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Hydrogeochemistry And Fate Of Trace Metal Elements In Water And Sediments Around The Kakobola Dam Site On The Lufuku River (Kwilu, DR Congo)

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Summary

The Kakobola Dam is the first to be built in the Kwilu Province of the Democratic Republic of Congo (DRC) since the colonial era. The objective of this work is to assess the hydrogeological conditions, in order to highlight the groundwater flow regime by analyzing trace metal elements on the site. Data from drilling on the site made it possible to develop hydrogeological logs and to derive a general hydrogeological conceptual model. It appears that the site is developed on an unconfined to semi-confined aquifer system towards polymorphic sandstones which, in places, are faulted. The water table is fed by the Lufuku River itself which then explains the causes of water inflows and percolations at the hydroelectric power plant. 32 water samples and 4 sediment samples were collected in the field for the determination of trace metal elements (TME) by X-ray fluorescence at the analytical chemistry Laboratoire Central d'Analyses (LCA) and soil physics laboratories of the General Atomic Energy Commission / Regional Nuclear Energy Center of Kinshasa (CGEA / CRENK). These analyses made it possible, on the one hand, to group the TMEs according to their affinities in all the samples, to compare them with other similar works and finally to compare them with respect to the sampling logic: upstream-downstream of the dam (for water) and above and below the base (for sediments); and on the other hand, to quantify the degree of their pollution which is absent to low for sediments and very significant for water, thus leading to the hypothesis of a permanent hydrogeological regime in the region. In sediment samples, the levels of TMEs taken as markers showed that they do not come from an industrial source but rather from geogenic sources predominantly associated with anthropogenic activities. Regarding water, the TME levels set by the WHO are very low compared to the measured levels, proving that these waters are not of good quality for the population's consumption. In any case, the local lithostratigraphy excludes the hypothesis of a local origin of these TMEs and therefore, they would come from a distant source. Isotopic analyses are recommended to better understand the hydrogeological regime of the site.

Keywords: *Water quality, trace metal elements, sediments, dam, Kakobola, Lufuku River*

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I. Introduction

This paper addresses the ubiquitous problem of the quality of water and the behavior of trace metals elements in aquatic environments, particularly around dams such as the Kakobola hydroelectric Dam site on the Lufuku River in the Kwilu province of the Democratic Republic of Congo, which is critical for ecosystem health and human use (Uddin and Uddin, 2018, Almeida et al., 2019). The cardinal question that triggered this research is whether the remote, pristine and quasi-uninhabited area of Kakobola, is the exception to the above-mentioned concern or not. Likewise, are the advanced alterations resulting to cavities found by Ndala et al. 2022a, Ndala et al, 2022b, Ndala et al. 2023 in the soft sandstone present in the region sourse of relatively hign concentration of trace metals elements in water and sediments of the study area?

We hypothesise that the construction of the Kakobola dam fused with the geological conditions of the soft sandstone cavities are changing trace metals elements fate and transport in water, soils and sediments of the stud tarea compared to the world mean values.

Literature is extremely rich on geogenic and anthropogenic causes affecting aquatic ecosystems health and wellness. Various factors, including human activities, natural sedimentation processes, and the chemical characteristics of the water and sediments, influence trace metal dynamics. The investigation of water quality and the fate of trace metal elements in water and sediments upstream and downstream of hydropower dams has gained prominence in the environmental sciences due to the significant ecological and social ramifications associated with dams' construction.

Hydropower represents both an opportunity for renewable energy and a challenge for freshwater ecosystems, as documented by various studies examining the impacts of dams on water quality. Firstly, the construction of hydropower dams has been shown to alter hydrological regimes, which can lead to degraded water quality, increased sediment trapping, and bioaccumulation of metals in aquatic systems. Almeida et al. emphasize that hydropower dams can disrupt local ecosystems, affect water supply and flood control, leading to significant social impacts, including habitat loss and alterations in sediment transport processes (Almeida et al., 2019). Kondolf et al. provide specific data by quantifying sediment trapping in the Mekong River caused by dam construction, highlighting that cumulative sediment starvation can result in substantial ecological consequences, with findings indicating that up to 68% of sediment load can be trapped, significantly influencing sediment dynamics (Kondolf et al., 2014). Baumgartner et al. discuss how hydropower operations can influence ecosystem services traditionally provided by rivers, such as fisheries productivity and land fertility, which are closely linked to sediment availability (Baumgartner et al., 2021). They also note that although hydropower is considered a renewable energy source, it may contribute to greenhouse gas emissions, particularly in tropical regions, complicating its perceived benefits (Baumgartner et al., 2021). This reflects that considerations regarding hydropower must encompass not only energy generation but also extensive ecological impacts, which significantly affect water quality through changes in flow and sediment regimes. Additionally, Uddin and Uddin highlight that hydropower dams contribute to water quality degradation through the alteration of river connectivity and habitat destruction (Uddin and Uddin, 2018). Their findings underline the multifaceted effects dams can have on water quality, particularly concerning trace metals and sedimentation patterns. In addressing sediment-related issues, Mạnh et al. identify concerning implications for ecosystems, where the planned construction of numerous dams could lead to drastic reductions in sediment input, negatively affecting floodplain dynamics and, subsequently, water quality downstream (Mạnh et al., 2015). This aligns with findings from Gai and Guo, who propose assessment methodologies for evaluating water quality influenced by sediment dynamics, which are crucial for understanding how hydropower constructions impact river health (Gai & Guo, 2023). Furthermore, the mobility of trace metals in sediments is also critical in assessing aquatic ecosystems. Devallois et al. pointed out that sediments, despite being a repository for metals, could release these contaminants back into the water column under changing environmental conditions, hence posing a risk to water quality (Devallois et al., 2009). This finding indicates that sediment management is vital for maintaining the integrity of the aquatic ecosystem upstream and downstream of a Dam. Moreover, the impact of land use, especially from logging and agriculture, is recognized as a significant contributor to water quality impairment. For instance, Durin et al. note that such anthropogenic activities can dramatically increase suspended sediments, leading to deteriorated water quality downstream of dam structures (Durin et al., 2022). This highlights critical questions regarding integrated watershed management and the necessity for sustainable practices to mitigate these effects. It is evident that trace metal dynamics in both water and sediments are extensively influenced by hydropower dams. Dams alter sediment transport and can enhance the risk of contaminant accumulation in aquatic systems. Increased sediment retention can exacerbate biochemical processes that lead to the mobilization of trace metals, making water quality management a critical priority in the context of hydropower development. While hydropower offers a renewable energy solution, its ecological footprint necessitates close attention to sediment and water quality dynamics. Understanding these interactions is vital for developing sustainable hydropower strategies that align energy needs with ecosystem preservation. As afore mentionned, previous geological, geotechnical and geophysical studies of the Kakobola hydroelectric development site have notably highlighted underground cavities and the nature of the geological formations (Ndala et al. 2022a, Ndala et al, 2022b, Ndala et al. 2023).

