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THE ASSESSMENT OF HEAVY METALS POLLUTION IN THE NYABARONGO RIVER SEDIMENTS – CASE STUDY: MAGERAGERE SECTOR

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ABSTRACT

The accumulation of heavy metals in rivers' sediments near industrial wastes and mining activities has been a serious issue in developing countries including Rwanda and it has caused different environmental impacts on aquatic and terrestrial lives. Environmental studies have reported heavy metals pollution (lead, manganese, copper, zinc, nickel, iron, and cadmium) in major Rwandese rivers such as Mpazi, Rusine, and Nyabugogo. The increase in heavy metal concentrations in the environment results in abnormal enrichment, which in turn, affects the surrounding environment. This study aimed to investigate the heavy metals in Nyabarongo sediments, Mageragere sector using both X-ray fluorescence (XRF) and Atomic Absorption Spectrometer (AAS) instruments. Sediments samples were collected systematically on four sampling stations and the results showed that the Cadmium (Cd), Lead (Pb), and Manganese (Mn) concentrations among the investigated heavy metals are above the Rwanda Standard Board (RSB) and World Health Organization (WHO) guidelines for soils and sediments, meaning that those metals are the measure pollutants in the sediments of Nyabarongo River and the study has recommended the people around the river to reinforce the erosion control measures and not to use Nyabarongo water for domestic use and animal farming activities because of the concentration of heavy metals it contains that are toxic to animals, plants and micro-organisms.

Keywords: Heavy metals; Nyabarongo River; Pollution; River sediments; World Health Organization (WHO).

1 INTRODUCTION

Heavy metal accumulation in river sediments originating from industry and mining activities has been a serious issue in developing countries including Rwanda and especially due to the toxicity effects of the metals mentioned [1]. The river sediments tend to accumulate heavy metals and other organic pollutants and therefore the sediment quality serves to be a good indicator of water pollution [2]. Unfortunately, concerning the subject of our study, researchers usually consider only sediments that do not mention the rivers of our concern. The presence of heavy metals in river sediments is of paramount importance because the aquatic environment provides living conditions for many marine creatures including fish and it affects human organs, like kidneys, digestive and nervous systems. Heavy metal sources are both natural and anthropogenic [3].

Mining activities such as milling and grinding operations, concentrating ores, and disposal of tailings from all mining scales (artisanal, small-scale, and large-scale mining) affect the rivers as well as the environment when they are not well managed [4].

There are two different pathways by which heavy metals enter the river sediments and those are point and non-point sources. A point source is where the waste containing heavy metals enters directly in rivers through pipes

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or canals from a known source such as industry, mining site or other known sources while a non-point source, also known as “Polluted runoff”, is a source of which the exact location cannot be easily qualified, like the pollution originating from entire landscape areas [5].

The Nyabarongo River and its tributaries are considered to be an important source of water for agriculture, human consumption, wildlife, and livestock. Even if it is highly useful, the Nyabarongo River water as well as the sediments are subject to different contamination. Environmental studies reported heavy metals pollution (manganese, copper, zinc, nickel, iron, lead, and cadmium) in major Rwandese rivers such as Mpazi, Rusine, and Nyabugogo in the Kigali section [6]. The increase in concentrations of heavy metals in the environment results in abnormal pollution of the soils with those heavy metals at the surface. Pollution of soil with those heavy metals may negatively affect community health concerning digestion, breathing as well as contact with the skin [7].

The Nyabarongo River and its tributaries in the Kigali section are presently becoming a major issue concerning uncontrolled growth of industrial waste as well as tailings from uncontrolled mineral processing in mining areas in and around waterways which increase water turbidity and concentration of heavy metals as is the case for many countries over the world [8], leading to instability of rivers physically, chemically and biologically [9]. Most of the reports and journals have focused on the assessment of water pollution levels in different catchment areas as well as the physicochemical quality of water and the associated health risks.

Heavy metals are natural constituents of rivers’ sediments. Nevertheless, they become a problem when they go beyond the standards of being safe mostly due to their toxic effects on human beings, plants, and different animals [1]. The World Health Organization reported 143,000 deaths and 600,000 new cases of child intellectual disabilities [10], 3,000 people have diseases resulting from heavy metals concentration, and 600 of them died in Japan [11]. Most heavy metals present in river sediment come from anthropogenic activities such as mining which pollutes it in processes of milling, grinding, concentrating ores, tailings disposal, and industrial waste as well as geomorphic processes [4].

The study conducted by Omara, et al. [9] listed the heavy metals contained using water samples but they failed to consider sediment samples that are in direct contact with the river, although they provide useful information on toxicity levels. Even if there are no anthropogenic activities that can release heavy metals in rivers, there is also another way like the formation of geochemical anomalies where ground and surface water migrate and transport metallic ions away from ore deposits and sometimes move in rivers [12]. To contribute to environmental monitoring, this study assessed the heavy metal pollution in Mageragere, part of Nyabarongo River (Figure 1) sediments, their level of pollution, and their toxicological effects on people and then suggested possible solutions.

