, and these were redried and packed in Ag cups. Calibration of $\delta^{13}$C-POC, $\delta^{15}$N-PN, POC, and PN measurements was performed with acetaldehyde ($\delta^{13}$C = $-27.65 \pm 0.05^{\circ}$, $\delta^{15}$N = $1.34 \pm 0.04^{\circ}$) and leucine ($\delta^{13}$C = $-13.47 \pm 0.07^{\circ}$, $\delta^{15}$N = $0.92 \pm 0.06^{\circ}$) as standards. All standards were internally calibrated against the international standard IAEA-C6 and IAEA-N1. Reproducibility of $\delta^{13}$C-POC and $\delta^{15}$N-PN measurement was typically better than $\pm 0.2^{\circ}$, and relative standard deviation for POC and PN measurement was always below 5%. Nutrients (NO$_3^-$, NO$_2^-$, NH$_4^+$, SRP, and TP) analysis was performed using a GENESIS 20 single beam spectrophotometer, according to standard colorimetric protocols following Rodier and Bazin (2005) and American Public Health Association (1998). The detection limits were 0.3, 0.03, and 0.15 $\mu$mol L$^{-1}$ for NH$_4^+$, NO$_3^-$, and NO$_2^-$, respectively.

3.3. GIS Analysis and Discharge Estimation

SRTM DEM (Shuttle Radar Topography Mission-Digital Elevation Model) data sampled at 3 arc sec (~30 m) pixel size were used to generate the topographical map of the VVP (Figure 1). The SRTM DEM data were collected by the NASA, the USA National Geospatial-Intelligence Agency, and the German and Italian space agencies joint team. A full description of the SRTM DEM data can be found in Farr et al. (2007). Maps of the dominant major soil groups (Figure 2a) and organic carbon distribution (Figure 2d) were produced using data from the FAO SOTWIScif, ver. 1.0, a central Africa soil features described in Batjes (2008). The spatial distribution of the aboveground live woody biomass (Figure 2c) was extracted from the Pantropical National Level Carbon Stock Dataset for tropical countries [Baccini et al., 2008]. Land cover (supporting information Figure S1) data were extracted from the FAO GLCN2000 [Global Land Cover 2000 database, 2003] (Global Land Cover Network) database for Africa, which is at ~300 m resolution and described in Mayaux et al. [2004]. The hydrographic network (Lake and rivers) is taken from the Building Environment for the Gorilla’s [BEGo (Synoptics, Keyobs, Royal Museum for Central Africa, Catholic University of Louvain), 2005]. Lithology (Figure 2b) is based on the GLIM (Global lithological map) from Hartmann and Moosdorf [2012].

The drainage areas (supporting information Figure S2) were derived from a high-resolution DEM computed by the HydroSHEDS mapping product (http://hydrosheds.cr.usgs.gov/index.php) and using the ArcHydro 2.0 Toolbox for ArcGis 10.2 software. Monthly discharges (supporting information Data Set S1) were estimated using an approach based on DEM and local precipitation data. The DEM grid was used to successively extract flow direction and flow accumulation grids. The latter represents the number of upslope cells that flow into each cell, and thus can be used to derive stream networks. The flow accumulation grid was converted into an accumulated area grid by multiplying the flow accumulation grid by the DEM grid resolution (here 92.43 m$^2$). Then, multiplying the value of the accumulated area determined at the outlet of a basin by a value of precipitation results in a measure of accumulated runoff per unit of time. Average monthly precipitations (supporting information Data Set S1) for each basin are derived from the 1 km$^2$ resolution WorldClim Database [Hijmans et al., 2005]. A comparison of the results obtained using this approach with the data from 10 USGS gauges across the U.S.A. provided satisfactory results [Wieczorek, 2012].

3.4. Annual Load and Weathering Rate Estimation

Discharge-weighted mean concentrations were calculated in order to avoid dilution and evaporation effects on the annual loads and weathering rates. For a given parameter, the discharge-weighted mean concentration ($C_w$) was calculated as follows:

$$
C_w = \frac{\sum_{i=1}^{n} C_i \times Q_i}{\sum_{i=1}^{n} Q_i}
$$

where $C_i$ is the monthly measured concentration and $Q_i$ the calculated monthly discharge.

The estimated monthly discharges can be found in the supporting information. The annual load was then obtained by multiplying the discharge-weighted mean concentration ($C_w$) with the annual discharge. Following the same procedure, atmospheric CO$_2$ consumption rate was estimated from the discharge-weighted mean HCO$_3^-$ (TA) concentration, based on the assumption that HCO$_3^-$ is generated by silicate rock weathering, as confirmed by analysis of major element property-property plots (see hereafter). The mechanical weathering rate was estimated from discharge-weighted mean TSM concentration. The cationic weathering rate was estimated from the sum of major cations (TDS$_{cat} = \sum$ Ca, Mg, Na, and K). The chemical weathering rate was estimated from the total dissolved solid (TDS$_{cond}$), the latter calculated from specific
conductivity as described in Atekwana et al. [2004]. All fluxes and weathering rates are expressed on an aer-eal basis, i.e., by dividing the annual load with the river catchment area. Major cations concentrations were corrected for atmospheric inputs using data from Cuoco et al. [2012a] which studied rainwater chemistry in the VVP between 2004 and 2010. Only data from rain samples col-lected to the N-NE and the W-SW of Mt Nyiragongo were considered. Samples from Nyiragongo crater and surrounding were not considered as they were not included in the drainage basins of this study. Further-more, this area is impacted by the plume from Nyiragongo’s permanent lava lake, and would thus only re-present a source of error.

4. Results and Discussion

Most measured physicochemical and chemical features showed no well-defined seasonality (e.g., Figure 3 and supporting information Data Set S2). The mean temperature for each river throughout the study period ranged between 17 and 29.4°C (Figure 4a). Temperature was almost constant in Chabiringa and Kamutoni, while the other rivers showed a relative increase during dry season period, i.e., mid June to August. Shallow rivers showed important temperature fluctuations except for the Rwankwi which is supplied with high alti-tude water. No large DOC and POC increases were observed during the rising stage of runoff (mid-Septem-ber to October) after the dry season, in contrast to what was observed in very large rivers such as the Oubangi River in the Congo River basin or other large tropical rivers [Meybeck, 2005; Bouillon et al., 2012]. Thus, the POC/DOC, HCO$_3^-$/DOC, and POC/PN ratios showed only minor variations over time.