At this stage of the project, it is imperative to continue investigations into hydrogeological and hydrogeochemical studies to improve knowledge of certain important and necessary parameters of the site, which can contribute to a better understanding of the ongoing hydrodynamic processes upstream and downstream the hydropower dam of Kakobola. This work is aimed at evaluating and analyzing the hydrogeochemical conditions as a baseline line study using mainly Trace Metal Elements as Ecosystems Health markers following Njofang et al. (2007, 2008).

II. Materials And Methods

Materials used

The field campaign equipment includes bags for sediment samples, a digital camera, plastic bottles (100ml) for water samples, filters, pH meter, a cooler for keeping water samples cool, nitric acid, distilled water, a GPS, and other accessories.

At the General Atomic Energy Commission / Regional Nuclear Energy Center of Kinshasa (CGEA / CREN-K), the analyses were carried out using standard equipment and QA/QC protocol from analytical chemistry of the Laboratoire Central d'Analyses (LCA) and soil physics laboratories. The equipment used includes cuvettes and pellets, pH meter, granulometric sieve column, a laptop, cuvettes and film, an X-ray fluorescence spectrometer, ovens, pipettes with tips, a sand bath, mold and mechanical pressing, scales, and several other accessories. All analytical equipmentd used throughout were calibrated usind standard procedures.

Methodological approach

The field campaign consisted of a classic geological survey. According to our goal, we collected water and sediment samples. The hydrogeological conditions of the site were assessed by compiling data from boreholes. The water samples in duplicate came from the springs located along the Lufuku River, the diversion area upstream of the Dam, the underpressure water rises next to the hydroelectric power plant and the surface waters of the Badi quarry (downstream). The samples were taken during the dry season in July 2017 at twelve points on the site. The collected samples were filtered and buffered with nitric acid to ensure preservation in an acidic environment. The samples were contained in sterile 100ml plastic bottles and stored in a cool place along side with blanks and spikes.

In addition, sediment sampling was carried out at four points on the site, two upstream and two downstream. These samples were collected manually using a sediment scooper at the surface and bottom and then stored in plastic bags, marked with a marker. Pollution was assessesd using World Health Organization (WHO) criteria, contamination factor and pollution index, and comparisons to regional and wolrd mean values.

Presentation of the study area

As aforementioned, the study area is located on the Lufuku River in the Kwilu Province of the D.R. Congo (Fig. 1). The geographical coordinates are respectively: latitude = 05°38'59.6" South; longitude = 19°03'30.2" East; altitude = 690m; and Latitude = 05°37'0.8" South; Longitude = 19°02'22.9"East; Altitude = 671m.

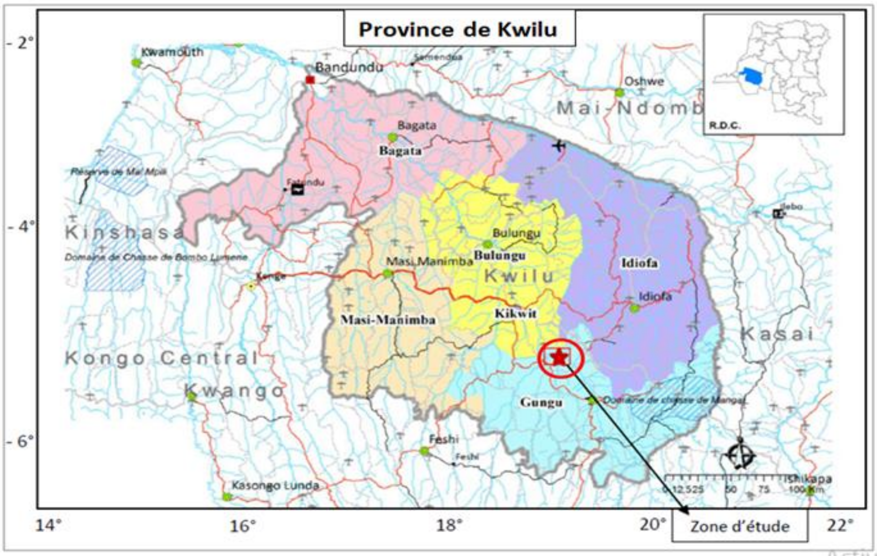


Fig. 1: Administrative map of the study area represented as "zone d'étude (study area)"

General lithostratigraphy

From a stratigraphic point of view, the province of Greater Bandundu of the DRC is dominated by a significant and thick cover. The basement formations hardly outcrop since the cover is significant, except in areas where there is strong erosive activity ***(Cahen, 1954).*** From top to bottom we have:

Blanket

It is represented by the Kwango series and the Kalahari series made up of polymorphic sandstones and ochre sand *(*Ndala et al. 2022a, Ndala et al, 2022b, Ndala et al. 2023*).*

From a stratigraphic point of view, the study area is dominated by a large and thick cover consisting of Carboniferous to Pleistocene age formations. These are moderately fossiliferous continental formations affected by faults and warping due to epirogenic movements. They are represented by the Kwango series and the Kalahari series (polymorphic sandstones and ochre sand).

Basement

The significant absence of stratigraphic fossils in this part complicates the study of these formations. However, there are red sandstones dating from the Carboniferous period and calcareous sandstones (Claeys, 1947).

Lithostratigraphy of the area under study

At the scale of the development site, the lithostratigraphy of the Kakobola hydroelectric site includes the sub-sequence of thick soft sandstone beds covered by 4m thick polymorphic sandstone. The bedrock is under the cover of regolith (soil) about 20m thick, on the right bank. At the Kakobola waterfall, the polymorphic sandstone series consists, in the surface fringe, of eluvial polymorphic sandstone blocks which overlie the generally fine-grained and/or coarse-grained calcareous soft sandstone *(*Ndala et al. 2022a, Ndala et al, 2022b, Ndala et al. 2023*)*.

III. Results

Hydrogeological context of the Kakobola hydroelectric development site

All the boreholes drilled on the site (BH-3, BH-4, BH-5, BH-6 and SK-4) are synthetically represented on a hydrogeological section (Fig. 2), where we can clearly see the hydrogeological configuration of the Kakobola hydroelectric development site. BH-3 and BH-4 boreholes were drilled upstream of the Dam and the hydroelectric power station. These boreholes do not cross natural cavities which are the basis of subsidence and collapse of the land but allow the piezometric levels to be assessed. Thus, boreholes BH-5 and BH-6 are located on the lower part compared to the first two boreholes where the level is high and also define the piezometric levels, but they both cross the cavities. In addition, the SK-4 borehole, which is part of the boreholes analyzed at the Kinshasa Road office, just refines the four others presented here in this section, which are part of those carried out by the AIL company. We therefore understand that we are dealing with a single unconfined aquifer, but semi-captive in certain places where the polymorphic sandstone could appear unfractured.