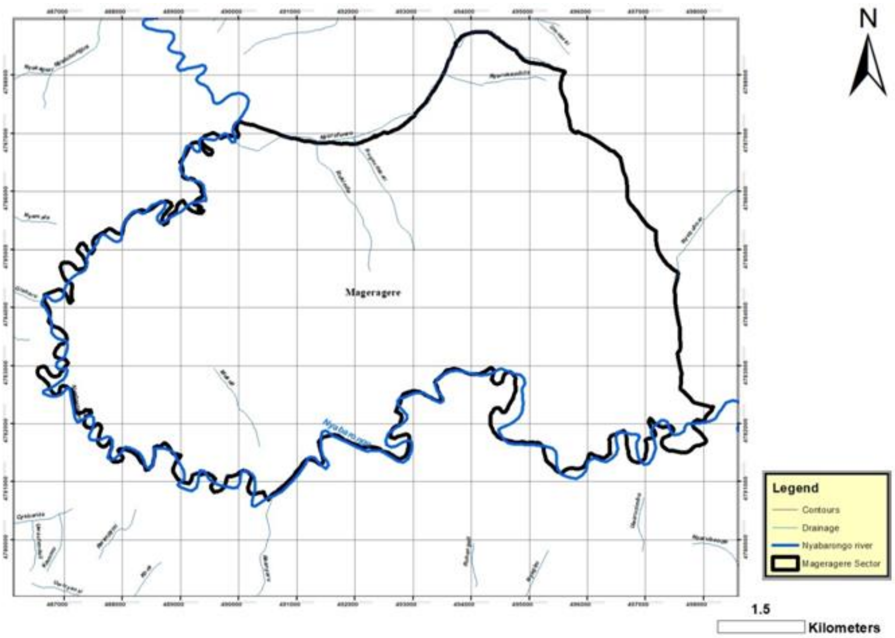

***Figure 1.** Hydrology of the study area / Mageragere (Source: Author)*

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All metals with high densities from 3500 to 7000 mg cm^{-3} which are toxic and/or poisonous even at low concentrations are referred to as “Heavy metals” [13]. The suitability of the water, which includes the Nyabarongo River and its tributaries, for different uses and its ability to support aquatic life depends on elements including heavy metals like manganese, zinc, copper, iron, nickel, lead, and cadmium [9].

Nyabarongo (Figure 2) is a major and the longest river entirely in Rwanda; it is 351 kilometres (218 mi) in length and covers an area of about 142.62 square kilometres. It is a tributary of the Nile River [14]. Nyabarongo starts its journey at the confluence of the Mwogo and Mbirurume rivers, which are also among the sources of the river Nile, the origin of these two rivers is in Nyungwe Forest. The river water is mainly used for agriculture, bathing as well as cooking. Therefore, it receives waste products containing heavy metals from industries and mining activities [15].

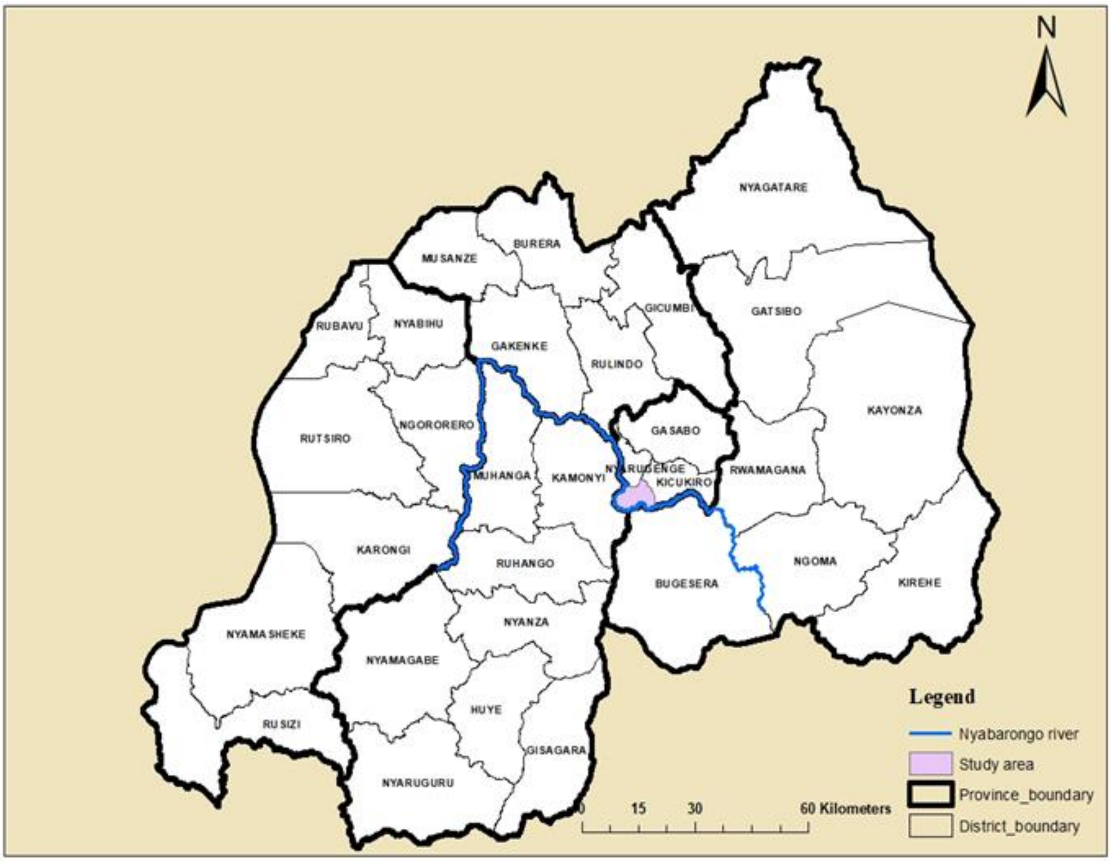

Figure 2. *Nyabarongo River at administrative map of Rwanda (Source: Author, data source: RNRA)*

The study conducted by Mushtaha, et al. [16], on heavy metals contamination in Nile River sediments and its main tributaries including Nyabarongo River, concluded that Iron (Fe) metal with values of concentration ranging from 0.42 to 2.46 mg/l was of high concentration while Molybdenum (Mo) had the lowest one.

As population growth is gradually increasing, industrialization, mining activities, and urbanization are also increasing which are responsible for increasing river sediment pollution. Therefore, there is always a gap in carrying out research activities for determining the increase in concentrations of heavy metals and their respective effects by analysing the samples collected from different locations in Kigali city [17].

Figure 3. *Google Earth satellite image showing the Nyabarongo River in the study area*

2 MATERIALS AND METHODS

2.1 Field method

Mageragere area is characterized by elevated mountains, swamps, rivers, and valleys. Geological data were collected using different materials such as administrative and topographic maps, hammers, geological compasses, and GPS receivers.