Given the general lack of marked seasonal variations, we principally focus on spatial variations of parame-ters. Mean concentrations of studied parameters are presented in Figures 4 and 6, the full database can be found in supporting information Data Set S2.
Figure 4. (a) Mean temperature, (b) nitrate, (c) ammonium, (d) nitrite, (e) soluble reactive phosphorus, (f) total phosphorus, (g) dissolved oxygen, (h) specific conductivity, (i) pH, and (j) total alkalinity in rivers of the Virunga Volcanic Province between December 2010 and February 2013. The gray and black bars represent rivers of Kabunu bay and Lake Edward catchment, respectively. The error bars represent one standard deviation.
Figure 5. (a) Relationships between total alkalinity (TA) and Si, (b) TA and calcium, (c) TA/Na\(^+\) and Ca\(^{2+}/\)Na\(^+\), (d) Mg\(^{2+}/\)Na\(^+\) and Ca\(^{2+}/\)Na\(^+\), (e) TA and \(\delta^{13}C\)DIC, and (f) TA/Na\(^+\) and \(\delta^{13}C\)DIC in rivers of the Virunga Volcanic Province between December 2010 and February 2013. The Na\(^+\) normalized plots show the composition fields for rivers draining different lithologies from a global compilation of the 60 largest rivers in the World [Gaillardet et al., 1999].
4.1. Spatial Variations in Nutrient Concentrations

Monthly NO$_3^-$ concentrations in the VVP rivers spanned a wide range (7–178 μmol L$^{-1}$), with large spatial variations (Figure 4b), and did not reach levels indicative of significant pollution or eutrophication. In parallel, the NH$_4^+$ and NO$_3^-$ (Figures 4c and 4d, respectively) remained below the ranges normally found in unpolluted rivers (18 and 1.2 μmol L$^{-1}$, respectively) [Meybeck, 1982, 1983a]. The observed variations in the NO$_3^-$, NH$_4^+$, and NO$_2^-$ concentrations were therefore of natural origin. On the other hand, mean SRP concentrations (Figure 4e) are higher compared to those of unpolluted rivers (10 μg L$^{-1}$) [Meybeck, 1982, 1993a], a discrepancy which could be related to a high degree of P mobilization during weathering of basaltic rocks (see below).

In rivers of the VVP, NH$_4^+$ represented between 1.5% and 11.9% of the total inorganic N pool, whereas NO$_3^-$ largely dominated and accounted for 87.9–98.3%. This might suggest the conversion of NH$_4^+$ into NO$_3^-$ through nitrification, leading to the dominance of NO$_3^-$ over NH$_4^+$. The TP mean (Figure 4f) were slightly correlated to the SRP ($r^2 = 0.54$) and to NO$_3^-$ ($r^2 = 0.33$). This implies the dominance of SRP in the P pool as SRP additionally represent >50% of TP in most rivers, and a possible common source for both P and N. In fact, P and N can be jointly mobilized from land runoff and groundwater.

Volcanic emissions are a possible source of nitrate and phosphate in active volcanic areas [Julley et al., 2008], and reach surface water through wet and dry deposits on the catchment. In the Virunga atmospheric inputs are important source of N and P, indeed Muvundja et al. [2009] found that total-N and total-P concentrations in atmospheric deposits were equal or larger than riverine values. P can also be produced in bio-available form (P$_4$O$_{10}$) when hot lava reacts with water [Vitousek, 2004]. Like many other elements, P is released during chemical weathering. In the Japanese archipelago, P-release from silica-dominated lithology is estimated at a rate of 1–390 kg km$^{-2}$ yr$^{-1}$ [Hartmann and Moosdorf, 2011]. Thus, even though P is a minor constituent of igneous rocks (mean from 0.42 to 1.55 wt % for the Virunga basalt; Table 1), volcanic products could be a minor source of P of VVP rivers.

Muvundja et al. [2009] reported nutrient data in Mukoni, Muzungu, Kihira, Chabiringa, and Kamutoni rivers during a monthly monitoring between October 2006 and July 2008. The SRP, Si, and TSM are comparable for both data sets. The higher NH$_4^+$ and TP values given by Muvundja et al. [2009] are possibly due to the difference in the sampling location, as they collected samples close to the mouth (near Kabuno bay) where contamination by wastewaters from villages along the course of the rivers may occur.

4.2. Major Cations and DIC Chemistry

Most rivers had mean O$_2$ concentrations near saturation, except Kamutoni and Chabiringa which were the most O$_2$-depleted waters, with means of 38.1% and 24.6%, respectively (Figure 4g), typical of high groundwater contributions as confirmed also by low temperature (Figure 4a) since they were sampled close to the resurgence points. The activity of the Nyamulagira seems to not influence temperatures of both rivers. The other rivers showed %O$_2$ > 60% which implies important water oxygenation, given the steep slopes and shallow depths. Rwankwi, Ndata, and Mubimbi showed lower temperature (mean of ~19°C) associated with their high altitude origin on Mt Mikeno of the Virunga Nation Park (Rwankwi and Ndata) and the Mitumba Range (Mubimbi) (Figure 1). Specific conductivity data allow us to define three groups of rivers in the VVP: (1) the low mineralized (<150 μS cm$^{-1}$), (2) moderately mineralized (200–800 μS cm$^{-1}$), and (3) highly mineralized rivers with >800 μS cm$^{-1}$ (Figure 4h).

The highly mineralized rivers, i.e., Kihira, Chabiringa, and Kamutoni are located on basaltic lithology in the field of active volcanoes, with a high major cation content and where the dominant cations are Na$^+$ > K$^+$ > Mg$^{2+}$ > Ca$^{2+}$ (Table 2). This is a result of the intense weathering of basalt, mediated by magmatic CO$_2$ and the subsequent release of major cations to groundwater. The high alkalic composition of Virunga basalt promotes the dominance of Na$^+$ and K$^+$ in the cation composition of Kihira, Chabiringa and Kamutoni.