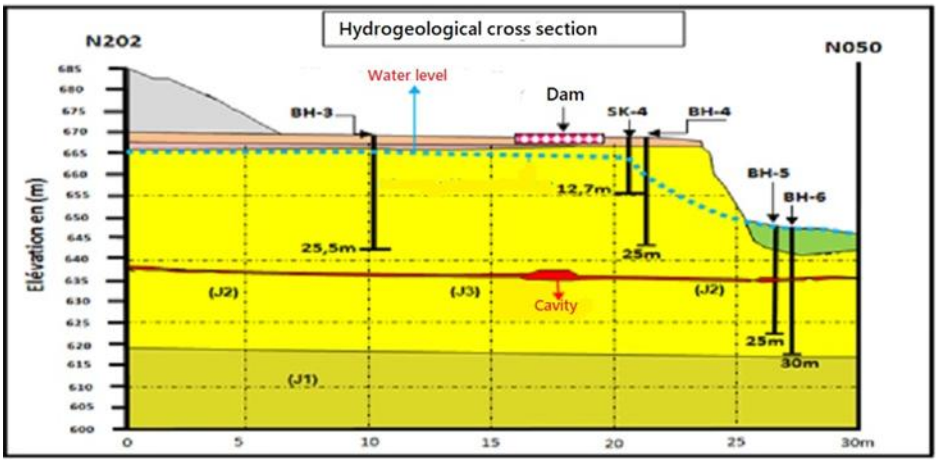
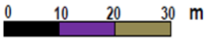


Fig. 2: Synthetic hydroeological model of the study area

Legend **Scale**:



⬜: Embankment
🟧: Cover formation
🟥: Polymorphic sandstone
🟨: Soft sandstone
🟨: Ground erosion (soft sandstone, fractured, fissured et altered)
🟩: Colluvium

Results of the physicochemical analyses of water and sediments of the Kakobola site

The major elements

The results of the analyses on the major elements (cations and anions) of the water samples from the Lufuku River and the sediments from the Kakobola hydroelectric development site are defined using two samples named E1 and E2 and are respectively presented in Tables 1 and 2.

Table 1: Chemical analysis values of Lufuku (Ndala, 2017)

No.	Settings	Results obtained		Test method
		E1	E2	
1	pH	4.32	4.68	Potentiometry

2	Carbonate alkalinity content	9.76 mg/l	7.32 mg/l	Alkalimetry
3	Chloride content	7mg/l	6.65 mg/l	Argentimetry
4	Calcium content ($CaCO_3$)	0.6 mg/l	0.96 mg/l	Complexometry
5	Magnesium content	0.39 mg/l	0.39 mg/l	Complexometry
6	Aluminum content	10.8 mg/l	14.04 mg/l	Complexometry
7	Iron content	2.24 mg/l	6.72 mg/l	Complexometry
8	Sulfate (SO_3) content	14.4 mg/l	26.3 mg/l	Gravimetry
9	Residue after drying	130mg/l	150mg/l	Calculation
10	Identification of nitrates	Negative	Negative	
11	Phosphate identification	Traces	Traces	
12	Carbonate content	0.70%		Complexometry
13	Silica content	93.03%		Gravimetry

The water of the Lufuku River is acidic (pH = 4.3 to 4.7 i.e. < 7) and brown in color, rich in ferro-humic complexes resulting from the decomposition of organic matter. Its mineralization is low overall.

Table 2: Presentation of the results of physicochemical analyses of the sediments

No.	**Settings**	**Results obtained (B)**				**Test method**
		E1	**E2**	CQ-P01 (2.0m of Depth)	CQ-P02 (2.0m of Depth)	
1	pH	4.32	4.68	3.93	4.19	Potentiometry
2	Carbonate alkalinity content	9.76 mg/l	7.32 mg/l	--	--	Alkalimetry
3	Chloride content	7mg/l	6.65 mg/l			Argentimetry
4	Calcium content ($CaCO_3$)	0.6 mg/l	0.96 mg/l	0.26	0.25	Complexometry
5	Magnesium content	0.39 mg/l	0.39 mg/l	--	--	Complexometry
6	Aluminum content	10.8 mg/l	14.04 mg/l	--	--	Complexometry
7	Iron content	2.24 mg/l	6.72 mg/l			Complexometry
8	Sulfate (SO_3) content	14.4 mg/l	26.3 mg/l	0.04	0.04	Gravimetry
9	Residue after drying	130mg/l	150mg/l	--	--	Calculation
10	Identification of nitrates	Negative	Negative	--	--	
11	Phosphate identification	Traces	Traces	--	--	

Analysis of physical parameters

The results are presented in two ways, the first on the descriptive parameters (8-fraction particle size and pH) and the second on the TME contents. On the one hand for the water samples, we have: MK1, MK2, MK3 (MK3a and MK3b), MK4, MK5, MK6, MK7, MK9, MK10, MK11 and MK12. And on the other hand, for the sediment samples, we have: MK8 (A1 and A2) and MK13 (A3 and A4).

a) Descriptive parameters of sediments and water

Tables 3 for sediments and 4 for waters present the results of the physical analyses.

Table 3: Results of physical sediments analyses

Samples		**Granulometry (on 10g)**								**pH**
		A (<2µm)	**Lemons**		**Sands**					
			Lf (2-20µm)	Lg (20-45µm)	45-125µm	125-250µm	250-500µm	500µm-1mm	1-2mm	
MK8	A1	0.73	0.17	0.08	2.31	4.45	1.96	0.30	0	6.89
	A2	0.92	0.29	0.33	2.50	3.94	1.84	0.14	0	6.37
MK13	A3	0.69	0.10	0.12	2.81	4.32	1.57	0.39	0	5.45
	A4	0.77	0.02	0.10	1.42	5.48	2.21	0	0	5.13

A: clay; Lf: fine silt; Lg: coarse silt

Our samples have a sandy to loamy-clayey texture. pH analyses of the site sediments indicate acidic to neutral sediments with values ranging from 4.0 to 10.0; and an increase in pH with depth (MK13 to MK8).

Table 4: Results of the physical analysis of water

Sample	MK1	MK2	MK3	MK4	MK5	MK6	MK7	MK9	MK11	MK12	WHO
pH	6	6	6	6	6	4.5	6	6	6	6	6.5-9.5

pH analysis of water at the Kakobola hydroelectric dam site and along the Lufuku River show acidic to neutral water.

b) TME of sediments and waters

TMEs are potentially toxic elements with relatively low concentration levels and therefore generally undesirable.

The figure below (Fig. 3) shows for illustrative purposes, a spectrum (of Aluminum) observed by X-ray fluorescence, through four targets (Mo, Co, Al_2O_3 and HOPG) used in the laboratory.

