PRINT ISSN 1119-8362
Electronic ISSN 2659-1502

Full-text Available Online at
https://www.ajol.info/index.php/jasem
https://www.bioline.org.br/ja

J. Appl. Sci. Environ. Manage.
Vol. 28 (1) 253-262 January 2024

Impact of anthropogenic Pollution on Bujumbura Rivers: Toward Rivers and Lake Tanganyika Biodiversity Conservation, Burundi

***SIBOMANA, C; BUHUNGU, S; Ntakirutimana, D; Nahimana, D**

Center of Research in Natural and Environmental Sciences, Faculty of Sciences, University of Burundi, P. O. Box: 2700, Bujumbura, Burundi

**Corresponding Author Email: claver.sibomana@ub.edu.bi; Tel: +257 77947201*
Co-Authors Email: simon.buhungu@ub.edu.bi; dieudonne.ntakirutimana@ub.edu.bi; david.nahimana@ub.edu.bi

ABSTRACT: Despite its importance, Lake Tanganyika is threatened by pollution especially around Bujumbura, the largest city on its shores, leading to its biodiversity loss, habitat destruction and trophic system disturbance. Hence, the objective of this paper is to assess the impact of the anthropogenic pollution of Bujumbura on rivers using water quality physicochemical and macroinvertebrates community parameters. Four rivers were sampled and two stations, upstream and downstream the city were considered. EC, TDS, NH_4, NO_2^- and BOD5 show high values downstream at all rivers on one hand and NO_3^- except for Kanyosha on the other hand, while DO values significantly decreased downstream the rivers except for Kanyosha too. This indicates the increasing water pollution from upstream to downstream, what is consistent with the dominance of the pollution-tolerant Chironomidae and Lumbriculidae dowmnstream and high density of the pollution-sensitive taxa from the EPT orders upstream the rivers. The same trend was observed with the reduction in macroinvertebrates diversity as Shannon diversity and Pielou evenness indices are lower downstream than upstream. The canonical correspondence analysis showed that the pollution-sensitive Hydropsychidae and Simuliidae and DO are associated with upstream stations while pollution-tolerant Chironomidae high densities on one hand and higher nutrients' concentrations, TDS, EC and BOD5 on the other hand were associated with downstream stations.. This study indicates that rivers crossing Bujumbura have caused anthropogenic pollution thathas negatively affected rivers' ecosystem causing biodiversity loss, community simplification and water quality alteration. More facilities should be installed for sufficient wastewater treatment before it is discharged into rivers and Lake Tanganyika.

DOI: https://dx.doi.org/10.4314/jasem.v28i1.29

Cite this paper as: SIBOMANA, C; BUHUNGU, S; NTAKIRUTIMANA, D; NAHIMANA, D (2024). Impact of anthropogenic pollution on Bujumbura rivers: toward rivers and Lake Tanganyika biodiversity conservation, Burundi. *J. Appl. Sci. Environ. Manage.* 28 (1) 253-262

Dates: Received: 02 December 2023; Revised: 20 January 2024; Accepted: 21 January 2024 Published: 30 January 2024

Keywords: Lake Tanganyika; physicochemical characteristics; pollution; bioindicator; macroinvertebrates; rivers water quality

Lake Tanganyika is the longest lake in the world with a length of 673 km along its major axis and the second deepest lake in the world with a shoreline shared between 4 countries including Burundi (Hanek et al. 1993). It contains almost 17 % of the world's available freshwater, harbors outstanding biodiversity, and is one of the richest freshwater ecosystems in the world (Salzburger et al. 2014). The littoral zone of Lake Tanganyika contains one of the world's most diverse freshwater fauna and serves as a spawning site for pelagic fish species with socio-economic importance and a habitat for their larval and juvenile stages (Bootsma et al. 1996). In addition, millions of people around the lake rely on the lake for food, drinking water and livelihood. Despite its importance, Lake Tanganyika is threatened mainly by overfishing, deforestation, climate change and water pollution (West 2001; Odada et al. 2003; O'reilly et al. 2003;