The moderately mineralized rivers are located in the field of dormant volcanoes to the NE and on nonvolcanic fields to the west (Figure 2b), where eruptive materials (i.e., ash, volcanic plume) were frequently deposited especially during Nyiragongo and Nyamulagira eruptions. Rwankwi and Ndata to the North-East, Mukoni and Muzungu to the West have similar specific conductivities (616–682 μS cm$^{-1}$) despite their location on different lithologies. The North-Eastern and Western rivers had different dominant cations...
depending on the soil and the lithology of each watershed (Figures 2a and 2b). This highlights the secondary role of soil weathering to the river chemical composition in the VVP. Thus, Mukoni and Muzungu flowing on haplic acrisols (Figure 2a) were Na+ and Ca2+ dominated; followed by K+ and Mg2+ whose concentrations compete (Table 2). In contrast, Rwankwi and Ndata kept the K+/Na+ dominance related to the presence of extinct volcanoes in the catchments (Figure 2b). The low mineralized rivers are found on haplic acrisols to the West and luvic phaeozems to the North (Figure 2a) with the most diluted water at both extremities of the sampling zone, away from the influence of active volcanoes.

Mean pH varied from neutral to relatively acid or basic (6.4–8.1; Figure 4i). The mean TA ranged from low (<1.0 mmol L−1) to exceptionally high (>10.0 mmol L−1) values (Figure 4j). The TA was overall positively correlated to Si (Figure 5a), and showed a larger scatter as a function of Ca2+ (Figure 5b). This is indicative of a strong contribution of silicate rock weathering to TA (Figure 5a), and this is confirmed by the Na+ normalized plots (Figures 5c and 5d). Both TA/Na+ and Mg2+ /Na+ versus Ca2+/Na+ (Figures 5c and 5d, respectively) are aggregated to values close to those expected for silicate rock weathering based on the average values proposed by Gaillardet et al. [1999].

The rivers with a lithology dominated by acid metaphoric rocks (Mubimbi, Kisheke, Renga, Mukoni, and Muzungu) had a Ca2+/Na+ > 1, while the rivers with a lithology dominated by basalt/volcanic ash (i.e., Kihira, Chabiringa, Kamutoni, Rwankwi, Ndata, and Rangira; Figure 2b) were characterized by a Ca2+/Na+ < 1 and a TA/Na+ close to 3. A few rivers (Kihira, Rwankwi, and Ndata) had Ca2+/Na+ values lower than the envelope of silicate rock end-member proposed by Gaillardet et al. [1999] (Figure 5c). This is probably related to the fact that Gaillardet et al. [1999] reported the chemical composition of the 60 largest rivers in the World, hence, excluding low mineralized small rivers such as some of those studied here. Another reason could be the atypical strong dominance of Na in the Virunga basalt, and consequently in the major cation composition of the stream network. The Na-normalized Ca2+ and Mg2+ ratios are consistent with high dissolution of Ca and Mg-rich silicate minerals, such as clinopyroxenes, mostly formed of diopside (CaMgSi2O6) [Morimoto, 1989] and which have been identified in Nyiragongo’s basalt [Platz, 2002; Platz et al., 2004].

No consistent simple relationship was observed between TA and δ13C-DIC (Figure 5e), but the river with the highest TA/Na+ (Kisheke) was also characterized by the lowest δ13C-DIC values (Figure 5f). Silicate weathering leads to the formation of HCO3− that has the isotopic signature of the CO2 driving the weathering reaction. Since in freshwaters, DIC is usually dominated by HCO3−, especially in high TA systems, the δ13C-DIC is close to the one of HCO3−, hence of the CO2 initially involved in the dissolution of silicate rocks. Considering the evidence discussed above that silicate weathering is a strong contributor to TA in the region, the observed range of δ13C-DIC (between −10.7‰ and 0‰; Figure 6a) indicates that the CO2 driving silicate weathering was not derived from organic matter mineralized in soils. Indeed, DOC and POC have a δ13C signature ranging between −28‰ and −18‰ (Figures 6b and 6c, respectively). However, the range of river δ13C-DIC matches well with the range of δ13C of CO2 in volcanic gases reported by Deines [2002]. We thus conclude that the δ13C-DIC signatures are to a large extent influenced by volcanic CO2 dissolution in groundwaters and involved in silicate rock weathering. This pattern is quite different from those observed
Figure 6. (a) Mean values of $\delta^{13}$C$_{DIC}$, (b) $\delta^{13}$C$_{DOC}$, (c) $\delta^{13}$C$_{POC}$, (d) total suspended matter, (e) %POC, (f) particulate organic carbon, (g) dissolved organic carbon, (h) particulate organic nitrogen, (i) methane, and (j) nitrous oxide in rivers of the Virunga Volcanic Province between December 2010 and February 2013. The gray and black bars represent rivers of Kabuno bay catchment and those of Lake Edward catchment, respectively. The error bars represent one standard deviation.
in the lower Congo basin, where δ^{13}C-DIC values as low as $\sim -26\%_o$ are found in rivers where silicate weathering also dominates, but where the CO₂ driving silicate weathering is produced by mineralization of organic matter derived from C3 vegetation [Bouillon et al., 2014].

Silicate weathering also strongly affected the SRP distribution as shown by the highly significant correlation between SRP and dissolved Si (when the three headwater rivers Kihira, Chabiringa and Kamutoni are excluded) (Figure 8a). This is in line with the general link between P release and rock weathering [Hartmann et al., 2014].