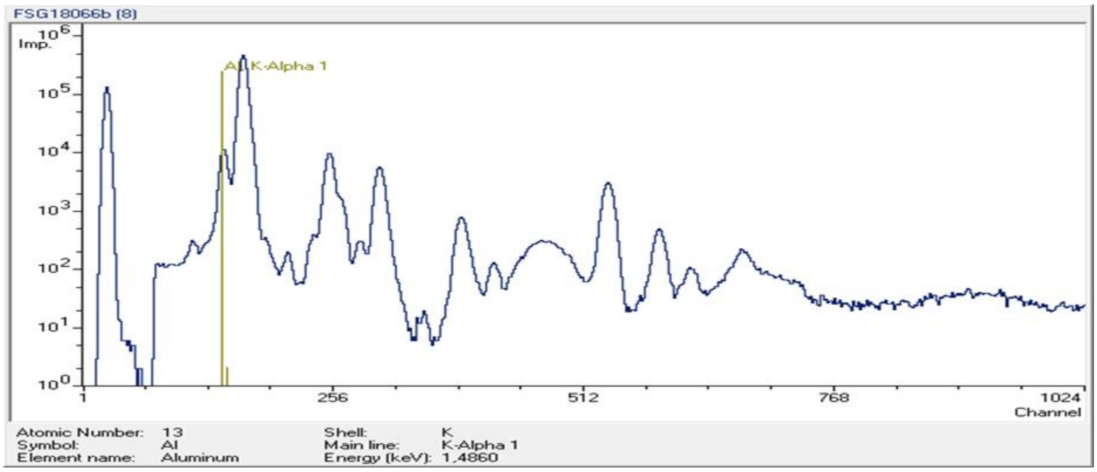


Fig. 3: The X-ray fluorescence spectrum of Aluminum

b1) Sediments

The values obtained from the site samples are presented in Table 5 with the values according to the WHO standard (2006 and 2014) and the maximum levels estimated worldwide.

Table 5: Element contents in sediments/soil samples and values estimated by WHO and FAO

Sample/ Element	MK8		MK13		Standards		Unit
	A1	A2	A3	A4	Average	Maximum value	
Al	21880	11400	31820	42000	/	/	mg/kg
V	20.18	21.04	27.65	61.99	18	200	mg/kg
Cr	21.12	11.55	27.65	31.27	12	150	mg/kg
Mn	44.7	10.39	49.48	31.75	Nd	2000	mg/kg
Fe	6750	3870	9720	12800	41000	/	mg/kg
Neither	1.65	0.65	-	-	12	50	mg/kg
Cu	4.04	1.83	2.94	3.75	24.84	100	mg/kg
Zn	3.49	2.33	4.31	6.58	45.13	300	mg/kg
Sr	6.09	2.75	3.38	3.48	100	/	mg/kg
Zr	265.48	207.37	331.61	212.63	237	/	mg/kg
Cd	0.49	0.39	0.13	0.45	0.44	3	mg/kg
Ba	53.88	65.75	47.83	43.93	175	/	mg/kg
Pb	3.37	2.1	3.2	4.62	12.65	100	mg/kg

Apart from aluminum and iron which are very abundant in our samples, with contents respectively around 3000 to 5000 mg/kg given their immense expansion and the composition of the substratum, there is also Zr which has a very high content. The order of abundance of the ETM is as follows: **Ba> Mn> V> Cr> Zn> Sr> Cu> Pb> Cd> Ni.** We note that the contents are far below the average, unlike for Cd, V, Cr and Zr which are too high compared to the average. In addition, the contents of V, Cr, Cu, Pb, Zn, Mn and Zr are more in the way of contamination on sample MK13 than on sample MK8, which is for Sr, Cd, Ba and Ni. We also note that Ni is only present in sample MK8.

Furthermore, the dendrogram following the Euclidean distance formula, in order to classify the TMEs according to their affinity (Fig. 4).

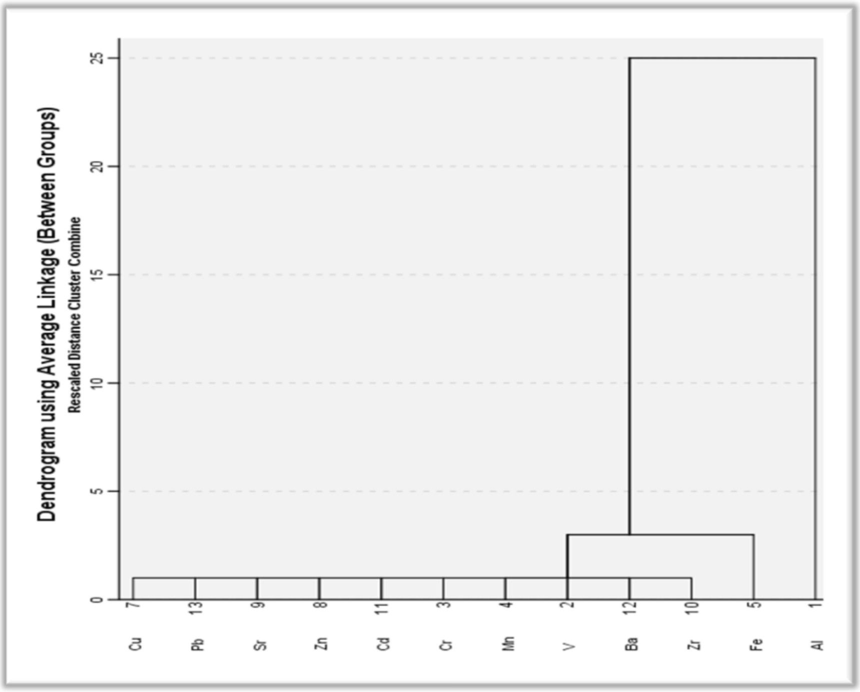


Fig. 4: Dendrogram classifying elements in soils by affinity

The dendrogram groups the trace element contents in order of three classes. The first class includes Cu, Pb, Sr, Zn, Cd, Cr, Mn, V, Ba and Zr with values between 0.10 and 350 mg/kg. The second class includes V, Ba, Zr and Fe, 20 to 13000 mg/kg and the third class includes Ba, Zr, Fe and Al with contents between 40 and 42100 mg/kg.

b.2. Waters

The contents obtained after analysis exceed the averages according to the WHO standard evaluated for certain elements (table 6).