**Corresponding Author Email: claver.sibomana@ub.edu.bi; Tel: +257 77947201*

Verburga and Hecky 2009, Phirri et al. 2023). Sources of pollution at its north end are concentrated around Bujumbura, the largest city on the lakeshore and major city of Burundi (Vandelannoote et al. 1996; Yu et al. 2018). Deforestation around the city increasing sediment discharge, fertilizers application, discharge of domestic and industrial sewage are the main drivers of pollution of rivers crossing Bujumbura (Chen and Kimirei 2015; Yu et al. 2018). These rivers ultimately discharge their waters into Lake Tanganyika causing pollution of its water especially in the littoral zone. This may cause loss of biodiversity, habitat destruction and trophic system disturbance (Cohen et al. 1993, Cohen et al 2005, Alin et al. 1999, Sibomana and Nduwayezu 2018). Recent studies indicated that the pollution in Bujumbura Rivers is increasing compared to previous studies (Vandelannoote et al. 1996; Yu et al., 2018; Buhungu et al. 2018; Buhungu et al. 2020). However, these studies were conducted either on one river with several sampling sites or main rivers but with only one sampling site per river and using only physicochemical parameters as pollution indicators. There is a need for the assessment of the impact of Bujumbura city with comprehensive methodology for better monitoring of pollution. The present study proposes to assess the pollution levels of the four rivers entering Bujumbura by using macroinvertebrates in conjunction with physicochemical methods. This has been considered the best approach for studies that measure water quality (Duran 2006). Macroinvertebrates are used as bioindicators for water quality assessment and can help detect polluted sites for water resources and biodiversity management (Gabriels et al. 2010).

Bujumbura is located in the western part of the country on the northeastern edge of Lake Tanganyika. Four main rivers, from north to south Kinyankonge, Ntahangwa, Muha, and Kanyosha, flow through the urban area into Lake Tanganyika. These rivers collect wastewater from residential areas, industrial discharges, agricultural runoffs, and untreated sewage that cause water pollution, thus threatening water supply on one hand, and rivers and Lake Tanganyika ecosystems functioning and biodiversity on the other hand. Hence, the objective of this paper is to assess the impact of the anthropogenic pollution of Bujumbura rivers using water quality physicochemical and macroinvertebrates community parameters for sustainable management of water resource and biodiversity of rivers and Lake Tanganyika.

METHODS AND METHODS

Study area: The study area is located in Bujumbura city, western Burundi at the northeastern tip of Lake Tanganyika. To determine the anthropogenic pollution levels of rivers of Bujumbura city, four main rivers crossing this city were sampled and two stations, one upstream and the other downstream, were considered at each river. These rivers are (in southward order): Kinyankonge, Ntahangwa, Muha and Kanyosha (Fig. 1). The upstream sites are near the entrance of the city where anthropogenic pollution is minimal except for Kinyankonge. Pollution upstream the rivers would be mainly caused by suspended solids and nutrients coming from soil erosion as most of the areas around the city are deforested and occupied by crop lands (Yu et al. 2018). The downstream sites are situated near Lake Tanganyika where the rivers carry pollutants from the city as they have different routes across the city, going through densely populated and/or industrial areas.

Sampling and laboratory processing: Samples were collected at each station twice a month; however, heavy rain prior to or on the same day did not allow sampling activities for some days at some stations. Sampling was carried out from December 12th, 2019 to September 11th, 2020, a period spanning both the wet and dry seasons.

Water samples were collected in the middle of the river using a bucket rinsed with water from the site (Varnosfaderany et al. 2010). They were transported in a cooler container to the laboratory and processed within 12 hours. Water velocity, depth, and width were measured at three equally-spaced points across the river, and averages were calculated (Herschy 1978). Temperature, pH, Dissolved Oxygen (DO), Electric Conductivity (EC) and Total Dissolved Solid (TDS) were measured in situ using a multi-parameter CONSORT C6010 whereas turbidity, NH_4^+, NO_2^-, NO_3^-, and PO_4^{3-} were measured in the laboratory using HACH DR/2800 spectrophotometer. The 5-days biological oxygen demand (BOD5) was measured using a Liebherr BOD analyzer. These analyses were carried out following the procedure of Rodier et al. (2009).

For macroinvertebrates, at each station, sampling was done using a kick-net of 500 µm mesh size and 10 drags of the net, each corresponding to a surface of 0.1 m², were carried out in different micro-habitats. Collected organisms were preserved in methanol 70% (Mandaville, 2002) and were taken to the laboratory for processing. Their identification was done in the laboratory using a stereoscope NIKON SMZ 745. The identification was done to the lowest possible taxonomic level using appropriate keys (Gerber and Gabriel 2002; Stals and De Moor, 2007; Tachet et al., 2010).

