Geochemical analysis of sediment samples from Asmara drinking water reservoirs for estimation of contamination by heavy metals (IV)

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Abstract

The aim of the present investigation is to identify and quantify the concentration levels of heavy metals in the sediment samples collected from two Asmara City drinking water reservoirs of Mainefhi and Toker. The objective is to determine the geochemical parameters of contamination that may contribute in the evaluation and description of the current pollution state of these two sites. The study was conducted during the period extended between August 2014 and August 2015. A total of 16 samples were collected from the reservoirs sites. Qualitative and quantitative analysis was performed via the use of both Atomic Absorption Spectrometry. The mean concentration levels of heavy metals in the sediment of Mainefhi were Co 0.79 mg/kg, Cr 14.61 mg/kg, Cu 8.17 mg/kg, Fe 11,422 mg/kg, Mn 87.25 mg/kg, Ni 4.54 mg/kg, Pb 1.75 mg/kg and Zn 5.77 mg/kg. Likewise, mean concentration levels for Toker sediment were Cd 0.005 mg/kg, Co 33.86 mg/kg, Cr 252.6 mg/kg, Cu 83.4 mg/kg, Fe 87,503 mg/kg, Mn 1455.7 mg/kg, Ni 87.8 mg/kg, Pb 5.01 mg/kg and Zn 88.9 mg/kg. With the exception of Cr, Fe, Mn, and Ni in Toker sediment, all the other values were below the consensus-sediment quality guidelines of NOAA. The calculated Geo-accumulation indices (*I-geo*) implied that Mainefhi sediment (*I-geo* < 0) was assessed as unpolluted and Toker sediment (*I-geo* < 0 to < 1) as unpolluted to moderately polluted. The calculated Enrichment factor (*EF*) for the sediments of Mainefhi (*EF* = 0-1) and Toker (*EF* = 0.01-1.5) were indicative of an environmental situation of no or little influence by anthropogenic pollution input. Similarly, the CF and CD) for Mainefhi sediment were both <1, indicative of low contamination and that of Toker with CF = 0.02-1.9 and CD = 12 demonstrated moderate contamination. Accordingly, all the geochemical parameters demonstrated that there was no or moderate pollution and little or no anthropogenic factors were involved in the current pollution state of the reservoirs.

Key Words: Sediment, Heavy Metals, Concentration Levels, Geochemical Parameters, Degree of Pollution, Geo-accumulation Indices, Enrichment Factor

Introduction

Sediment is the loose sand, clay, silt and other soil particles that settle at the bottom of a body of water. Most mineral sediment comes from erosion and weathering, while organic sediment is typically detritus and decomposing material from plants and animals. Wind, water and ice help carry these particles to rivers, streams, lakes and reservoirs. Sediment is a naturally occurring element in many bodies of water, though it can be influenced by anthropogenic factors (Mid-America Regional Council, 2016; Fondriest Environmental Inc., 2014). The Environmental Protection Agency lists sediment as the most common pollutant in such surface water bodies (Mid-America Regional Council, 2016).

Heavy metals are among the most common environmental pollutants in reservoirs and their occurrence in the sediment, waters and biota indicate the presence of pollution from natural (e.g. eroded minerals within sediments, leaching of ore deposits and volcanism extruded products) or anthropogenic (e.g. solid waste disposal, industrial or domestic effluents, agricultural and mining runoffs) sources (Momodu and Anyakora, 2010). After being introduced into the aquatic environment, heavy metals from the aqueous phase eventually become deposited to sediment through complex physical and chemical adsorption mechanisms depending on the nature of the sediment matrix and the properties of the adsorbed compounds (Ankley et al., 1992; Caccia et al., 2003). Sediment acts as both carrier and potential source of contaminants for the aquatic environment. The sediment does not necessarily fix contaminants permanently, under changing environmental conditions (temperature, pH, redox potential, salinity), they may be released to the water column by various processes of remobilization. Interactions commonly occur in the sediment-water interface (Chapman, 2000; Soares et al., 1999).

The Contamination of sediment by heavy metals and other pollutant chemicals is one of the major threats to aquatic ecosystems and leads to serious environmental problems (Loizidou et al., 1992). Of the chemical pollutants, heavy metals being non-biodegradable, can increase in concentration along the food chain producing their toxic effect even at points far removed from the source of the pollution (Thomlinson et al, 1980). Exposure to heavy metals is linked to several human health problems such as developmental malformation, kidney damage, cancer, abortion, effects on intelligence and behavior, and even death in some cases of exposure to very high concentrations (Ghrefat and Yusuf, 2006; Thomlinson et al, 1980).