Table 6: Results of TMEs in waters and the WHO/FAO standard

Sample/element	MK1	MK2	MK3		MK4	MK5	MK6	MK7	MK9	MK11	MK12	WHO	Normal range
			MK3a	MK3b									
Al	11.45	9,315	5.41	5.9	8.48	10,635	7.89	10,895	8.39	7.63	7.58	0.2	10–1,000
V	1.52	1,255	0.73	0.68	0.905	1.34	0.69	1.45	1.23	1.13	0.77	/	0.001–1.5
Cr	2,625	2.56	2.37	3.18	3,015	3.77	3,925	3.49	2.53	3,775	4,015	0.05	0.03–14
Mn	1,845	1.17	1.55	1.16	1.48	1.57	0.825	1.02	1,165	1,435	1,345	/	20–1,000
Fe	6,905	10,515	5.92	8.67	7,925	12,715	13.03	9.47	6,885	11,055	9,315	0.3	20–100
Neither	4.4	5,325	2.81	3.76	4.19	5.19	5,055	5,375	4,485	4,105	4.57	/	0.02–5
Cu	1.53	2	0.58	1.34	0.96	1.86	1,815	1.54	1.56	1.54	1.72	2.0	5–20
Zn	0.38	0.365	0.31	0.46	0.335	0.395	3,575	0.505	0	0.385	0.38	0.05	1–400
Sr	0.42	0.42	0.33	0.38	0.345	0.375	0.405	0.385	0.395	0.42	0.435	/	3–3,000
Zr	0.24	0.32	0.33	-	0.23	0.34	0.41	0.45	0.38	0.4	0.23	/	
Ba	7.72	11,525	2.34	6.2	6,895	13,965	9.57	-	-	12.55	-	/	1–198
Pb	0.48	0.37	0.61	0.4	0.37	0.33	0.305	0.545	0.565	0.71	0.495	0.01	0.2–20

In the following dendrogram (Fig. 5), the elements are grouped in order of six classes. The first class of Sr, Pb, V, Mn, Cu, Zn (0.3 to 2.5 mg/kg), the second class of Mn, Cu, Zn and Cr (0.3 to 4.5 mg/kg), the third class of Cr and Ni (2.4 to 5.5 mg/kg), the fourth class of Al and Fe (5.4 to 13.5 mg/kg), the fifth class of Al, Fe and Ba (5.4 to 14 mg/kg), the sixth class of Cu, Zn, Cr, Ni, Al and Fe (1.4 to 13.5 mg/kg).

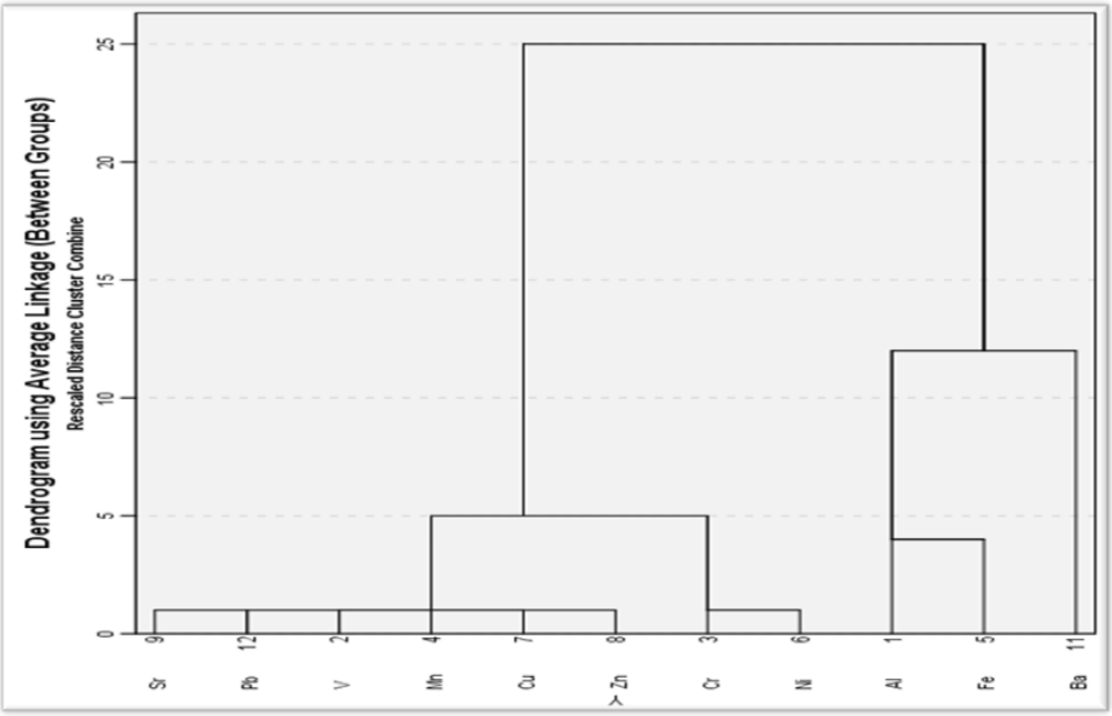
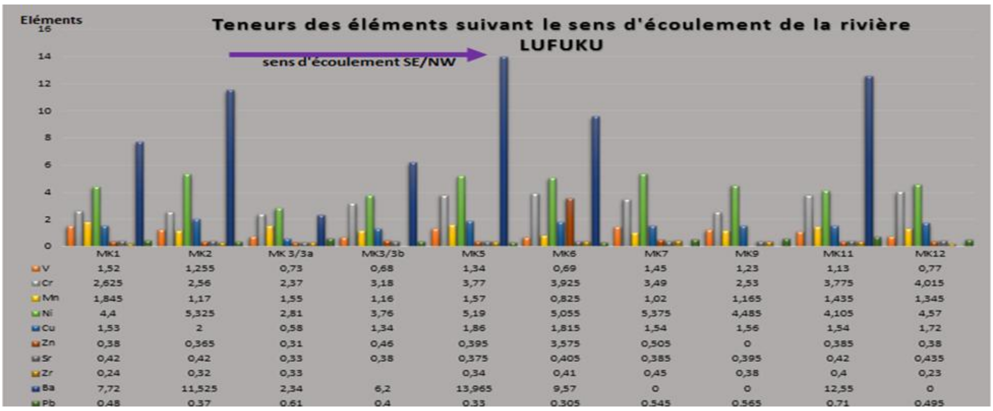


Fig. 5: Dendrogram classifying elements in water by affinity

The following histograms (Fig. 6) gradually lead to the conclusion that the hydrogeological regime of the site is a quasi-permanent regime because they show that there is no considerable variation in the contents according to the direction (SE/NW) of the flow of the river. Furthermore, we observe high contents of Ba, Cr and Ni which do not vary considerably according to the direction of flow, although at certain points Ni appears to be zero.