4.3. Organic Matter Dynamics and Origin

Large differences in the TSM load were observed in the VVP rivers. Higher TSM (289–1467 mg L⁻¹) was found in rivers located in the west of Kabuno bay basin, i.e., in Mubimbi, Kisheke, Renga, Mukoni, Muzungu, and Kihira (Figure 6d). These are second-order rivers draining a basin where steep slopes (supporting information Data Set S2), combined with high rainfall and agricultural land use practices, result in high erosion rates. The TSM load of these rivers is characterized by a relatively low organic matter content (mean %POC < 9%, Figure 6e). The catchment of Kabuno bay is composed of haplic acrisols (Figure 2a) which are clay-enriched soils. The land is mainly used for farming (crops and pastures; supporting information Figure S1) which
promotes soil erosion. Chabiringa, Kamutoni, Rwankwi, Ndata, and Rangira showed the lowest TSM, with values ranging from 0.5 to 86.3 mg L$^{-1}$ (Figure 6d). These rivers flow on mollic andosols of volcanic parent material from the Nyamulagira and Mikeno volcanoes (Figure 2a), with shrubs or forest cover (supporting information Figure S1). Thus, the lower TSM observed in the rivers draining volcanic fields are a result of the lower sensitivity of volcanic rocks toward mechanical erosion processes. The TSM could however be potentially enriched in organic matter (%POC $>10$, e.g., in Kamutoni, Rwankwi, and Ndata; Figure 7a) from the dense vegetation cover. Ngwenda and Rwahambi flow on luvic phaeozems which are humic-rich and highly productive soils. The latter have favored the development of farming activities that generate high TSM with a low %POC (Figure 7a) found in Ngwenda and Rwahambi.

Most Virunga rivers have mean TSM and POC (Figure 6f) that are higher than main stem Congo River (26.3 mg/L for TSM, 1.7 mg/L for POC) [Coynel et al., 2005] or other large rivers [Meybeck, 1982; Spitzy and Leenheer, 1991; Martins and Probst, 1991]. Mean TSM loads in the VVP rivers draining mountainous catchments (128.3–270.4 mg L$^{-1}$) were also higher compared to volcanic mountainous rivers of Guadeloupe (11.8–56.2 mg L$^{-1}$) [Lloret et al., 2013]. Nevertheless, Guadeloupe rivers have mean TSM somewhat high than that of Virunga rivers draining basaltic field (1.3–29.8 mg L$^{-1}$). POC concentrations were extremely variable among rivers, while DOC showed lower spatial variability (Figure 6g). In the majority of rivers, POC dominated the organic C pool. Differences in the POC/DOC ratios can be explained by differences in soil type, soil leaching and/or erosion and the relief. Both lower mean DOC (<0.9 mg L$^{-1}$) and POC...
(<2.5 mg L⁻¹) were observed in rivers draining volcanic fields (Figure 2a). These rivers (i.e., Chabiringa, Kamutoni, Rwankwi, and Ndata rivers) are characterized by low terrestrial biomass (Figure 2c) and low organic C soil content (Figure 2d).

The total organic C (TOC = DOC + POC) generally increased as one moves away from the volcanic area toward the NE and W. Thus, the TOC was found to be 6 to ~20 times higher in the most remote rivers. While DOC has typically been suggested to be the dominant C pool in large tropical rivers [Meybeck, 1993b], C of rivers of the VVP was largely DIC dominated. This is due to the high rates of silicate weathering and magmatic CO₂ inputs. The DOC/DIC ratios were below those of rivers draining carbonate rocks (<0.2) [Meybeck, 2005].

There was no straightforward relationship between the riverine POC and DOC and the vegetation or soil organic carbon distribution in the catchments. For instance, Rwahambi had among the highest mean DOC, and yet was draining catchment of both low organic C soil (Figure 2d) and woody biomass (Figure 2c). In contrast, DOC/POC ratios were well correlated to TSM (Figure 7b), with ratios above 1 (dominance of the DOC in the TOC pool) in the headwater streams (e.g., Chabiringa and Kamutoni). DOC became dominant in more erosive and turbid systems as previously described in other studies [e.g., Meybeck, 1982; Ittekkot and Laane, 1991; Ralison et al., 2008; Bouillon et al., 2009]. Mean DOC, POC, and PN (Figure 6h) in the VVP rivers were almost similar to those reported by Lloret et al. [2013] for Guadeloupan rivers of volcanic fields (0.69–2.25, 0.98–6.70, 0.1–2.31 mg L⁻¹, respectively, for DOC, POC, and PN). Natural vegetation in the Virunga consists of a mixture of Hatch-Slack photosynthetic pathway plants (C4) and grasslands employing Calvin pathway (C3), with the former dominating in quantity [Still and Powell, 2010] (supporting information Figure S1). Agricultural practices have introduced both new C4 (e.g., maize, sorghum, sugar cane, etc.) and C3 (e.g., banana, potato, cassava, etc.) plants. Thus, Virunga riverine δ¹³C-DOC (Figure 6b) and δ¹³C-POC (Figure 6c) showed a mixed origin for organic C, from both C3 and C4: C3 plants have a typical δ¹³C of −26‰, while C4 plants show a δ¹³C of −12‰ (−10‰, −14‰) [Ehleringer, 1991]. We found however a slight dominance of C3-derived C to the riverine organic C pool, with mean δ¹³C-DOC and δ¹³C-POC of −23.5‰ and −22.5‰, respectively. There were no clear relationships between individual paired δ¹³C-DOC and δ¹³C-POC data, indicating both C pools were not closely coupled (Figure 7c). Literature data on the δ¹³C of riverine POC and DOC in the Congo Basin are only available for low-altitude regions [e.g., Mariotti et al., 1991, Spencer et al., 2012, Bouillon et al., 2012, 2014], and show much more limited C4 contributions than those found in Virunga highlands, with the majority of data ranging between −30‰ and −26‰.

As also reported in the lowland Congo [Bouillon et al., 2014], the δ¹³C-POC was positively correlated to TSM (Figure 7d) and might indicate higher sediment inputs in catchments where C4 vegetation (grassland) is more substantial. The negative relationship between %POC and TSM (Figure 7a) has been previously observed within a given catchment [Tamooh et al., 2012; Bouillon et al., 2014] or globally across catchments [Meybeck, 1982]. This pattern is typically driven by the combination of inputs from direct litter or organic-rich surface soil layers (high %POC-low TSM) and more soil-derived sediments (low %POC-high TSM).

4.4. CH₄ and N₂O

Virunga rivers were sources of methane to the atmosphere as most rivers of the world [Bastviken et al., 2011], the observed CH₄ concentrations (Figure 6i) were above atmospheric equilibrium (~2 nmol L⁻¹). Overall there was a positive relationship between CH₄ and POC (Figure 8b) driven by enhanced in situ CH₄ production fuelled by the availability of organic matter and the removal of both POC and CH₄ in groundwaters.