Data analysis: Macroinvertebrates community structure was determined using number of taxa, total number of individuals, relative abundance of each taxon overall and for each station, Shannon-Wiener diversity index (H') (Magurran 1988) and Pielou evenness index (H'/H'max) (Pielou 1975) at each station. The EPT/C index was calculated by dividing the sum of the total number of individuals classified as Ephemeroptera, Plecoptera, and Trichoptera (EPT) by the total number of individuals from the Chironomidae family. The ratio of pollution-intolerant taxa – Ephemeroptera+Plecoptera+Trichoptera (EPT) to Chironomidae is widely used as an indicator of disturbance to stream communities (Lenat and Crawford 1994). Comparison between upstream and downstream stations was performed for these data.

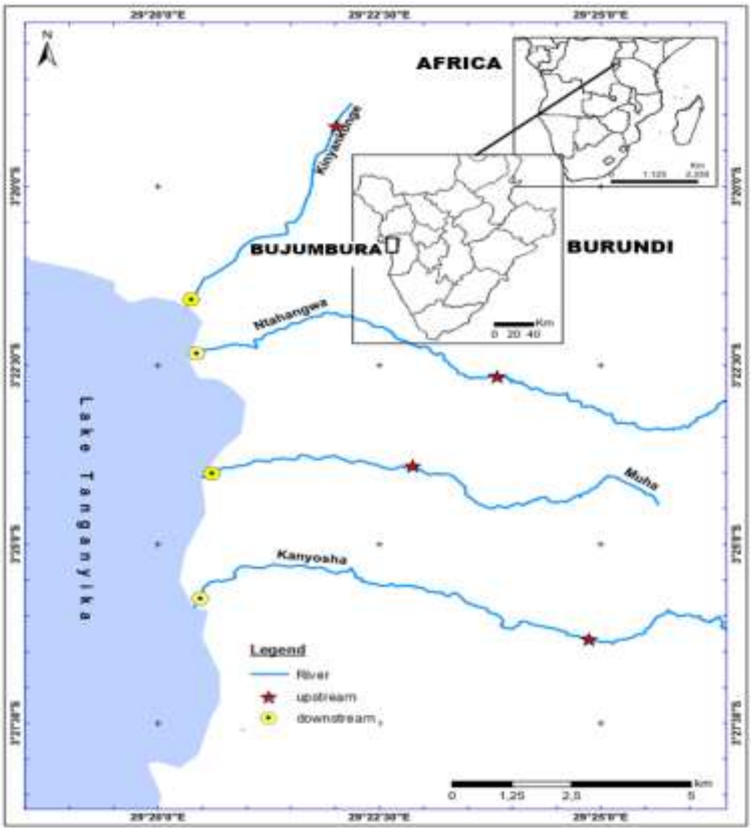

Fig. 1: Map showing the rivers and sampling stations in Bujumbura.

ANOVA for comparison of means for physicochemical parameters between stations at each river was performed using RStudio (version 1.2.5019) under R software version 4.0.2. (R Core Team 2020). Based on the mean values of selected variables at upstream and downstream stations, the actual water quality was assessed using the limits of a quality evaluation system developed in France for superficial waters (SEQ-Eau, 2003). Associations between macroinvertebrates community composition, physicochemical variables and sampling stations (upstream and downstream) were visualized and significance tested using ordination plots of a Canonical Correspondance Analysis (CCA) for each river separately using CANOCO 5 software (Lepš and Šmilauer 2003). Families with less than 10 individuals were removed from the analysis since rare species are often positioned as outliers in correspondence analysis ordinations (Greenacre 2013).

RESULTS AND DISCUSSION

Environmental characteristics and water quality: Kruskal-Wallis ANOVA indicates that some of the analyzed physicochemical parameters significantly differ upstream and downstream after the rivers have flowed through Bujumbura city with higher values downstream. These parameters are EC, TDS, NH_4^+, NO_2^- and BOD5 for all the rivers and NO_3- except for Kanyosha. On the other hand, for DO, values are significantly higher upstream the rivers except for Kanyosha (table 1). These results indicate that water quality is altered from upstream to downstream; similar results were found from previous studies that assessed the impacts of human activities and urbanization on rivers water quality with PO_4 and NO_2

in Ghana (Adiyiah et al. 2013), EC, DO, PO_4 in Ethiopia (Ambelu et al. 2013), EC, TDS, nitrogen ions, PO3+ and BOD5 in Cameroun (Tchakonté et al. 2015).