	MK1	MK2	MK 3/3a	MK3/3b	MK5	MK6	MK7	MK9	MK11	MK12
V	1,52	1,255	0,73	0,68	1,34	0,69	1,45	1,23	1,13	0,77
Cr	2,625	2,56	2,37	3,18	3,77	3,925	3,49	2,53	3,775	4,015
Mn	1,845	1,17	1,55	1,16	1,57	0,825	1,02	1,165	1,435	1,345
Ni	4,4	5,325	2,81	3,76	5,19	5,055	5,375	4,485	4,105	4,57
Cu	1,53	2	0,58	1,34	1,86	1,815	1,54	1,56	1,54	1,72
Zn	0,38	0,365	0,31	0,46	0,395	3,575	0,505	0	0,385	0,38
Sr	0,42	0,42	0,33	0,38	0,375	0,405	0,385	0,395	0,42	0,435
Zr	0,24	0,32	0,33		0,34	0,41	0,45	0,38	0,4	0,23
Ba	7,72	11,525	2,34	6,2	13,965	9,57	0	0	12,55	0
Pb	0,48	0,37	0,61	0,4	0,33	0,305	0,545	0,565	0,71	0,495

Fig. 6: Variation of TMEs according to the flow direction of the Lufuku River

IV. Discussion

This discussion is based on several result approaches (diagrams, calculations, etc.), in order to better understand the hydrogeochemical regime of the site studied. Pollution is assessesd using World Health Organization (WHO) criteria, contamination factor and pollution index, and comparisons to regional and wolrd mean values.

Waters

The studied waters are slightly to moderately polluted (Fig. 7); probably due to the contents of Al, Cr, Fe, Zn and Pb which are close to the average estimated according to the WHO standard at certain points, then immediately deviate from it by a long way (diagram of the element contents of the samples and according to the WHO standard).

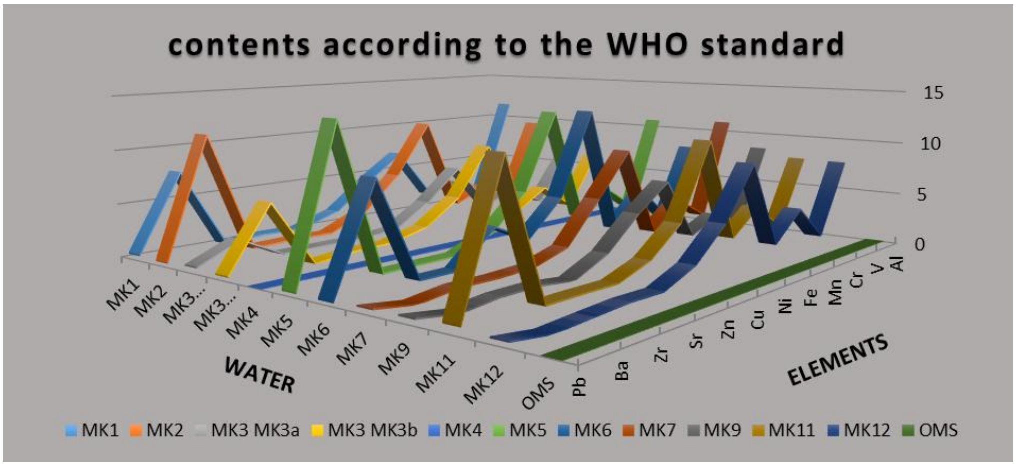


Fig. 7: TME contents according to the WHO standard for water

Sediments

According to the WHO standard, the V and Cr contents are similar for all samples, but in sample A4 the V value is considerably different from the standard. Despite this, the contents are still higher than the average estimated by the WHO. In addition, the remaining elements (Fe, Ni, Cu, Zn, Sr, Cd, Ba and Pb) have contents below the average. Therefore, our soils are zero to slightly polluted (Fig. 8).

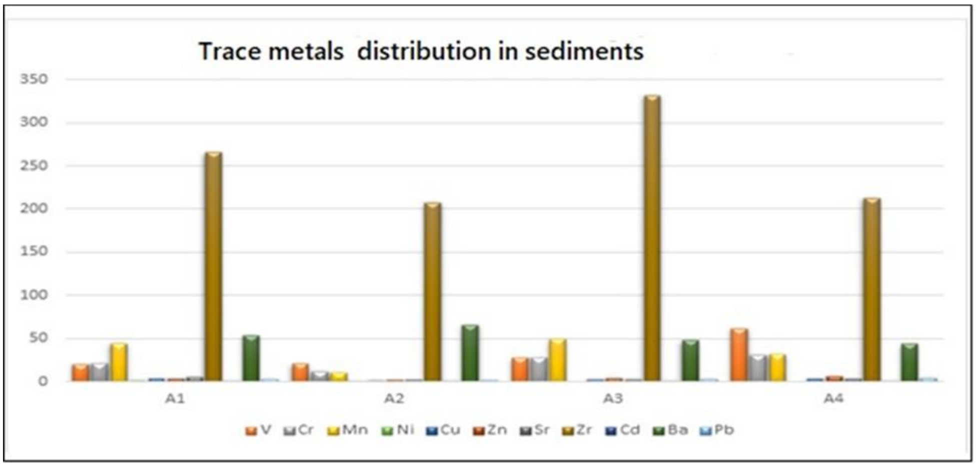


Fig. 8: Variation in the contents of TMEs in soils

a) Contamination factor

Enrichment factors (EF) are used to identify anthropogenic contamination compared to natural levels measured in deep horizons and inherited from the alteration of the parent rock *(Redon et al., 2013)*. Most frequently, enrichment factor calculations are carried out with aluminum (Al), which is a conservative element with a concentration that is relatively constant with depth in the natural environment in many soils *(Tessier, 2012)*. Silica (Si) can also be used. However, after measurements of major elements using X-ray fluorescence, irregularities in the concentrations of Al and Si appeared for several sites. The choice of element was then redirected to scandium (Sc), a rare earth. The calculation of the enrichment factor is as follows:

$$\mathbf{FE} = \frac{\boldsymbol{ETM/Sc\ (horizon\ de\ surface}}{\boldsymbol{ETM/Sc\ (horizon\ profond}}$$

When the enrichment factor is less than 2, anthropogenic enrichment is considered non-existent or very low (Table 7). Enrichment factors can be grouped into 5 classes (Table 8).

Table 7: Classes of enrichment factors (Tessier, 2012)

EF <2	No or low enrichment
2 < EF < 5	Moderate enrichment
5 < EF < 20	Significant enrichment
20 < EF < 40	Very strong enrichment
EF > 40	Extreme enrichment

Table 8: Enrichment factors calculated with Sc as reference element

Elts/écht	MK8	MK13	
		A3	A4
V	0.6	0.6	0.6
Cr	0.6	0.6	0.6
Mn	0.6	0.6	0.6
Neither	0.6	0.6	0.6
Cu	0.6	0.4	0.6
Zn	0.6	0.6	0.6
CD	0.6	0.6	0.6
Pb	0.6	0.6	0.6

We note that in the table above, all our samples have an EF lower than 2, which explains the non-existent or weak enrichment of our sediments. But we note a lower EF of copper (0.4) on the A3 horizon (sample MK13), which corresponds to the superficial part of our study area and is very rich in organic matter (referring to our granulometric analysis).

b) Pollution Index (PI)

Several authors have introduced the soil IP index to identify multi-element contamination resulting from an increase in metal toxicity (Chon et al., 1998; Jung et al., 1995; El Morhit et al., 2009). Thus, according to Chon et al. (1998), the pollution index is defined as the average of the ratios of metal concentrations in soil samples compared to the limit values.