2.2 Sampling

Four river sediment samples were collected at 4 sampling stations (Figure 4) using a hand auger, with a depth range from 25 to 30 cm. Station 1 and Station 4 were placed at the sections where Nyabarongo River enters and ends its course in the Mageragere sector. Station No. 2 and No. 3 were placed before and after the confluence of the Akanyaru River in the Nyabarongo River/Mageragere sector.

At every station, after making site descriptions (weather conditions and geomorphic process), the sample was kept in a labelled plastic bottle; geographic coordinates were taken and recorded in the field notebook.

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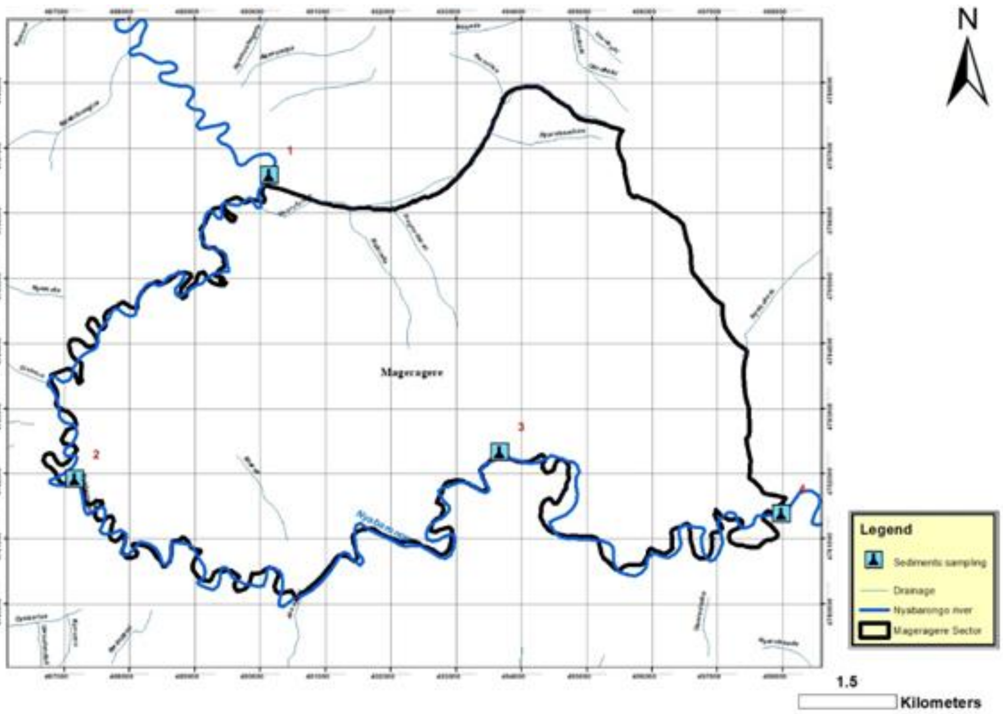

Figure 4. *Sampling stations at the study area (Data source: RNRA)*

2.3 Laboratory Analysis Methods

2.3.1 Sample Conservation

After sampling, samples were conserved in a secured and cold place to reduce loss of volatiles and bacteria activities reduction as well as to avoid mixing with other chemicals following the procedures illustrated by Simpson & Batley [18].

2.3.2 Sample Preparation and Element Analysis

After sample conservation, samples were subjected to drying by sun and oven so that moisture as well as organic matter content would be reduced. The sample sizes were reduced to 2 mm in diameter by crushing using a jaw crusher of Ngororero Mining Company and pulverized in the University of Rwanda laboratory following the procedures illustrated by Simpson & Batley [18].

i. XRF Method

The X-ray fluorescence (XRF) elements analysis was performed using the X-MET8000 instrument manufactured by Hitachi High-Tech. The sediment samples were dried before XRF scanning. Dry sediments of 50 g were analysed concerning each sample.

ii. Flame Atomic Absorption Spectrometer (F AAS) Analysis

Flame AAS developed by Agilent was used to analyse the concentration of the following heavy metals Cadmium (Cd), Iron (Fe), Lead (Pb), Manganese (Mn), and Zinc (Zn) present in samples by using Beer Lambert’s law detailed in Filip, et al. [19].

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iii. Data Analysis

The concentration of heavy metals identified in sediment samples was compared with World Health Organization (WHO) standards for soil and water as well as Rwanda Standard Board (RSB) guidelines. Heavy metals above allowable limits often lead to negative effects on living creatures and the environment.

The enrichment factor (EF) defined by Muller [20] was calculated to assess sediment contamination in the Nyabarongo River. This factor can also be used to determine the metals of anthropogenic sources as opposed to those of natural sources [21].

EF is calculated as below:

$$EF = \frac{Cn(sample)/CFe(sample)}{Cn\ (UCC)/CFe(UCC)} \qquad (1)$$

where Cn/C_{Fe} for the sample is the ratio of the concentration of the element concerned to the reference element in the sediments sample, Cn/CFe for UCC (upper continental crust) background is the ratio of the concentration of the concerned element to that of the reference element in the geochemical background. Many studies have taken different reference elements for normalization based on their natural occurrences. The commonly used reference metals for normalization are found to be iron and aluminium due to their abundance in the earth's crusts. This study used iron as a reference element to distinguish the sources, whether they were of natural or anthropogenic origin as it has been used by different successful studies [22–24].

Sutherland [25] has divided soil contamination into 5 categories based on EF values (see Table 1).

Table 1. *Contamination categories based on EF values as shown by Sutherland [25]*

EF value	Contamination category
< 2	Deficiency to minimal enrichment
2–5	Moderate enrichment
5–20	Significant enrichment
20–40	Very high enrichment
> 40	Extremely high enrichment

3 RESULTS AND DISCUSSION

The lithology of the Mageragere sector is generally made up of Quartzite, meta-sandstone (dominant lithology), schist, and laterite to a later degree. The results of heavy metal measurements in river sediment samples were discussed with the references of different previous studies and World Health Organization (WHO) standard guidelines. The results of the analysis are presented by tables and graphs to show linear interdependence between variables.

i. XRF Results

Four sediment samples were collected at four different stations along the Nyabarongo River. The results of heavy metals identified by XRF(X-MET8000) are in Table 2.