Sediment can be sensitive indicator for monitoring contaminants in aquatic environments (Pekey et al., 2004). Therefore, the environmental problem of sediment pollution by heavy metals has received increasing attention in the last few decades in both developing and developed countries throughout the world (Zhang et al., 2007). Sediment is responsible for the transport, release and accumulation of toxic compounds and nutrients, and may represent a source of metal contamination of the aquatic environment. Therefore, sediment is an important compartment for the study of contamination of the water reservoir since it acts as a sink for environmental contaminants (Power and Chapman, 1992) and the knowledge of their chemical characterization is necessary for the understanding of natural processes and human influence on these proceedings (IAEA, 2003). In the aquatic ecosystem, sediment has been commonly used as an environmental indicator due to its high physical-chemical stability and its chemical analysis can provide considerable information on the assessment of anthropogenic activities (Malhotra e al., 2014). Moreover, distinguishing the anthropogenic inputs from the natural ones is the basis of environmental management (Wu et al., 2007). The occurrence of elevated levels of trace metals in sediments can be a good indication of man-induced pollution where high levels of heavy metals can often be attributed to anthropogenic influences, rather than natural enrichment of the sediment by geological weathering (Davies et al., 1991).

The assessment of sediment contamination and enrichment with elements can be carried out in many ways. The most common ones are the Geochemical parameters that include, geoaccumulation index (Igeo), enrichment factor (EF), contamination factor (CF), contamination degree (CD) and pollution load index (PLI). These parameters are designed to assess the pollution status, indicate the source of contamination as to whether natural or anthropogenic and give a summative picture of the overall level of heavy metal toxicity in the sediment samples (Priju and Narayan, 2006).

The main objective of the present study, which is the first of its kind on the Mainefhi and Toker reservoirs that supply drinking water to Asmara city (Eritrea), is to determine the concentration levels of the heavy metals Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb and Zn in the surface sediment of the two reservoirs, to assess the pollution status of the sediment and identify the anthropogenic or natural sources of the heavy metals by the application of different methods of geochemical criteria parameters. These reservoirs, in addition to serving as drinking water sources, are also used for the development of freshwater fish breeding which are intended for the surrounding communities. Accordingly, the study and evaluation of heavy metals in the sediment of these reservoirs is essential. Moreover, the outcomes of this study may give a preliminary insight and indication of the mineralogical composition of the surrounding highlands around these reservoirs. The results obtained can also be used by the authorities for the monitoring, management, and remediation of the water quality and serve as a baseline for further studies of these water reservoirs.

Materials and methods

Description of Sampling Site

The current study was carried out on the two main water reservoirs of Mainefhi and Toker supplying the bulk of the raw water to the Asmara drinking water supply system. These reservoirs collect rainwater from the surrounding catchment of hills and mountains during the rainy season months of June to September. Asmara city is the capital of the state of Eritrea and is located at coordinates of 15.33º N, 38.93º E and an elevation of 2,325 meters above sea level in the central highlands of Eritrea (Figure 1).

Figure 1: Map of Eritrea.

Sample Collection

A total of 16 sediment samples were collected from four sites within each of the two reservoirs, during the rainy season period in August (2014) and the dry season period in March (2015). The sediment samples were collected by using clean plastic scoop and stored in polyethylene bags. The samples were then, air dried, carefully packed and transported to the laboratory in Khartoum where they were processed and analyzed upon arrival.

Preparation of Sediment Samples

In the laboratory, the sediment samples were grounded using pestle and mortar and sieved with 2 mm sieve to obtain fine powder. Conventional aquaregia (1:3 HNO_3–HCl, v/v) digestion was performed in 250 ml Teflon beakers. A well-mixed sample of 0.5 g of the sieved sediment was digested in 12 ml of freshly prepared aquaregia solution on a hotplate for 3 hours at 110ºC. The solution was then evaporated to near dryness. The sample was diluted with aqueous nitric acid (20 ml, 2%), filtered through Whatman No. 42 paper into a 100 ml volumetric flask, and then diluted to 100 ml with deionized distilled water (Chen and Ma, 2001). Every precaution was taken to avoid contamination during sampling, drying, grinding, sieving and storage.

Determination of heavy metals by Atomic Absorption Spectrometer

Determination of metal concentrations present in the sediment samples was done by Flame Atomic Absorption Spectrometer (Model: *Shimadzu AA-7000*, Japan) using air-acetylene flame. Calibration line method was used for the quantification of selected metals and the digests were appropriately diluted whenever required (Radojevic and Bashkin, 1999). All measurements were made in triplicate. Blank solutions prepared similarly and standard reference materials were also analyzed alongside with the samples.