The pollution index in our case is then as follows:
IP = (V/200+ Cr/150+Mn/2000+ Ni /50+ Cu/100+ Zn/300+ Cd/3+ Pb/100) /8.

Therefore, for our case we have, taking into account the elements listed above, the following (table 9).

Table 9: Results of IPs in soils

Elts/écht	MK8		MK13	
	A1	A2	A3	A4
V	0.1	0.1	0.14	0.31
Cr	0.14	0.08	0.18	0.21
Mn	0.02	0.01	0.02	0.02
Neither	0.03	0.01	-	-
Cu	0.04	0.02	0.03	0.04
Zn	0.01	0.01	0.01	0.02
CD	0.16	0.13	0.04	0.15
Pb	0.03	0.02	0.03	0.05
IPS	**0.06**	**0.05**	**0.06**	**0.11**

After these calculations, we notice that the contamination in our samples is *absent or low*. This is explained by the fact that all IP values are less than 1. On the other hand, the highest IP value is displayed on the MK13 sample, more precisely at the A4 horizon, i.e. 0.11, but which is however not always greater than 1.

Correlation of descriptive parameters and trace elements

Having previously four components (A1, A2, A3, A4) which cannot have a normal representation, we produced a two-component matrix (Table 10), which can allow us to correlate our descriptive parameters in two dimensions.

The correlation in the descriptive parameter space shows that coarse sand is anti-correlated with coarse silt. The same is true for pH and fine sand. On the other hand, a positive correlation between clay and coarse silt is highlighted.

Additionally, we have the trace element correlation matrix, which shows us the effective, negative, and positive correlation (Table 11).

Table 10: Component matrix for the two-dimensional representation of descriptive parameters

Component matrix		
	Component	
	1	2
HAS	0.905	-0.120
Lf	0.940	0.113
Lg	0.924	-0.374
pH	0.573	0.710
Sf	-0.921	-0.283
Sg	-0.383	0.835

Table 11: Correlation of elements according to their variability (correlation coefficients "r")

Correlations													
		Al	**V**	**Cr**	**Mn**	**Fe**	**Neither**	**Cu**	**Zn**	**Sr**	**Zr**	**Ba**	**Pb**
Al	Pearson correlation	1	0.883 **	0.058	0.202	0.222	0.738 **	0.522	-0.084	0.317	0.358	0.209	-0.225
V	Pearson correlation	0.883 **	1	-0.195	0.307	0.007	0.524	0.388	-0.387	0.270	0.404	0.156	0.142
Cr	Pearson correlation	0.058	-0.195	1	-0.299	0.754 **	0.398	0.445	0.441	0.358	0.140	0.204	-0.152
Mn	Pearson correlation	0.202	0.307	-0.299	1	-0.411	-0.406	-0.343	-0.564	-0.148	-0.229	0.191	0.230
Fe	Pearson correlation	0.222	0.007	0.754 **	-0.411	1	0.651 *	0.704 *	0.568	0.361	0.307	0.642 *	-0.439
Neither	Pearson correlation	0.738 **	0.524	0.398	-0.406	0.651 *	1	0.855 **	0.268	0.511	0.406	0.238	-0.461
Cu	Pearson correlation	0.522	0.388	0.445	-0.343	0.704 *	0.855 **	1	0.267	0.791 **	0.223	0.373	-0.363
Zn	Pearson correlation	-0.084	-0.387	0.441	-0.564	0.568	0.268	0.267	1	0.139	0.252	0.234	-0.451
Sr	Pearson correlation	0.317	0.270	0.358	-0.148	0.361	0.511	0.791 **	0.139	1	0.088	0.143	0.050
Zr	Pearson correlation	0.358	0.404	0.140	-0.229	0.307	0.406	0.223	0.252	0.088	1	0.026	0.292
Ba	Pearson correlation	0.209	0.156	0.204	0.191	0.642 *	0.238	0.373	0.234	0.143	0.026	1	-0.367
Pb	Pearson correlation	-0.225	0.142	-0.152	0.230	-0.439	-0.461	-0.363	-0.451	0.050	0.292	-0.367	1
**** The correlation is significant at the 0.01 level**													
*** The correlation is significant at the 0.05 level**													

About eighty percent (80%) of the element ratios show positive correlations, such as Mn/V, Ni/Zn and Ba/Cu. But only about twenty percent (20%) show negative correlations, i.e., they are anti-correlated, such as Zn/Al, Ni/Mn and Pb/Ba. On the other hand, Cu and Mn show low coefficients, which seem to indicate that these elements do not show affinity with other MNEs.

Regarding positive and significant correlations, 3 categories can be defined:
- ✓ the first grouping together TMEs having a relatively low correlation coefficient ($r < 0.5$) such as Zr/Zn or Ni/Cr for example;
- ✓ the second concerning the moderately correlated ETMs ($0.5 < r < 0.7$) such as Ni/Sr or V/Ni;
- ✓ the third grouping the positive and strong correlations with $r > 0.7$. These are the cases of the Cu/Sr couple.

All of these correlations highlight a common behavior and/or a common origin of these metals.

Comparison of sediment and water results

The values obtained in water are lower than those in soil. Consider the practical example of lead (Pb) in the figures below (Fig. 9 and 10).