Table 2. *Heavy metal concentration results by XRF (Concentration in percentages (%))*

Name of heavy metals	Station1	Station2	Station3	Station4
Cr	0.0688	0.0459	0.0393	0.0452
Mn	0.0561	0.0448	0.0562	0.0443
Fe	4.609	3.7454	4.5015	3.889
Zn	0.0079	0.0089	0.0077	0.0055

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As	ND	ND	ND	ND
Pb	0.0054	0.0041	0.0051	0.0032
Th	0.0029	0.0032	0.0042	0.003

ii. Atomic Absorption Spectroscopy (AAS) Results

Table 3. *Heavy metals concentration results by AAS (Concentrations of heavy metals mg.kg^{-1})*

Name of heavy metal	Average composition of the upper continental crust (UCC)	Station1	Station2	Station3	Station4	WHO standards quality guidelines for sediments
Fe	35,000	47,030	38,454	46,015	39,896	50,000
Pb	17	48	45	47	29	35
Cd	0.098	3.25	3.56	3.95	4.22	0.6
Zn	71	81	91	79	59	123
Mn	600	551	438	552	433	300

The results of heavy metal concentration at each station are presented in Tables 2 and 3.

a. Iron (Fe)

Iron is the second most abundant metal in the Earth's crust making up 5 per cent which makes the average content of iron in the upper continental crust (UCC), 35,000 mg.kg^{-1}. Elemental iron is rarely found in nature, as the iron ions Fe^{2+} and Fe^{3+} readily combine with oxygen and sulphur-containing compounds to form oxides, hydroxides, carbonates, and sulphides. Iron observed in Nyabarongo sediments ranged from 38,454 mg.kg^{-1} to 47,030 mg.kg^{-1} which is below the allowable limit of 50,000 mg.kg^{-1} by World Health Organization standards (see Table 3). The following graph (Figure 5) shows the variation of Iron concentration in sediments of the Nyabarongo River at different sampling stations. The iron concentration found in the analyzed samples shows normal variation as compared to the background.

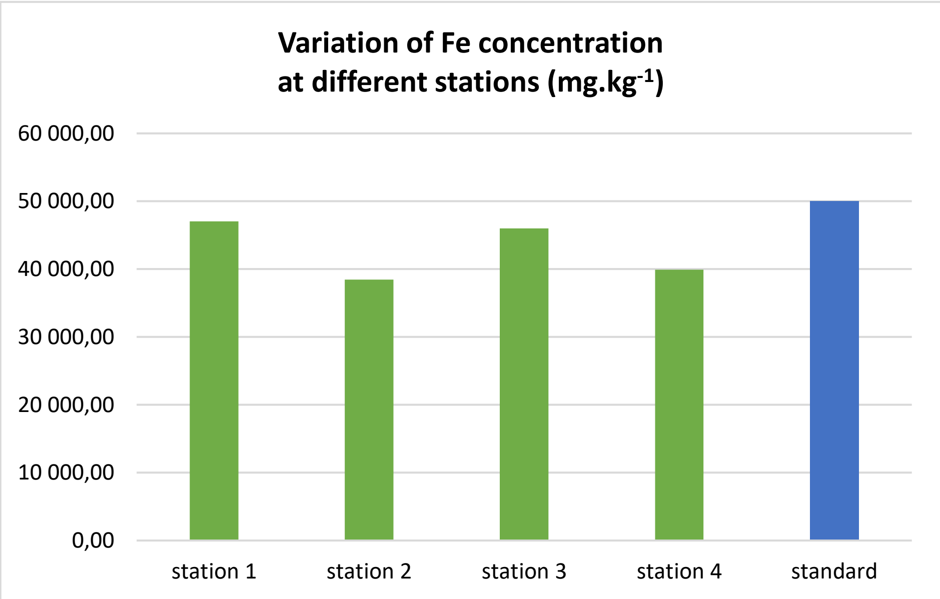

Figure 5. *Variation of Iron concentration in sediments of Nyabarongo River*

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b. Lead (Pb)

Lead (Pb) is a minor element in the Earth's continental crust. It is distributed at low concentrations in soils that are not contaminated, river sediments, and rocks. Pb is one of the highly poisonous metals that affect human soft tissues and organs, causing cancer in the kidneys, lungs, or brain, and acts synergistically with other carcinogens. The possible sources of lead include mining, lead-containing gasoline, smelting, and Pb paint [26].

In this study, Lead metal was analyzed using AAS (Atomic Absorption Spectrometer) and the results show the Lead metal in Nyabarongo river sediments ranging from 29.00 mg.kg^{-1} to 48.00 mg.kg^{-1} at all stations which lay the above values of WHO standards for soils and sediments. Below is the graph (Figure 6) showing the variation of Lead concentration in the sediments of the Nyabarongo River at all stations. Red colour indicates the values that are above the allowable limit, green indicates the concentrations values below the standards and blue indicates the standard.