Table 1: Anova 1 summary for environmental parameters comparison between stations (Upstream and Downstream) at all rivers

	T°	pH	DO	EC	TDS	Turbidity	Velocity	NH_4^+	NO_2^-	NO_3^-	PO_4^{3-}	BOD5
Kinyankonge												
Sum Sq	5.64	1445	172.09	3450000	988843	44078	0.2715	82.38	0.027	5.52	0.00065	161280
Mean Sq	5.643	14446	172.09	3450000	988843	44078	0.27147	82.38	0.0271	5525	0.00065	161280
F value	1.256	9248	120	76.86	75.08	2043	5842	9925	13.27	4299	1065	11.76
p-value	0.273	**0.005**	**<0.0001**	**<0.0001**	**<0.0001**	0.166	**0.0227**	**0.00396**	**0.00113**	**0.0478**	0.312	**0.00196**
Kanyosha												
Sum Sq	1.19	0.0019	0.844	9578	3093	200078	2187	4501	0.02851	1508	0.00162	258.6
Mean Sq	1.193	0	0.8438	9578	3093	200078	21.866	4.501	0.0285	15.081	0.00162	258.62
F value	0	0	3.351	78.2	45.15	2.537	25	11	5.622	2.387	1.492	20.28
p-value	0.698	0.883	0.0807	**<0.0001**	**<0.0001**	0.13	**<0.0001**	**0.00326**	**0.0261**	0.135	0.234	**0.00015**
Muha												
Sum Sq	3.28	0.0009	1247	169927	46304	1049809	0.5096	6.17	0.09873	1050	0.00015	291.1
Mean Sq	3.284	0	12471	169927	46304	1049809	1	6.168	0.09873	10.500	0.1522	291.12
F value	1	0	11	65.77	66.23	9.024	4.982	4.606	10	2.558	1.623	6093
p-value	0.399	0.921	**0.00252**	**<0.0001**	**<0.0001**	**0.0102**	**0.0352**	**0.0422**	**0.00406**	0.123	0.215	**0.0211**
Ntahagwa												
Sum Sq	8.46	0.435	17862	70416	19107	127775	0.1713	8141	0.0971	1231	0.00166	1358
Mean Sq	8.459	0	17862	70416	19107	127775	0	8.141	0.09715	12.310	0.00166	1358
F value	2	10	75	307.1	228.1	3	2.589	6.813	5.816	3.287	1.683	23.18
p-value	0.208	**0.0034**	**<0.0001**	**<0.0001**	**<0.0001**	0.0825	0.12	**0.0148**	**0.0232**	0.0814	0.206	**<0.0001**

p-values showing significant differences (<0.05) are in bold.

Using the limits of a quality evaluation for surface waters (SEQ-eau 2003) and based on selected variables, table 2 shows that in general, change in BOD5 values from upstream to downstream the rivers shows that Bujumbura city causes the alteration of the water quality of all rivers either to "bad quality" or "very bad quality". Water quality has turned into "bad" downstream after the values showed tolerable water quality for NH4 upstream Ntahangwa and Kinyankonge rivers. At Kinyankonge River, most variables showed alteration of the water to bad or very bad quality downstream; temperature and ammonium (NH4) showed bad quality downstream while DO, TDS and BOD5 show very bad water quality of water. This assessment confirms the alteration of water quality with disturbing effect on the rivers' ecosystem function and household use.

Table 2: Mean ± SD of environmental parameters at studied sites and water quality assessment based on the French water quality system SEQ-Eau (2003). The colors yellow and red show "bad quality" and "very bad quality" respectively. The remaining values are within the ranges of very good, good, and tolerable limits