In contrast, only Chabiringa, Kamutoni, and Kihira were sources of N₂O to the atmosphere as they showed concentrations (Figure 6j) above the atmospheric equilibrium (~10 nmol L⁻¹). Two of these rivers (Chabiringa and Kamutoni) showed low CH₄ while the third (Kihira) had the highest CH₄ of all rivers sampled. Chabiringa and Kamutoni were sampled close to springs, and therefore have chemical characteristics close to those of groundwaters such as high TA, conductivity and major cation concentrations, and low pH, temperature, DOC, and POC concentrations. These rivers were also characterized by low NO₂⁻ and high N₂O which might be indicative of denitrification in the groundwaters. These features drive the positive correlation between N₂O and NO₂⁻ (Figure 8c) and the negative correlation between N₂O and %O₂ (Figure 8d). Chabiringa and Kamutoni were also characterized by lower CH₄ concentrations indicative of CH₄ removal by bacterial oxidation in the groundwaters [Borges et al., 2015].
Table 3. Estimated Annual TSM, POC, PON, DOC, Si, and Nutrient Fluxes in Rivers of the Virunga Volcanic Province

<table>
<thead>
<tr>
<th>River</th>
<th>TSM (10^3 t/yr)</th>
<th>POC (t/yr)</th>
<th>PON (t/yr)</th>
<th>DOC (t/yr)</th>
<th>Si (t/yr)</th>
<th>NO$_2$ (t/yr)</th>
<th>NO$_3$ (t/yr)</th>
<th>NH$_4$ (t/yr)</th>
<th>SRP (t/yr)</th>
<th>Total P (t/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mubimbi</td>
<td>20.79</td>
<td>793.33</td>
<td>60.38</td>
<td>290.56</td>
<td>1061.75</td>
<td>231.31</td>
<td>0.34</td>
<td>6.63</td>
<td>2.55</td>
<td>8.67</td>
</tr>
<tr>
<td>Kishke</td>
<td>1.47</td>
<td>121.56</td>
<td>9.03</td>
<td>15.23</td>
<td>196.87</td>
<td>29.43</td>
<td>0.03</td>
<td>0.48</td>
<td>0.64</td>
<td>2.37</td>
</tr>
<tr>
<td>Renga</td>
<td>13.10</td>
<td>661.38</td>
<td>46.96</td>
<td>162.07</td>
<td>1145.21</td>
<td>319.94</td>
<td>0.19</td>
<td>6.43</td>
<td>4.38</td>
<td>10.39</td>
</tr>
<tr>
<td>Mukoni</td>
<td>2.52</td>
<td>71.10</td>
<td>5.64</td>
<td>40.20</td>
<td>305.96</td>
<td>127.75</td>
<td>0.08</td>
<td>1.94</td>
<td>1.65</td>
<td>2.40</td>
</tr>
<tr>
<td>Muzungu</td>
<td>6.86</td>
<td>159.71</td>
<td>14.62</td>
<td>99.84</td>
<td>711.54</td>
<td>340.54</td>
<td>0.37</td>
<td>2.90</td>
<td>5.44</td>
<td>8.18</td>
</tr>
<tr>
<td>Kahira</td>
<td>15.06</td>
<td>411.68</td>
<td>36.01</td>
<td>70.77</td>
<td>1368.97</td>
<td>245.06</td>
<td>0.42</td>
<td>7.49</td>
<td>1.80</td>
<td>2.73</td>
</tr>
<tr>
<td>Chabiringa</td>
<td>0.04</td>
<td>3.20</td>
<td>0.35</td>
<td>20.22</td>
<td>752.99</td>
<td>49.59</td>
<td>0.27</td>
<td>1.47</td>
<td>1.08</td>
<td>0.64</td>
</tr>
<tr>
<td>Kamutoni</td>
<td>0.03</td>
<td>3.20</td>
<td>0.41</td>
<td>11.55</td>
<td>406.14</td>
<td>20.36</td>
<td>0.14</td>
<td>0.84</td>
<td>0.67</td>
<td>0.35</td>
</tr>
<tr>
<td>Rwankwi</td>
<td>1.76</td>
<td>196.10</td>
<td>16.37</td>
<td>107.42</td>
<td>4696.05</td>
<td>776.76</td>
<td>0.87</td>
<td>4.92</td>
<td>27.62</td>
<td>24.89</td>
</tr>
<tr>
<td>Ndata</td>
<td>0.74</td>
<td>138.19</td>
<td>10.11</td>
<td>51.96</td>
<td>1726.19</td>
<td>277.44</td>
<td>0.30</td>
<td>1.85</td>
<td>12.07</td>
<td>9.85</td>
</tr>
<tr>
<td>Rangira</td>
<td>56.17</td>
<td>4206.60</td>
<td>379.14</td>
<td>7437.30</td>
<td>23689.23</td>
<td>3651.04</td>
<td>6.49</td>
<td>92.32</td>
<td>96.75</td>
<td>90.73</td>
</tr>
<tr>
<td>Ngwenda</td>
<td>56.47</td>
<td>1737.54</td>
<td>163.21</td>
<td>687.11</td>
<td>2516.19</td>
<td>518.14</td>
<td>0.52</td>
<td>17.58</td>
<td>8.67</td>
<td>13.53</td>
</tr>
<tr>
<td>Rwahambi</td>
<td>28.11</td>
<td>356.82</td>
<td>39.71</td>
<td>431.45</td>
<td>970.14</td>
<td>153.30</td>
<td>0.39</td>
<td>3.85</td>
<td>3.15</td>
<td>3.97</td>
</tr>
<tr>
<td>Virunga total</td>
<td>203.12</td>
<td>8860.42</td>
<td>781.94</td>
<td>9425.68</td>
<td>39547.22</td>
<td>6740.68</td>
<td>10.42</td>
<td>148.69</td>
<td>166.67</td>
<td>178.32</td>
</tr>
</tbody>
</table>

Kihira was sampled downstream of a confluence, one river is from the west in the Mitumba range (Figure 1) and the other from the east. During the last three sampling campaigns, the two tributaries of Kihira were also sampled, and the eastern was found to bring in O$_2$-deficient water, of high specific conductivity, TA, CH$_4$, and N$_2$O. Except for CH$_4$, these previous parameters (%O$_2$, TA, and N$_2$O) showed similar patterns as Chabiringa and Kamutoni. The eastern tributary collects inflowing water containing CH$_4$ produced in a small swamp (supporting information Figure S1), which could explain the elevated CH$_4$ found in Kihira. In contrast, the western tributary brought almost the entire TSM and POC load, as a consequence of its mountainous origin in the Mitumba range and its course along a clayey and steep catchment.