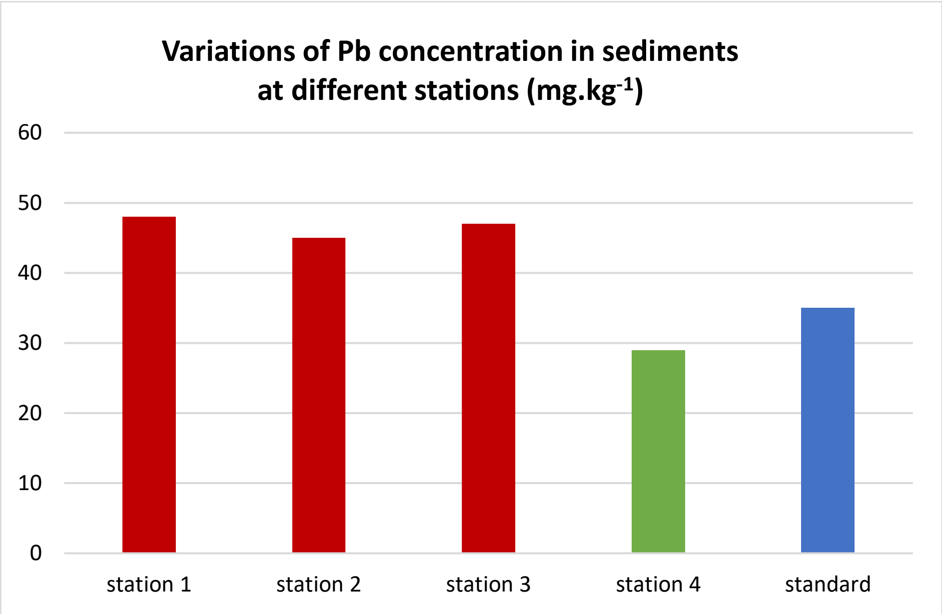

Figure 6. *Variation of Lead concentration in sediments of Nyabarongo River*

c. Cadmium (Cd)

Cadmium (Cd) is considered a toxic element, the results obtained from the Atomic Absorption Spectrometer (AAS) show a higher concentration of cadmium at all stations compared to the WHO standards of sediments and soils. The results range from 3.25 mg.kg^{-1} to 4.22 mg.kg^{-1} where 0.6 mg.kg^{-1} is the maximum allowable limit in sediments.

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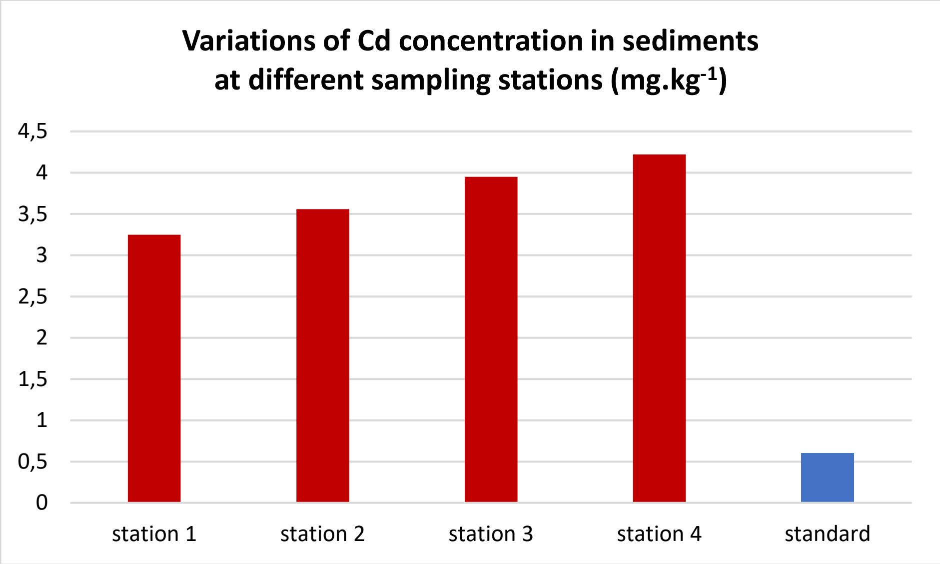

Figure 7. *Variation of Cd concentration in sediments of Nyabarongo River*

d. Zinc (Zn)

Zinc naturally occurs in sulphides and as carbonates in many rocks and soils at low concentrations. Zinc gets in sediments in two ways rock weathering, erosion of minerals from rocks and soils, or anthropogenic activities. Zinc is slightly soluble in water. Almost all zinc in water comes from artificial sources like steel production, burning of waste materials, and fertilizer usage containing zinc which may leach into groundwater [27].

The results show that the concentrations of Zinc metal at all stations range from 59.00 $mg.kg^{-1}$ to 91.00 $mg.kg^{-1}$. The Nyabarongo sediments are not polluted with Zn because the values lie below the maximum allowable limits of 123 $mg.kg^{-1}$ by the World Health Organization. Figure 8 shows the variations of Zinc concentrations at all sampling stations.

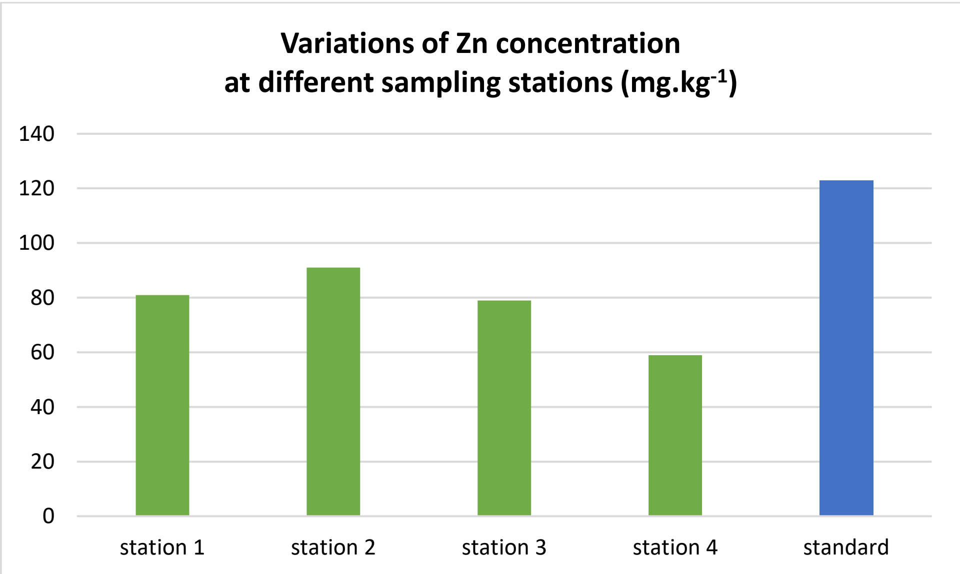

Figure 8. *Variation of zinc concentration in sediments of Nyabarongo River*

e. Manganese (Mn)

Manganese is a heavy metal found in nature combined with Iron and is very useful in industrial alloy production, but it is considered a pollutant if its concentration in soils is above the World Health Organization standards.