River	Site	Temp	pH	DO	EC	Turb	NH4	NO2	NO3	PO4	BOD5
Kanyosha	Up	23.05±2.1	7.09±0.3	7.30±0.3	37.21±6.4	95.48±51.4	0.52±0.4	0.06±0.04	0.34±0.3	0.004±0.0	8.08±3.3
	Dow	23.47±3.3	7.07±0.3	6.93±0.6	75.60±14.3	301±382.9	1.35±0.8	0.13±0.1	0.82±1.1	0.02±0.05	14.38±3.9
Muha	Up	25.0±2.0	8.10±0.3	7.26±0.3	133.76±31.2	83.98±130.2	0.68±0.6	0.06±0.05	0.43±0.5	0.001±0.0	10 ±5
	Dow	25.71±2.2	8.11±0.3	6.81±0.3	295.45±64.8	614.26±448.9	1.66±1.5	0.18±0.1	0.83±0.7	0.006±0.01	16.69±8.4
Ntahangwa	Up	22.79±2.2	7.61±0.2	7.51±0.5	83.80±11.7	116.35±65.1	1.01±0.9	0.05±0.04	0.55±0.6	0.006±0.0	11.79±5.4
	Dow	23.89±2.3	7.36±0.2	5.85±0.4	184.1±17.9	262.28±270.1	2.09±1.2	0.17±0.2	0.97±0.66	0.02±0.04	25.71±9.4
Kinyankonge	Up	26.36±2.6	7.38±0.4	5.82±1.5	222.40±89.7	170.53±80.9	1.18±0.9	0.05±0.03	0.53±0.9	0.01±0.02	11.43±6.0
	Dow	27.26±1.5	7.83±0.4	0.86±0.8	924.44±285.9	252.88±191.3	4.56±3.9	0.11±0.06	1.40±1.3	0.02±0.3	160.67±162.5

These results are consistent with findings of Yu et al. (2018) who indicate that rivers crossing Bujumbura city had higher values of water quality parameters than peri-urban and rural rivers. This study assessed water environmental variables downstream of 7 rivers tributaries to Lake Tanganyika in and around Bujumbura. Similar to our results which show that Kinyankonge river had higher pollution levels downstream, Yu et al. (2018) also found highest nutrients values and DO lowest value downstream. This increase in nutrients and depletion of dissolve oxygen endanger many aquatic species and would therefore reduce their diversity to only tolerant taxa.

Macroinvertebrates community

Macroinvertebrates abundance and biotic indices: A total of 19315 individuals of macroinvertebrates have been collected; they belong to 4 classes, 15 orders, 58 families, 84 identified genus and 120 species. Four orders, Arhynchobdellida, Rhynchobdellida, Lumbriculida and Haplotaxida belong to Class Clitellata, three orders, Caenogastropoda, Basommatophora and Architaenioglossa belong to the Class Gastropoda, the order Decapoda belongs to Class Custacea while the other orders belong to the Class Insecta. However, due to the lack of appropriate keys, identification could not be performed to genus and species level for some specimens. Among the 58 families, Chironomidae (64.9%), Baetidae (15.9%), Hydropsychidae (5.7%), Simuliidae (3.3%), Lumbriculidae (2.3%), Glossiphonidae (2.2%), Caenidae (1.3%) and Physidae (0.8%) are the most abundant. This macroinvertebrate community is highly dominated by Chironomidae family followed by Baetidae and Hydropsychidae; the latter are considered pollution-sensitive. Chironomidae are the dominant taxa in freshwater systems in general (Bass, 1986; Cohen, 1986, Kleine and Trivinho-Strixino 2005), although the presence of their larvae in large numbers may indicate environmental disturbance (Marques *et al.*, 1999). However, this disturbance needs to be assessed using information about collected taxa from this family and their relative tolerance to water pollution. Indeed, these Diptera are considered opportunistic organisms and tolerant to water pollution (Tachet et al., 2010; Colas et al., 2013; Milosevic et al., 2014) and can reach relatively high density (up to 25,000 ind./m2) (Armitage *et al.,* 1995). Results on other macroinvertebrates biotic indices also show discrepancies between upstream and downstream stations at all rivers. Chironomidae family individuals were present at all stations, however the high-pollution indicators Chironomus were dominant downstream while they were absent or much fewer upstream (table 3; table 4). On the other hand, the sensitive taxa EPT outweigh the tolerant Chironomidae upstream except for Kinyankonge River where more Chironomidae individuals have been collected at the two stations. However, the index is more than ten times higher upstream than downstream (table 3, Fig. 2). In addition, the organic pollution-tolerant Lumbriculidae are more abundant downstream at all rivers except for Muha where no Lumbriculidae individuals have been found at both stations (table 4). Therefore, this is a good proof of the degraded status of rivers downstream Bujumbura city. The proportions between EPT/Chironomidae can be a good indicator of pollution levels and macroinvertebrates community characteristics.