As mentioned above, most rivers were only small sources of N$_2$O to the atmosphere, as observed in other near-pristine tropical rivers with low NO$_3$ and NH$_4^+$ [Bouillon et al., 2012; Borges et al., 2015] and unlike most nitrogen-enriched temperate rivers that have high N$_2$O concentrations [Beaulieu et al., 2010a, 2010b; Baulch et al., 2011]. The higher N$_2$O in Chabiringa, Kamutoni and Kihira were associated with high NO$_3$ and low NO$_2$ and O$_2$ (Figures 8c and 8d; respectively) that suggests active denitrification in the groundwaters. Such correlations between N$_2$O and NO$_3$ were also observed in some temperate rivers [Dong et al., 2004].

The CH$_4$ concentration of Virunga rivers (4—5052 nmol L$^{-1}$) have a broader range than previous data from African rivers such as Comoé, Bia, and Tanoé rivers in West Africa (50—870 nmol L$^{-1}$) [Koné et al., 2010], Tana river in Kenya (50—500 nmol L$^{-1}$) [Bouillon et al., 2009], the Oubangui river in Central Africa (50—300 nmol L$^{-1}$) [Bouillon et al., 2012], but similar to the Athi-Galana-Sabaki rivers in Kenya (2—6729 µmol L$^{-1}$) [Marwick et al., 2014], although for the latter the highest values were related to organic matter inputs from the city of Nairobi. CH$_4$ of rivers of the VVP were also characterized by higher values than the adjacent Lake Kivu were CH$_4$ in surface waters varied from 18 to 197 nmol L$^{-1}$ in the main basins of the lake and 89—303 in the Kabuno bay [Borges et al., 2011, 2012]. On the other hand, rivers of the VVP contain N$_2$O close to that observed in the Oubangui river [Bouillon et al., 2012] and the Athi-Galana-Sabaki rivers (18—198 nmol L$^{-1}$) [Marwick et al., 2014] but remain largely below concentrations normally found in temperate rivers where human activities have increased the DIN concentrations (see compilation by Zhang et al. [2010]).

4.5. Riverine Material Fluxes

Our estimated annual TSM, Si, NH$_4^+$, and SRP fluxes for Kihira (Table 3) are comparable with fluxes reported by Muvundja et al. [2009], except for the TP fluxes which were ~90 times higher in their study compared to our estimate. For Chabiringa-Kamutoni, the TSM and SRP annual fluxes are similar for both studies, but our mean TP flux is 48 times higher, and our NH$_4^+$ flux is 23 times lower. In Mukoni-Muzungu, our TSM, Si, NH$_4^+$, and SRP fluxes are 18, 10, 12, and 8 times higher, respectively, while their mean TP flux is 4 times higher. The observed dissimilarities in fluxes between the two studies are due to differences already discussed among TSM and nutrients concentrations, and are even more pronounced due to differences in the annual discharges used. Muvundja et al. [2009] estimated their annual discharge using the float method described in Harrelson et al. [1994], which assumes a steady and uniform flow and does not offset flood and low flow conditions. For rivers of mountainous catchments (e.g., Kabuno bay), such a method results in discharges with errors of 30% or greater [Bathurst, 1990].
The estimated mean TSM (198.0 t km\(^{-2}\) yr\(^{-1}\)) and POC (7.43 t km\(^{-2}\) yr\(^{-1}\)) yields of VVP rivers were much higher when compared to those of the Congo River (8.8 t km\(^{-2}\) yr\(^{-1}\) for TSM and 0.6 t km\(^{-2}\) yr\(^{-1}\) for POC) [Coyne et al., 2005], the Oubangui River (4.8–5.1 t km\(^{-2}\) yr\(^{-1}\) for TSM and ~0.3 t km\(^{-2}\) yr\(^{-1}\) for POC) [Coyne et al., 2005; Bouillon et al., 2012], and the world largest rivers (see compilation by Meybeck [1982], Spitz and Leenheer [1991], and Coyne et al. [2005]). The estimated mean DOC yields (3.11 t km\(^{-2}\) yr\(^{-1}\)) were similar to that of the Congo River (3.5 t km\(^{-2}\) yr\(^{-1}\)) [Coyne et al., 2005], but higher compared to the Oubangui River (1.1–1.4 t km\(^{-2}\) yr\(^{-1}\)) [Coyne et al., 2005; Bouillon et al., 2012].

The estimated DOC (0.74–6.19 t km\(^{-2}\) yr\(^{-1}\)) and POC (0.31–21.08 t km\(^{-2}\) yr\(^{-1}\)) yields in the VVP were almost in the same range with those reported for Guadeloupe volcanic islands [1.9–8.9 t km\(^{-2}\) yr\(^{-1}\) and 8.1–25.5 t km\(^{-2}\) yr\(^{-1}\), respectively, for DOC and POC] [Lloret et al., 2011, 2013]. This could partly be explained by two major similarities between the areas. First, both fields experience tropical wet season, and second; their organic C soil content are similar: 1–25% for Virunga and 10–15% for Guadeloupe [Lloret, 2010].