The concentrations of heavy metals in Nyabarongo River sediments range from 433.00 $mg.kg^{-1}$ to 552.00 $mg.kg^{-1}$ (Figure 8) and it is a pollutant since it exceeds the allowable limits of the World Health Organization standards of 300.00 $mg.kg^{-1}$, this concentration may affect the reproduction system of humans, plants and animals. The concentration of Mn in the study area is above the World Health Organization standards. Mn usually comes from a terrestrial source through crustal weathering that can be converted to complex hydroxyl manganese compounds, which eventually precipitate into the sediments [23]. The possible source is the surrounding geology, municipal and industrial wastes as the area is surrounded by municipals and small industries as well as Mageragere prison.

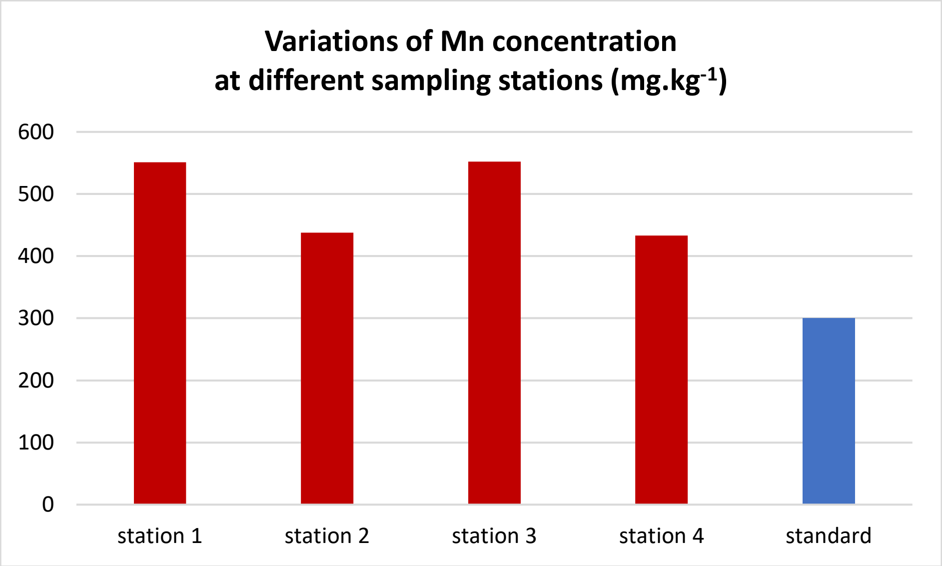

Figure 9. *Variation of Manganese concentration in sediments of Nyabarongo River*

Table 4 summarizes the results; red colour indicates heavy metal as a pollutant (value exceeds the World Health Organization standards) and green colour indicates that the metal is not a pollutant (value lies below the World Health Organization standards).

Table 4. *Pollutant metal concentration (red) and non-pollutant metal concentration (green)*

Name of heavy metal	Station1	Station2	Station3	Station4	Average	WHO standards quality guidelines for sediments
Fe	47,030	38,454	46,015	39,896	42,848.75	50,000
Pb	48	45	47	29	42.25	35
Cd	3.25	3.56	3.95	4.22	3.74	0.6
Zn	81	91	79	59	77.5	123
Mn	551	438	552	433	493.5	300

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Table 4 clearly shows that the three heavy metals namely Lead, Cadmium, and Manganese are the major pollutants of Nyabarongo River sediments. Table 5 summarizes the values of enrichment factors calculated for each pollutant metal shown above.

Table 5. *Enrichment factors (EF) for the pollutant metals in Nyabarongo River sediments*

	EF values		
Station	**Lead (Pb)**	**Cadmium (Cd)**	**Manganese (Mn)**
1	2.101	24.680	0.683
2	2.410	33.063	0.664
3	2.103	30.658	0.670
4	1.500	37.778	0.633
Average	2.027	31.545	0.670

Enrichment Factor

Table 5 shows the enrichment factors of pollutant metals at each sampling station, according to the contamination category by Sutherland [25], Table 1 above; This study used iron metal as the reference for normalization due to its abundance in the earth's crust because the study did not consider its enrichment factor, and because its concentration is below the World Health Organization standards for water. Fe mainly originated from the weathering of the crustal rocks and may precipitate into the sediments. the study confirmed that the iron impurities in the study area do not have a higher significance.

In terms of enrichment factor, Lead can be classified as moderate enrichment for the first three stations and deficiency to minimal enrichment at station 4, in Nyabarongo River sediments. The deficiency enrichment of Lead as well as the concentration can be due to two factors, the first being that the sampling station is far from the pollution source, and this can be confirmed with the variations of other heavy metals which show less concentration compared to other stations, the second being related to the geology of the area where the station is located in sandstone which is generally depleted in Lead concentrations as it has been shown by Morin, et al. [28].

The concentration of Cadmium ranging from 3.25 to 4.22 in Table 4 shows that this metal is highly concentrated in the study area and its concentration exceeds the World Health Organization standards. The study of Kaushik, Kansal [29] has shown that the source of Cd could be from the dye and pigment industries, coal-fired thermal power plants, paper mills, fertilizer industry or municipal wastewater. In the case of the Mageragere sector (study area), the Cd is probably derived from fertilizers and municipal wastes as evidenced by the high values in the downstream sites of the area and its concentration is increasing from upstream to downstream. In terms of enrichment factor, Cd can be classified in the category of very high enrichment, it is highly enriched in Nyabarongo river sediments with enrichment factor ranging from 24.680 to 37.778. The enrichment factor for Manganese (Mn) and Zinc (Zn) is considered a low enrichment factor and is categorized as a deficiency to minimal enrichment in Nyabarongo river sediments referring to Table 1.