Data Analysis

Geochemical criteria, that is, Geo-accumulation index (*I-geo*) as defined by Müller (1969), enrichment factor (*EF*) as defined by Rubio et al, (2000), contamination factor (*CF*) of heavy metals and contamination degree (*CD*) of sampling sites defined by Håkanson (1980) and pollution load index (*PLI*) defined by Thomlinson et al. (1980) were determined as essential calculations for assessment of the sediment pollution status.

The Geo-accumulation index (*I-geo*) was calculated as follows (Mediola et. al, 2008):

$$I\text{-geo} = \log_2 [C_n / 1.5 B_n] \tag{1}$$

Enrichment factor *EF* was calculated as the ratio of elemental concentration of sediment normalized to *Fe* (Muller, 1981):

$$EF = (C_n / Fe)\text{sediment} / (C_n / Fe)\text{reference} \tag{2}$$

Contamination factor *CF* was determined as (Håkanson, 1980):

$$CF = C_n / B_n \tag{3}$$

The contamination degree (*CD*) was defined as (Aksu et al., 1998):

The sum of all contamination factors (*CF*)   (4)

Pollution load index (PLI) was developed as (Thomlinson et al., 1980):

$$PLI = (CF1 \ x \ CF2 \ x \ CF3 \ x .... \ x \ CFn)^{1/n} \tag{5}$$

In the above formulas, C_n is the concentration of the examined element 'n' in the surface sediments, and B_n is the geochemical background concentration of metal 'n'; whereas in the PLI formula, 'n' is taken as the number of metals. The world surface rock average (Martin and Maybeck, 1979) is used as background concentration reference for this study. The factor *1.5* in the *I-geo* formula (1) is incorporated to account for possible variation in the background data due to lithologic effect (Mediola et. al, 2008). The *EF* geochemical normalization (2), was obtained using *Fe* as the reference element and as a conservative tracer to differentiate natural from anthropogenic components, following the hypothesis that its content in the earth crust has not been troubled by anthropogenic activity and because natural sources (98%) greatly dominate its contribution (Tippie, 1984).

Statistical Analysis

The computer software ''Statistical Program for Social Sciences'' (SPSS, PASW Statistics 18, SPSS Inc.) was used for data analysis. Comparisons and significance tests were run with *Mann-Whitney U* (2-tailed) test from within the SPSS statistical program. Differences were considered significant if calculated *p*-values were < 0.01.

Results and Discussion

The results of the mean annual concentration levels of the heavy metals in the sediment of both the reservoirs of Mainefhi and Toker are shown in Table 1 together with the National Oceanic and Atmospheric Administration (NOAA) standard guideline levels for heavy metals in freshwater surface sediments called the consensus-sediment quality guidelines (CSQGs).

Table 1: Mean concentrations of heavy metals (ppm) in the sediment samples of Mainefhi and Toker reservoirs with NOAA guidelines

Source	Cd	Co	Cr	Cu	Fe(%)	Mn	Ni	Pb	Zn
Mainefhi Sed.	BDL	0.79	14.61	8.17	1.14	87.25	4.54	1.75	5.77
Toker Sed.	0.005	33.86	252.6	83.4	8.75	1455.7	87.81	5.01	88.92
TEC[a]	0.99	50[b]	43.3	31.6	2[b]	460[b]	22.7	35.8	121.0
PEC[a]	4.90	NG	111.0	149.0	4[c]	1100[c]	48.6	128.0	459.0

BDL= Below detection limit; Sed. = Sediment; TEC = Threshold Effect Concentration; PEC = Probable Effect Concentration.
a = TEC and PEC Source is the National Oceanic and Atmospheric Administration (NOAA) (NOAA, 2009).
b = The Lowest effect level (LEL) concentration is used instead. (For Co, only LEL is given as 50+ ppm) (NOAA, 2009).
c = The Serious effect level (SEL) concentration is used instead (NOAA, 2009).