### 4.6. Weathering and Atmospheric CO\(_2\) Consumption Rates

The discharge-weighted mean TDS\(_{\text{scat}}\), TDS\(_{\text{scat}}\), and TSM yielded cationic weathering rates from 7.9 to 978.7 t km\(^{-2}\) yr\(^{-1}\), chemical weathering rates from 39.0 to 2779.9 t km\(^{-2}\) yr\(^{-1}\), and mechanical weathering rates between 2.5 and 474.5 t km\(^{-2}\) yr\(^{-1}\) (Table 4). The Si weathering rates and CO\(_2\) consumption rates ranged from 9.0 to 88.4 t km\(^{-2}\) yr\(^{-1}\), and 0.4 \times 10\(^6\) to 37.0 \times 10\(^6\) mol km\(^{-2}\) yr\(^{-1}\), respectively. Chemical weathering was more important in rivers draining basaltic fields, whereas mechanical weathering was prevailing in others lithological formations; i.e., acid metamorphic and lacustrine (Table 4). An opposite trend, with higher chemical than chemical weathering rates, has been observed in the tropical basaltic field of Réunion, [Louvat and Allègre, 1997]. The large influence of lithology on the chemical weathering and CO\(_2\) consumption rates in the Virunga is evident, and illustrated, for example, by comparing Chabiringa (basaltic terrain) with Ngwenda (lacustrine terrain). Thus, Chabiringa (drainage area of 8.5 km\(^2\)) showed the highest weathering (Si, cationic, and chemical) and CO\(_2\) consumption rates; whereas Ngwenda (231.8 km\(^2\) drainage area) showed the lowest. Similar trends are observed when comparing rivers draining basaltic terrain (i.e., Kihira, Chabiringa, Kamutoni, Rwankwi, and Ndata) with those of lacustrine and metamorphic rocks. As a result, the five rivers of basaltic terrain cover only 10.6% of the total studied drainage area, but are responsible for 23.4% of the total CO\(_2\) consumed, 22.6% of the total Si weathered, and 25.8% of the total major cations weathered. Basalt was characterized by a mean chemical weathering rate and mean CO\(_2\) consumption rate 2.87 and 2.88 times higher, respectively, compared to values in acid metamorphic rocks terrain; and 24.6 and 32.7 times higher than in lacustrine terrain.

Chemical weathering rates were found to depend strongly on runoff, since there were strong linear relationships between runoff and CO\(_2\) consumption rates ($r^2 = 0.63$; Figure 9a), cationic weathering rates ($r^2 = 0.62$; Figure 9b), and Si weathering rates ($r^2 = 0.66$; Figure 9c). In contrast, no positive temperature dependency

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**Table 4.** Drainage Areas, Climatic Settings, Mean Solute Concentrations and Rates for Rivers in the Virunga Volcanic Province

<table>
<thead>
<tr>
<th>Drainage Area (km(^2))</th>
<th>Runoff (mm/year)</th>
<th>T (°C)</th>
<th>CHO(_2) (mmol/L)</th>
<th>TSM (mg/L)</th>
<th>TDS(_{\text{scat}}) (mg/L)</th>
<th>TDS(_{\text{scat}}) (mg/L)</th>
<th>CO(_2) Consumption Rate (10(^6) mol km(^{-2}) yr(^{-1}))</th>
<th>Si Weathering Rate (t km(^{-2}) yr(^{-1}))</th>
<th>Chemical Weathering Rate (t km(^{-2}) yr(^{-1}))</th>
<th>Mechanical Weathering Rate (t km(^{-2}) yr(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mubimbi(^a)</td>
<td>55.7</td>
<td>1670</td>
<td>19.3</td>
<td>0.9</td>
<td>223.3</td>
<td>20.7</td>
<td>78.8</td>
<td>1.5</td>
<td>19.0</td>
<td>34.5</td>
</tr>
<tr>
<td>Kisheke(^a)</td>
<td>5.8</td>
<td>1508</td>
<td>20.5</td>
<td>3.2</td>
<td>168.6</td>
<td>65.0</td>
<td>214.0</td>
<td>4.9</td>
<td>34.1</td>
<td>98.0</td>
</tr>
<tr>
<td>Renga(^b)</td>
<td>43.6</td>
<td>1651</td>
<td>21.7</td>
<td>2.6</td>
<td>181.7</td>
<td>61.6</td>
<td>195.6</td>
<td>4.4</td>
<td>26.2</td>
<td>101.7</td>
</tr>
<tr>
<td>Mukoni(^b)</td>
<td>15.4</td>
<td>1119</td>
<td>22.5</td>
<td>5.2</td>
<td>146.0</td>
<td>118.6</td>
<td>384.9</td>
<td>5.8</td>
<td>19.8</td>
<td>132.8</td>
</tr>
<tr>
<td>Chabiringa(^b)</td>
<td>31.7</td>
<td>1559</td>
<td>20.3</td>
<td>10.9</td>
<td>304.4</td>
<td>275.2</td>
<td>808.1</td>
<td>17.0</td>
<td>43.1</td>
<td>428.9</td>
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<tr>
<td>Kamutoni(^b)</td>
<td>8.5</td>
<td>3326</td>
<td>17.1</td>
<td>111</td>
<td>294.3</td>
<td>835.9</td>
<td>37.0</td>
<td>88.4</td>
<td>978.7</td>
<td>2779.9</td>
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<tr>
<td>Rwankwi(^b)</td>
<td>10.2</td>
<td>1430</td>
<td>17.7</td>
<td>111</td>
<td>308.1</td>
<td>433.1</td>
<td>10.4</td>
<td>49.4</td>
<td>239.4</td>
<td>651.8</td>
</tr>
<tr>
<td>Mubimbi(^a)</td>
<td>95.0</td>
<td>1505</td>
<td>19.1</td>
<td>6.9</td>
<td>123.1</td>
<td>159.1</td>
<td>433.1</td>
<td>10.4</td>
<td>49.4</td>
<td>239.4</td>
</tr>
<tr>
<td>Ndata(^a)</td>
<td>70.5</td>
<td>829</td>
<td>19.4</td>
<td>6.7</td>
<td>127.1</td>
<td>149.6</td>
<td>398.0</td>
<td>5.6</td>
<td>24.5</td>
<td>124.0</td>
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<tr>
<td>Rangiri(^b)</td>
<td>1351.0</td>
<td>1313</td>
<td>20.4</td>
<td>4.0</td>
<td>317.8</td>
<td>83.5</td>
<td>250.3</td>
<td>5.2</td>
<td>17.5</td>
<td>109.6</td>
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<td>Ngwenda(^c)</td>
<td>231.8</td>
<td>1279</td>
<td>22.9</td>
<td>0.3</td>
<td>187.7</td>
<td>6.1</td>
<td>30.1</td>
<td>0.4</td>
<td>10.9</td>
<td>7.9</td>
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<tr>
<td>Rwambam(^a)</td>
<td>107.3</td>
<td>1120</td>
<td>21.6</td>
<td>0.6</td>
<td>233.8</td>
<td>16.6</td>
<td>55.5</td>
<td>0.7</td>
<td>9.0</td>
<td>18.6</td>
</tr>
</tbody>
</table>

\(^a\)Rivers draining basaltic formations.