4 CONCLUSIONS

This study is of major contribution concerning environmental monitoring, concerning assessment of heavy metal pollution in Nyabarongo river sediments. The assessment carried out in the Kigali-Mageragere sector shows that the concentrations of three heavy metals, namely Lead Pb, Cadmium Cd, and Manganese Mn are above the World Health Organization standards for soils or sediments. This means that the sediments studied are polluted by the heavy metals mentioned. On the other hand, the results of the resting two heavy metals, namely Iron Fe and Zinc Zn, demonstrate concentrations which are below the World Health Organization standards for soils or sediments. This means that the Nyabarongo River is not polluted by those two heavy metals. This study concludes that Nyabarongo River water is not safe for domestic use and animal farming activities due to the toxicological effects of the pollutants present in the sediments. This study recommends that people living in the river vicinity do not use Nyabarongo water for domestic purposes and animal farming activities. Public institutions and commercial centres should properly manage and purify their waste discharge (treatment facilities) and avoid disposing of it in rivers. For this purpose, a tailing disposal facility design is needed using a multi-criteria evaluation analysis. The study also recommends annual assessments of heavy metal pollution both in water and river sediments in the country of Rwanda which would provide for proper environmental impact control.

REFERENCES

[1] EL-AMIER, Y.A., A.Z. EKOA BESSA, A. ELSAYED, M.A. EL-ESAWI, M.S. AL-HARBI, B.N. SAMRA & W.K. KOTB. Assessment of the heavy metals pollution and ecological risk in sediments of Mediterranean Sea drain estuaries in Egypt and phytoremediation potential of two emergent plants. *Sustainability*. 2021, vol. 13(21), art. no. 12244. ISSN 2071-1050. DOI: 10.3390/su132112244

[2] SAKAN, S.M., D.S. ĐORĐEVIĆ, D.D. MANOJLOVIĆ & P.S. PREDRAG. Assessment of heavy metal pollutants accumulation in the Tisza River sediments. *Journal of Environmental Management*. 2009, vol. 90(11), pp. 3382–3390. ISSN 1095-8630. DOI: 10.1016/j.jenvman.2009.05.013

[3] SHIFAW, E. Review of heavy metals pollution in China in agricultural and urban soils. *Journal of Health and Pollution*. 2018, vol. 8(18), art. no. 180607. ISSN 2156-9614. DOI: 10.5696/2156-9614-8.18.180607

[4] GABRIELYAN, A.V., G.A. SHAHNAZARYAN & S.H. MINASYAN. Distribution and identification of sources of heavy metals in the Voghji River basin impacted by mining activities (Armenia). *Journal of Chemistry*. 2018, vol. 2018, art. no. 7172426. ISSN 2090-9063. DOI: 10.1155/2018/7172426

[5] AKHTAR, N., M.I. SYAKIR ISHAK, S.A. BHAWANI & K. UMAR. Various natural and anthropogenic factors responsible for water quality degradation: A review. *Water*. 2021, vol. 13(19), art. no. 2660. ISSN 2073-4441. DOI: 10.3390/w13192660

[6] HAKIZIMANA, P., A. MANIRAGABA & F.X. NSHIMIYIMANA. Assessment of heavy metals in Amaranthus spinosus, Kigali, Rwanda. *International Journal of Advanced Research and Publications*. 2019, vol. 3(10), pp. 7–12. ISSN 2456-9992. Available at: https://www.ijarp.org/published-research-papers/oct2019/Assessment-Of-Heavy-Metals-In-Amaranthus-Spinosus-Kigali-Rwanda.pdf

[7] JAISHANKAR, M., T. TSETEN, N. ANBALAGAN, B.B. MATHEW & K.N. BEEREGOWDA. Toxicity, mechanism and health effects of some heavy metals. *Interdisciplinary Toxicology*. 2014, vol. 7(2), pp. 60–72. ISSN 1337-9569. DOI: 10.2478/intox-2014-0009

[8] NHAPI, I., U.G. WALI, B.K. UWONKUNDA, H. NSENGIMANA, N. BANADDA & R. KIMWAGA. Assessment of water pollution levels in the Nyabugogo Catchment, Rwanda. *The Open Environmental Engineering Journal*. 2011, vol. 4(1), pp. 40–53. ISSN 1874-8295. DOI: 10.2174/1874829501104010040

[9] OMARA, T., P. NTEZIYAREMYE, S. AKAGANYIRA, D.W. OPIO, L.N. KARANJA, D.M. NYANGENA, B.J. KIPTUI, R. OGWANG, S.M. EPIAKA, A. JEPCHIRCHIR & A. MAIYO. Physicochemical quality of water and health risks associated with consumption of African lungfish (Protopterus annectens) from Nyabarongo and Nyabugogo rivers, Rwanda. *BMC Research Notes*. 2020, vol. 13(1), art. no. 66. ISSN 1756-0500. DOI: 10.1186/s13104-020-4939-z

[10] WHO. *World Health Statistics 2021: Monitoring Health for the SDGs, Sustainable Development Goals* World Health Organization, 2021. ISBN 978-92-4-002705-3. Available at: https://www.who.int/publications/i/item/9789240027053

[11] DAVIDSON, P.W., G.J. MYERS & B. WEISS. Mercury exposure and child development outcomes. *Pediatrics*. 2004, vol. 113(Supplement_3), pp. 1023–1029. ISSN 0031-4005. DOI: 10.1542/peds.113.S3.1023

[12] HOEFS, J. *Stable Isotope Geochemistry*. 4th ed. Berlin, Heidelberg, New York, London, Paris, Tokyo, Hong Kong: Springer-Verlag, 1997. ISBN 3 540 61126 6.