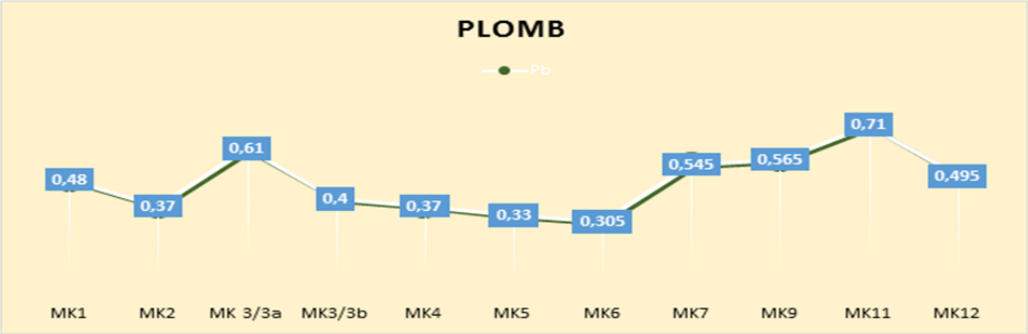


Fig. 9: Behavior of Pb in water samples

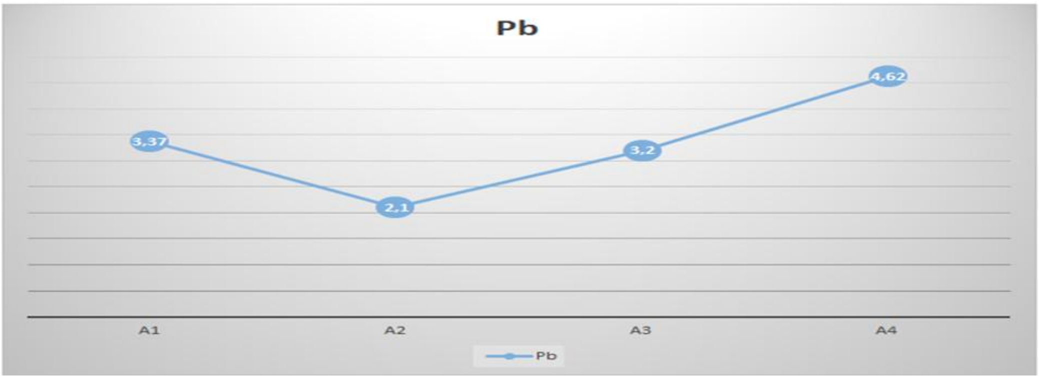


Fig. 10: Behavior of Pb in sediment samples

In water, the lead content varies as a function of the fluctuation of the water table. This clearly explains the ineffectiveness of a tactical geochemical study in an aquifer. On the other hand, in sediments, the content increases approximately from bottom to top (if we consider A1=A2). That is to say, this element, which is probably mobilized by the water of the Lufuku River, upon reaching the cofferdam level, infiltrates through the site formations, giving at the outlet, much higher contents than their source zone. That being said, we note that at the level of sample MK11 (the diversion zone), the content is higher than at the water outlet; this is due, as a result, to the accumulation of elements that probably occurs during infiltration. We also note that the TME contents in sediments are higher than in water.

Comparative evaluation between the soils of the Kakobola hydroelectric development site, the Noun watershed (West Cameroon) and world averages

The table below (Table 12) shows us the contents of TMEs contained in the soils located below and above the soft sandstone in the Kakobola Hydropower Site (KHS), and the analyses obtained for the soils of the Noun watershed (Njofang et al., 2007 and Njofang et al., 2008) compared to global soils.

Table 12: Comparison between soils of Kakobola, the Noun watershed and global soils

TME	KHS				Noun watershed	World average	Unit
	A1	A2	A3	A4			
Al	21,880	11,400	31,820	42,000	85,989	150,000	mg/kg
Ba	53.88	65.75	47.83	43.93	188	500	mg/kg
CD	0.49	0.39	0.13	0.45	0.05	0.3	mg/kg
Cr	21.12	11.55	27.65	31.27	99	80	mg/kg
Cu	4.04	1.83	2.94	3.75	34	25	mg/kg
Fe	6,750	3,870	9,720	12,800	91,886	50,000	mg/kg
Mn	44.7	10.39	49.48	31.75	767	700	mg/kg
Neither	1.65	0.65	-	-	55	20	mg/kg
Pb	3.37	2.1	3.2	4.62	18	17	mg/kg
V	20.18	21.04	27.65	61.99	185	90	mg/kg
Zn	3.49	2.33	4.31	6.58	90	70	mg/kg

For most of the trace elements in the soils of the Noun River watershed, the concentrations are equal to or less than slightly above the geochemical background. For example, lead (18 mg. kg $^{-1}$) is slightly above the average value (17 mg. kg $^{-1}$) or a five percent excess. Similarly, Cd (0.05 mg. kg $^{-1}$) is ten times lower than that of polluted or slightly polluted soils, but six times lower than the global average value of 0.3 mg. kg $^{-1}$. On the other hand, most of the TMEs in Kakobola Hydropower Site are far below the global average. For example, manganese with 44.7; 10.39; 49.48; 31.75 mg. kg $^{-1}$ respectively for A1, A2, A3 and A4, are below the average or one to ten percent of the global average.

Moreover, the soils of the Noun River watershed are more polluted than those of the KHS. Consequently, the latter's depletion in cultivation is due to the soil texture, which is ninety percent sandy, hence the low retention of nutrients constitutive for plants.

It is worth mentioning that trace element values higher than or equal to the global average values such as in the case of Cr, Cu, Fe, Mn, Ni, Zn, V and Pb do not necessarily mean an anthropogenic factor of contamination or pollution. The raw values used to calculate the global values are taken from studies using an array of analytical techniques, different types of soils and rocks. Furthermore, the assumption of anthropogenic influence cannot be based solely on global average values. Comparison to normal ranges and acceptable levels in soils must be taken into consideration. In this context, all trace elements showing values higher than the global average values are in fact within normal ranges (Fiedler and Rösler; 1993) and below the thresholds of acceptable levels (Henin, 1983). Overall, a geogenic origin is more plausible for most cases, as far as MTEs are concerned.

V. Conclusions

For a definitive conclusion, we would first like to emphasize that the problems of water ingress and percolation are due to the geological conditions of the site where a relatively competent sandstone sill overhangs a significantly softer, more eroded and more permeable sandstone formation in which there are significant cavities and voids. Thus, all of this should be well known and understood to foresee the work of treating this ground, at the risk of jeopardizing the safety and stability of the SAHK structures.

On the Hydrogeochemical level :

In sediments samples, the levels of TMEs showed that they do not come from an industrial source but rather from anthropogenic activities, including incineration, agriculture, liquid and solid waste, erosion and infiltration, thus leading to low contamination of these. Concerning water, the levels of TMEs set by the WHO are very low compared to the levels measured after analysis, which proves that these waters are not of good quality for the population's food supply. In addition, groundwater cannot tactically constitute a real source of the origins of TMEs, therefore, the TME levels they contain come from a distant source.

On the Hydrogeological level :

The problem that has arisen since then has been to determine the origin of the percolation water flowing into the downstream part of the Kakobola Dam site. Firstly, the drilling carried out has shown that the area is entirely occupied by a water table.

Regarding the hydrogeological section, the KHS sits entirely on a shallow water table. The water table is fed by the Lufuku River itself. This recharge occurs quickly due to the physical behavior of the site's geological formations. This then explains the causes of water inflows and percolation at the power plant.

After the chemical analyses, we found that the TME contents do not have considerable differences, starting from the water sources discovered much further upstream of the dam, passing through the Lufuku River itself to the downstream level of the dam, more precisely at the power plant and even going beyond there to the Badi River. This leads us to conclude that these water inflows only come from the Lufuku River, but which flow to the power plant through the cofferdam through the permeability of the geological formations of the site. Given the unavailability and inaccessibility of equipment that could be used to further study the hydrogeochemical regime of our study area, we suggest isotopic analyses of water and soil in the wider area; qualitative studies of major elements for all waters in the sector; geochemical analyses of rocks in the area; and microgravimetric studies of the sector.

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