Table 3: EPT/*Chironomidae* biotic index at the sampled stations for the four rivers

River	Site	EPT	*Chironomidae*	EPT/Chir
Kanyosha	Upstream	963	129	7.465116
	Downstream	244	960	0.254167
Kinyankonge	Upstream	20	225	0.088889
	Downstream	4	584	0.006849
Muha	Upstream	1397	423	3.3026
	Downstream	152	925	0.164324
Ntahangwa	Upstream	1419	269	5.275093
	Downstream	28	8993	0.003114

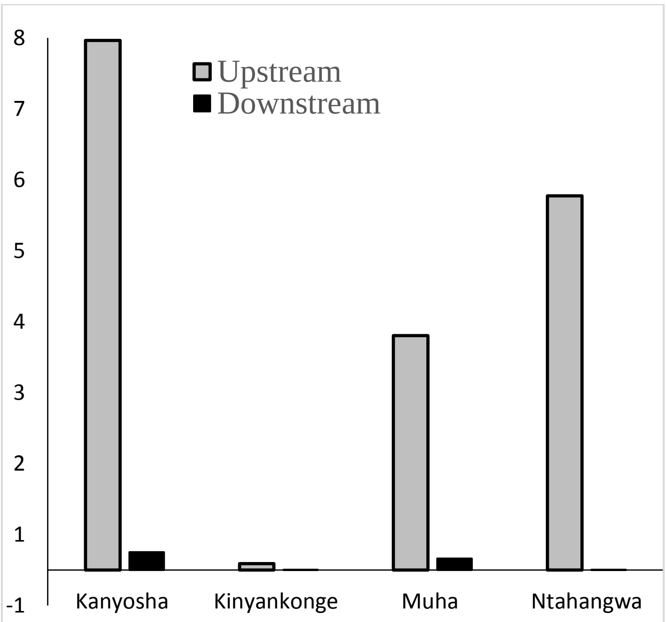

Fig. 2: Comparison of the EPT/*Chironomidae* biotic index between sampling stations and rivers

Table 4: Tolerant taxa metrics (number of individuals and ratio) of the sampled stations for the four rivers

River	Site	*Chironomidae*		*Lumbriculidae*	Chi-mus/ Chi-dae*
		Chimus*	Non-Chironomus		
Kanyosha	Upstream	8	121	0	0,06
	Downstream	366	594	8	0,38
Kinyankonge	Upstream	210	15	13	0,93
	Downstream	574	10	418	0,98
Muha	Upstream	0	423	0	0
	Downstream	669	256	0	0,72
Ntahangwa	Upstream	23	246	0	0,09
	Downstream	8670	323	10	0,96

**Chi-mus: Chironomus, Chi-dae: Chironomidae*

The differences between upstream and downstream the rivers observed with EPT richness, EPT/Chironomidae along with Chironomus/Chironomidae certainly reflect the pollution from the input of domestic and municipal effluents getting storm water and surface runoff into the rivers, leading to the reduction of EPT abundance and subsequently to dominance of Chironomidae downstream. This index has been used by other authors for water quality estimate (Resh and Jackson, 1993; Brabec *et al.,* 2004; Kleine and Trivinho-Strixino 2005). It is well known that urbanization affect aquatic ecosystems with the reduction in species richness especially the sensitive taxa which most often disappear following environmental disturbance (Song *et al.,* 2009; Xu *et al.,* 2013; Zhang *et al.,* 2013; Wang *et al.,* 2012). The distribution of Oligochatae from the family Lumbriculidae which are indicative of organic pollution showing higher richness downstream especially at Kinyankonge River confirms pollution of these lotic systems