[13] ROSENBERG, E. Heavy Metals in Water: Presence, Removal and Safety. *Johnson Matthey Technology Review*. 2015, vol. 59(4), pp. 293–297. ISSN 2056-5135. DOI: 10.1595/205651315X689009

[14] MINISTRY OF ENVIRONMENT. *Upper Nyabarongo Catchment Management Plan (2018–2024)*. Kigali: Republic of Rwanda, Ministry of Environment, 2018. Available at: https://faolex.fao.org/docs/pdf/rwa203904.pdf

[15] RWANDA ENVIRONMENTAL MANAGEMENT AUTHORITY. *Technical Assistance in Environment and Natural Resources Management: Nile Nyabarongo Lower Catchment Integrated Pollution Management Plan*. 2020. Available at: https://rema.gov.rw/fileadmin/user_upload/Nile_Nyabarongo_Lower_Integrated_Pollution_Management_Plan-Final__Jan._2021_.pdf

[16] ALI, M., A. ELHAGWA, J. ELFAKI & M. SULIEMAN. Influence of the artisanal gold mining on soil contamination with heavy metals: A case study from Dar-Mali locality, North of Atbara, River Nile State, Sudan. *Eurasian Journal of Soil Science*. 2017, vol. 6(1), pp. 28–36. ISSN 2147-4249. DOI: 10.18393/ejss.284261

[17] GAUTAM, R.K., S.K. SHARMA, S. MAHIYA & M.C. CHATTOPADHYAYA. Chapter 1: Contamination of heavy metals in aquatic media: transport, toxicity and technologies for remediation. In: SHARMA, S. (ed.). *Heavy Metals in Water: Presence, Removal and Safety*. Royal Society of Chemistry, 2014. ISBN 978-1-84973-885-9. DOI: 10.1039/9781782620174

[18] SIMPSON, S.L. & G.E. BATLEY (eds.). *Sediment Quality Assessment: A Practical Guide*. 2nd ed. Clayton, Victoria: CSIRO Publishing, 2016. ISBN 9781486303847.

[19] SNĚŽANA, F., S. POPOV, S. ŠORGIĆ & S. ĐUROVIĆ. Analytical Techniques for Analysis of Metals and Minerals in The Soil Samples. *Recent Advances in Analytical Techniques*. 2022, vol. 5, pp. 159–191. ISSN 2542-5617. DOI: 10.2174/9789815036930122050006

[20] MULLER, G. Index of geoaccumulation in sediments of the Rhine River. *GeoJournal*. 1969, vol. 2, pp. 108–118.

[21] MUZERENGI, C. Enrichment and Geoaccumulation of Pb, Zn, As, Cd and Cr in soils near new union gold mine, Limpopo Province of South Africa. In: WOLKERSDORFER, C., L. SARTZ, M. SILLANPÄÄ & A. HÄKKINEN (eds.). *Proceedings of the 13th International Mine Water Association Congress – "Mine Water & Circular Economy – A Green Congress" (IMWA 2017): June 25–30, 2017, Rauha, Lappeenranta, Finland*. IMWA, 2017, vol. II, pp. 720–727. ISBN 978-952-335-065-6. Available at: https://imwa.info/docs/imwa_2017/IMWA2017_Muzerengi_720.pdf

[22] GOHER, M.E., H.I. FARHAT, M.H. ABDO & S.G. SALEM. Metal pollution assessment in the surface sediment of Lake Nasser, Egypt. *The Egyptian Journal of Aquatic Research*. 2014, vol. 40(3), pp. 213–224. ISSN 1687-4285. DOI: 10.1016/j.ejar.2014.09.004

[23] GOPAL, V., R.R. KRISHNAMURTHY, R. VIGNESH, C.S. NATHAN, R. ANSHU, R. KALAIVANAN, P. MOHANA, N.S. MAGESH, K.M. BHARATH, A.Z.E. BESSA, K. ABDELRAHMAN & M. ABIOUI. Assessment of heavy metal contamination in the surface sediments of the Vedaranyam coast, Southern India. *Regional Studies in Marine Science*. 2023, vol. 65, art. no. 103081. ISSN 2352-4855. DOI: 10.1016/j.rsma.2023.103081

[24] KALPANA, G., A. SHANMUGASUNDHARAM, S. NETHAJI, A. VISWAM, R. KALAIVANAN, V. GOPAL & M. JAYAPRAKASH. Evaluation of total trace metal (TTMs) enrichment from estuarine sediments of Uppanar, southeast coast of India. *Arabian Journal of Geosciences*. 2016, vol. 9, art. no. 34. ISSN 1866-7511. DOI: 10.1007/s12517-015-2048-4

[25] SUTHERLAND, R.A. Bed sediment-associated trace metals in an urban stream, Oahu, Hawaii. *Environmental Geology*. 2000, vol. 39, pp. 611–627. ISSN 0943-0105. DOI: 10.1007/s002540050473

[26] O'SHEA, M.J., J. TOUPAL, H. CABALLERO-GÓMEZ, T.P. MCKEON, M.V. HOWARTH, R. PEPINO & R. GIERÉ. Lead pollution, demographics, and environmental health risks: The case of Philadelphia, USA. *International Journal of Environmental Research and Public Health*. 2021, vol. 18(17), art. no. 9055. ISSN 1660-4601. DOI: 10.3390/ijerph18179055

[27] OBASI, P.N. & B.B. AKUDINOBI. Potential health risk and levels of heavy metals in water resources of lead–zinc mining communities of Abakaliki, southeast Nigeria. *Applied Water Science*. 2020, vol. 10(7), art. no. 184. ISSN 2190-5487. DOI: 10.1007/s13201-020-01233-z

[28] MORIN, G., F. JUILLOT, P. ILDEFONSE, G. CALAS, J.-C. SAMAMA, P. CHEVALLIER & G.E. BROWN. Mineralogy of lead in soil developed on a Pb-mineralized sandstone (Largentiere, France). *American Mineralogist*. 2001, vol. 86(1–2), pp. 92–104. ISSN 1945-3027. DOI: 10.2138/am-2001-0110

[29] KAUSHIK, A., A. KANSAL, SANTOSH, MEENA, S. KUMARI & C.P. KAUSHIK. Heavy metal contamination of river Yamuna, Haryana, India: assessment by metal enrichment factor of the sediments. *Journal of Hazardous Materials*. 2009, vol. 164(1), pp. 265–270. ISSN 0304-3894. DOI: 10.1016/j.jhazmat.2008.08.031