For Mainefhi reservoir sediment, the mean concentration levels of the metals were (Table 1): Co 0.79 mg/l, Cr 14.61 mg/l, Cu 8.17 mg/l, Fe 11,421.9 mg/l (1.142%), Mn 87.25 mg/l, Ni 4.54 mg/l, Pb 1.75 mg/l and Zn 5.77 mg/l, whereas the concentration for Cd was below detection limit. The mean levels in Toker sediments also were: Cd 0.005 mg/l, Co 33.86 mg/l, Cr 252.6

mg/l, Cu 83.4 mg/l, Fe 87,502.6 mg/l (8.75%), Mn 1455.7 mg/l, Ni 87.81 mg/l, Pb 5.01 mg/l and Zn 88.92 mg/l. Comparison between mean concentrations of heavy metals of both reservoirs with Mann-Whitney 2-tailed Test showed that concentration levels for the metals at Toker reservoirs significantly exceeded (p<0.01) those of Mainefhi, with the exception of Pb (p=0.450).

It is important to mention, in this context, that especially the catchment area of Toker reservoir includes the *Embaderho* locality, which is described as an area rich in minerals and a prospective mining site (Ministry of Energy and Mines, 2014). This could be the reason for the significant difference in the concentration of metals in the sediment of this reservoir with that of Mainefhi sediment. However, anthropogenic pollution of the area is unlikely as there are no industries and not much transport or traffic related activities around these reservoirs so far (Zerabruk et al, 2015).

The concentration levels in the sediments of both reservoirs were also compared to the CSQGs of NOAA (2009) to assess their status, because once environmental conditions are changed, heavy metals in sediments can be secondary sources of pollution to the reservoir water (Chen et al, 1996). CSQGs include a threshold effect concentration (TEC) and a probable effect concentration (PEC) (Table 1). Concentration of the contaminant in sediment below TEC means adverse biological effects are unlikely to occur (US EPA, 2000). Conversely, adverse biological effects are likely to occur if contaminant is above PEC level (Smith, et al, 1996). MacDonald, et al (2000), noted that most of the TEC provide an accurate basis for predicting the absence of sediment toxicity, and most of the PECs, provide an accurate basis for predicting sediment toxicity. In this study, the mean concentration levels of all the heavy metals in the sediment samples of Mainefhi and that of Cd, Co, Pb and Zn in Toker are lower than the proposed TECs, indicating that there are no harmful effects from these metals in the sediments. On the other hand, the concentrations of Cr, Fe, Mn, and Ni in the Toker sediment exceeded PEC levels, which suggest that these metals are most likely to cause adverse effects on the aquatic organisms living in the reservoir.

Geochemical criteria analysis:

To assess whether the presence of the trace metals in the sediment of these reservoirs was due to natural processes or anthropogenic activities and to estimate the contamination degree, geochemical analyses of the concentration levels of the metals in the sediments were done. These included the geoaccumulation index (*Igeo*), enrichment factor (*EF*), contamination factor (*CF*), contamination degree (*CD*) and pollution load index (*PLI*).

Geoaccumulation index (*Igeo*)

Geoaccumulation index values are widely used to assess the degree of metal accumulation and contamination in terrestrial, aquatic and marine environments (Tijani and Onodera, 2009). The

geoaccumulation index scale, as defined by Muller (Muller, 1969), consists of seven grades (0-6) ranging from unpolluted to extremely polluted (Table 2).

Table 2: Muller's classification for Geoaccumulation index (*Igeo*) scale

Igeo value	Class	Qualification of sediment
0	0	Unpolluted
0-1	1	From unpolluted to moderately polluted
1-2	2	Moderately polluted
2-3	3	From moderately polluted to strongly polluted
3-4	4	Strongly polluted
4-5	5	From strongly polluted to extremely polluted
>5	6	Extremely polluted

The calculated Igeo results for the sediment samples (Table 3) indicated that according to the Muller scale, the Mainefhi sediment was unpolluted, with values for all metals being Igeo $\leq$ 0. On the other hand, the Toker sediment was 'from unpolluted to moderately polluted' for Co (0.18), Cr (0.90), Cu (0.31), Fe (0.34), and Mn (0.19), all having Igeo = 0-1, with the exception of Cd, Ni, Pb and Zn which were below zero. On the basis of the mean values of Igeo, the Toker sediment is enriched for metals in the following order: Cr > Fe > Cu > Mn > Co.