Macroinvertebrates diversity: Shannon-Weiner diversity index shows a clear difference between upstream and downstream stations with higher values observed upstream for all studied rivers although there is a slight difference at Muha River. Therefore, upstream stations are more diverse than downstream stations. The Pielou evenness diversity index indicates the same trend with high values upstream than downstream for all rivers. For both diversity and evenness indices, 2 rivers, Kinyankonge and Ntahangwa, show a drastic reduction from upstream to downstream (Fig. 3). Biodiversity indices can be used to explain other ecosystem properties such as habitat heterogeneity, habitat complexity and disturbance (Pielou 1975). Connell (1978) suggested that species diversity is moderate in stable ecosystems, highest in intermediate and low in severely degraded ecosystems. The reduction in macroinvertebrates diversity observed downstream Bujumbura rivers is undoubtedly due to pollution. It coincided with the degradation of the water quality reflected in the change of physicochemical parameters and the lower numbers of pollution-sensitive taxa and higher number of pollution-tolerate taxa. This is consistent with results from studies that indicated that the polluted status of rivers crossing urban areas was associated with very poor benthic macroinvertebrates diversity in Kenya (Ndaruga et al. 2004), Cameroon (Nyamsi Tchatcho *et al.* 2014) and Nigeria (Emere and Nasiru 2009).

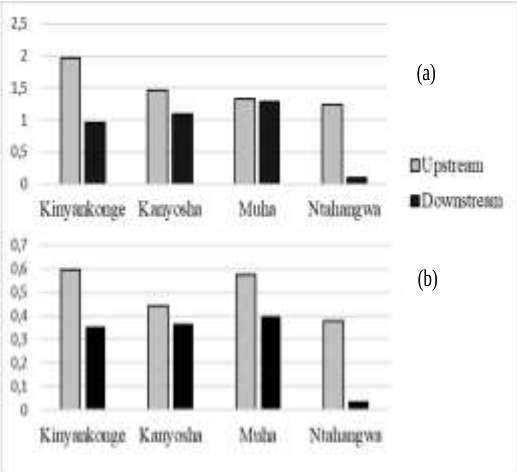

Fig. 3: Comparison of Shannon-Weiner diversity index (a) and Pielou evenness index (b) for macroinvertebrates community between sampling stations and rivers

Macroinvertebrates and environmental relationship: In the CCA results plots, environmental factors are identified by lines with arrows and the line length indicates the relationship between environmental variable and the taxa. Angles between lines and axes indicate the degree of correlation, with small angles indicating a higher correlation. This analysis is a direct gradient analysis which can simplify complex data sets and allows integrated analysis of both taxa and environmental data (TerBraak and Smilauer 2002). In general, axis 1 analysis shows that the distribution of the sampled macroinvertebrates families was found to be influenced by DO and velocity showing higher values upstream while BOD5, turbidity, TDS, EC and nutrients values seem to be greater downstream rivers. While Hydropsychidae and Simuliidae are found upstream at all rivers except for Kinyankonge where no Simuliidae were observed, no family seems to be common to downstream stations (Fig. 4, table 5).

Hydropsychidae are from the pollution-sensitive order Trichoptera, Simuliidae larvae are considered pollution-tolerant but some species can be found in moderately polluted water and even in pristine breeding sites (Docile et al. 2015). While the identification of collected specimens could not be done to the species level, we argue that Simuliidae species found upstream of the studied rivers could be in that category. At Kanyosha river, NO_2^-, EC, TDS, PO_4^{3-}, NH_4^+ and BOD5 are positively correlated to the downstream station, suggesting nutrients loading from the city. At Kinyankonge River, all environmental variables seem to be associated with downstream except for DO which is highly correlated with the upstream stations.

For Muha, fewer physicochemical parameters are associated with downstream station: TDS, EC, NO_2^-, and NH_4^+. At Ntahangwa river, the upstream station is associated with higher values of DO and pH while downstream site is positively correlated with TDS, EC, BOD5, turbidity and NH_4^+ (Fig. 4). The dominance by pollution-sensitive Diptera from Chironomus genus is consistent with the CCA ordination analysis which shows that higher DO concentration was associated with upstream less-impacted stations while the higher nutrients' concentrations, TDS, EC and BOD5 were associated with downstream stations at all rivers.