\(^b\)Rivers draining acid metamorphic rock formations.

\(^c\)Rivers draining lacustrine formations.

\(^d\)Estimated runoff.
was found for either the CO$_2$ consumption rate (Figure 9d), cationic weathering rate (Figure 9e), and Si weathering rate (Figure 9f). In addition, no dependency on temperature was found for elements released during chemical weathering (Figures 9h and 9i), or for the HCO$_3^-$ ions which balance the major cation charge (Figure 9g), as previously noted by Amiotte-Suchet and Probst [1995] and Bluth and Kump [1994] in the French basaltic basins. Dessert et al. [2003] attributed this pattern to the relative similarity among temperatures of neighboring watersheds, and thus only the effect of runoff could be observed.

The mean CO$_2$ consumption rate estimated for the study area (9.46 \times 10^6 \text{ mol km}^{-2} \text{ yr}^{-1}, or 1.72 \times 10^7 \text{ mol km}^{-2} \text{ yr}^{-1} if only considering the basaltic fields is markedly higher than data reported in the literature for other tropical basaltic regions (Figure 10). On the other hand, the measured mean atmospheric C yield (113.68 \text{ t C km}^{-2} \text{ yr}^{-1}) is much higher than previous model estimates for the Virunga (0.5–5 \text{ t C km}^{-2} \text{ yr}^{-1}) [Hartmann et al., 2009]. Since the Virunga mean CO$_2$ consumption rate is >10 times the global average (1.99 \text{ t C km}^{-2} \text{ yr}^{-1}) [Hartmann et al., 2009], the VVP can thereby be considered as CO$_2$ consumption “hot spot zone” according to a classification by Meybeck et al. [2006].

Factors contributing to the high CO$_2$ consumption rates in the VVP include the high chemical weathering rate of volcanic rocks [Dessert et al., 2001], the high reactivity of basaltic glasses and minerals [Berner and Berner, 1996; Oelkers and Gislason, 2001; Gislason and Oelkers, 2003], and the high annual mean runoff (1613 mm yr$^{-1}$) and temperature (20.3°C).

Furthermore, the CO$_2$ consumption rates that can be calculated with the model of Dessert et al. [2003] based on a compilation of data in other basalt dominated areas are lower than those we computed (Figure 11).
Figure 10. Comparison of Virunga basalt mean and Virunga mean CO₂ consumption rates with the rates of other tropical basaltic provinces, and the Caribbean basalt-andesite formations. (a) represents the mean CO₂ consumption rate for the rivers draining Virunga basalt, (b) the mean CO₂ consumption rate for the whole Virunga, i.e., basalt, metamorphic rocks and lacustrine; (c) is from Dessert et al. [2003], (d) Schopka et al. [2011], (e) Louvat and Allègre [1997], (f) Rad et al. [2006], (g) Lloret et al. [2011], (h) Goldsmith et al. [2010], and (i) is from Louvat [1997].

Figure 11. Comparison between the CO₂ consumption rates from field data (measured) and calculated CO₂ consumption (calculated) rates applying the regression model as a function of runoff and temperature as suggested by Dessert et al. [2003].
This is indicative of the high solubility of the rocks in the watershed which is probably related to the fact that the VVP is a young active tectonic and volcanic area.

5. Conclusions

The present study offers the first geochemical data set from an under-documented area, in terms of river GHGs and major cations concentrations, DOC, POC, and DIC concentrations and their respective $\delta^{13}$C signatures, chemical weathering rates, and atmospheric $\text{CO}_2$ consumption rates. The VVP is a tropical, young active tectonic and volcanic area, relatively undisturbed by anthropogenic activities.

Our results showed that soil, land use, and morphology control the spatial distribution of riverine organic matter (POC and DOC concentrations and origin), TSM, and nutrient concentrations. The DIC was found to largely dominate the C pool. Intense soil erosion leads to high TSM yields in the mountainous rivers draining into Kabuno bay. Lithology and volcanism exert a strong control on the major cation and DIC concentrations, and their spatial distribution. Thus, high basalt (and secondary soil) chemical weathering and leaching mediated by magmatic $\text{CO}_2$ inputs yielded markedly high $\text{Na}^{+}$, $\text{K}^{+}$, $\text{Mg}^{2+}$, and $\text{Si}$; particularly in basaltic fields. $\text{CH}_4$ concentrations were consistently above atmospheric equilibrium, and thus Virunga rivers were sources of $\text{CH}_4$ to the atmosphere. In contrast, only a few rivers were a net source of $\text{N}_2\text{O}$ to the atmosphere, as denitrification in groundwaters depleted $\text{N}_2\text{O}$ concentrations below their atmospheric equilibrium levels in other rivers.

The multithorological state of the VVP highlights the strong influence of lithology on the chemical weathering rates, and the associated atmospheric $\text{CO}_2$ consumption rate under the same climatic conditions. In fact, we noticed that the mean chemical weathering rate and mean $\text{CO}_2$ consumption rate in basalt terrain were respectively $\sim 3$ higher compared to values in acid metamorphic rocks terrain; and $\sim 25$ and $\sim 33$ higher compared to lacustrine terrain. Our study additionally showed that runoff and lithology are the main factors controlling the rates of local chemical weathering and atmospheric $\text{CO}_2$ consumption rates. The $\delta^{13}$C-DIC data indicate that part of the $\text{CO}_2$ involved in chemical weathering is geogenic, and thus the active volcanism may partly explain the higher $\text{CO}_2$ consumption and weathering rates reported in this study compared to the literature data.

Note that much of the Virunga lava field is not drained by rivers. This zone is composed of macroporous materials, slightly fractured, and therefore considerably permeable. Rainfall is influenced by the Nyiragongo and Nyamulagira emissions and pH values as low as three have been recorded [Cuoco et al., 2012a, 2012b]. The precipitation interacts with surface and deep basalts, but the resulting atmospheric $\text{CO}_2$ consumption rate is not included in the data we report.

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