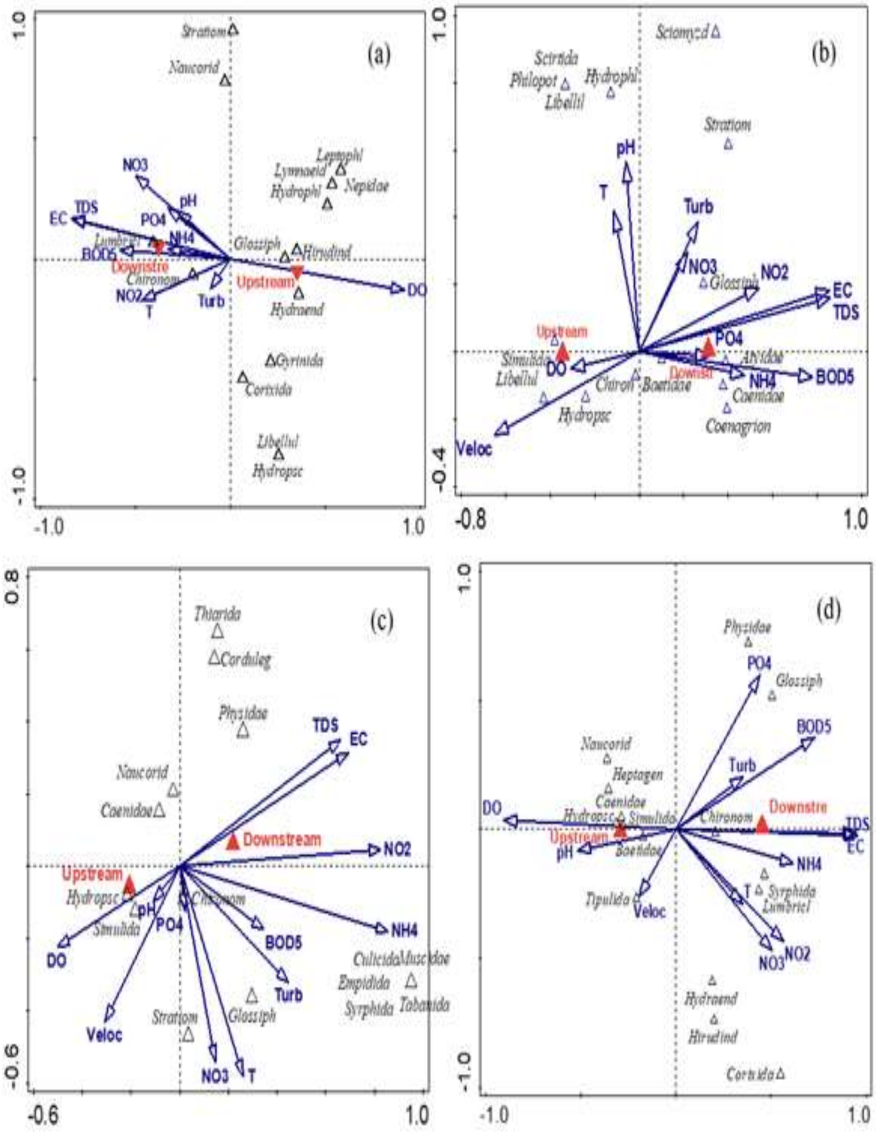

Fig. 4: CCA of the relationship between environmental variables and macroinvertebrates community composition at the 2 sampled stations of all rivers. Monte-Carlo test of all canonical axes is significant for all rivers, 1000 permutations.

Table 5: Statistics of the CCA of the relationship between environmental variables and macroinvertebrates community composition at the 2 sampled stations of all rivers.

Rivers	Eigenvalues		Explained variance		Biotic-environmental variables correlation		p-value
	Axis 1	Axis 2	Axis 1	Axis 2	Axis 1	Axis 2	
Kanyosha	0.47	0.39	21.73%	17.93%	98.68%	98.42%	0.03
Kinyankonge	0.59	0.39	16.55%	10.87%	98.68%	95.09%	0.002
Muha	0.47	0.46	21.59%	21.36%	99.98%	99.98%	0.006
Ntahangwa	0.50	0.23	23.62%	10.85%	98.73%	97.83%	0.002

Conclusion: Pollution from Bujumbura has negatively affected the water quality and macroinvertebrates diversity of rivers crossing this city. There is loss of macroinvertebrates diversity and worst water quality downstream the rivers compared to upstream. Our results will serve as a reference for the regular assessment using environmental parameters and bioindicators for the management of the Bujumbura Rivers for the preservation of these rivers and Lake Tanganyika biodiversity and water quality in particular and rivers from Burundi and the region in general.

Acknowledgement: This research was carried out thanks to the financial support from National Geographic Society, grant number EC-60310R-19, and University of Burundi. The authors thank students and technical team from the Center of Research in Natural Sciences and Environment of the Faculty of Sciences, University of Burundi for their valuable help during samples collection and analysis in laboratory. The authors are grateful to the anonymous reviewers for their contributions to improve the manuscript.

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