Table 3: Geo-accumulation index of metals in Mainefhi and Toker reservoirs sediment

Reservoir	Cd	Co	Cr	Cu	Fe	Mn	Ni	Pb	Zn
Minefhi	0	-5.25	-3.21	-3.05	-2.59	-3.87	-4.49	-4.10	-4.63
Toker	-6.49	0.18	0.90	0.31	0.34	0.19	-0.22	-2.58	-0.68

Igeo levels of the metals Cr, Cu, Mn, Ni and Zn in sediments from the reservoirs in this study agree with those of Asejire resorvior, Nigeria (Godwin, et al. 2015). With the exception of the levels for Cr (0.9), Cu (0.31) and Mn (0.19) of Toker sediment, which are classified as unpolluted to moderately polluted, all the calculated levels for the metals of Mainefhi sediment and levels of Ni and Zn for Toker sediment were below zero (unpolluted). For Fe, however, the Igeo of 12.62 (extremely polluted) for Asejire reservoir is several folds higher than the Fe values in the sediment of both Mainefhi (-2.59) and Toker (0.34) reservoirs, which are of levels no and moderately polluted.
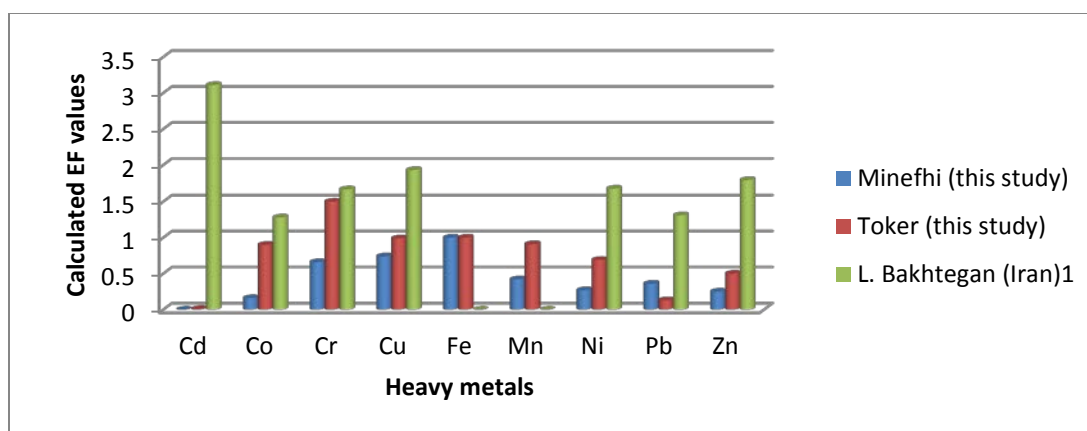
Enrichment Factor (EF)

To differentiate between the metals in sediments originating from anthropogenic activities and those from natural processes, and to assess the degree of anthropogenic influence a normalized enrichment factor (*EF*) is calculated using the metal concentrations. *EF* is calculated by a comparison of each tested metal concentration with that of a reference metal (Muller, 1981). The normally used reference metals are manganese, aluminum and iron (Liu et al, 2005). In this study iron was used as a conservative tracer to differentiate natural from anthropogenic components, following the hypothesis that its content in the Earth's crust has not been troubled by anthropogenic activity and it has been chosen as the element of normalization because natural sources (98%) greatly dominate its contribution (Tippie, 1984). According to Sutherland (2000), five contamination categories are defined for the enrichment factor, 'EF < 2' is deficiency to minimal enrichment, 'EF = 2-5' moderate enrichment, 'EF = 5-20' significant enrichment, EF = 20-40 very high enrichment and EF > 40 as extremely high enrichment (Table 4). As the EF values increase, the contributions of the anthropogenic origins also increase (Sutherland, 2000).

Table 4: Classification of enrichment factor categories

EF value	Qualification of sediment
EF < 2	Deficiency to minimal enrichment
EF = 2-5	Moderate enrichment
EF = 5-20	Significant enrichment
EF = 20-40	Very high enrichment
EF > 40	Extremely high enrichment

The *EF* values calculated for the metal contents of the Mainefhi reservoir sediment (Figure 2) were, in descending order: Fe (1.0) > Cu (0.74) > Cr (0.66) > Mn (0.42) > Pb (0.36) > Ni (0.27) > Zn (0.25) > Co (0.16) > Cd (0); likewise, the EF values for Toker reservoir sediment were: Cr (1.5) > Fe (1.0) > Cu (0.99) > Mn (0.91) > Co (0.9) > Ni (0.69) > Zn (0.5) > Pb (0.13) > Cd (0.01). The calculated *EF* values for the heavy metals in the sediments of both reservoirs indicate that there is little or no influence by anthropogenic input in regards to the measured heavy metals with *EF < 2*.

1 = Assessment of trace elements contamination in surface sediments of the Bakhtegan lake, Iran (Shakeri et al, 2014)

Figure 2: Enrichment Factor (EF) values of the metals in sediments of this study compared to Lake Bakhtegan (Iran)[1].

The EF values of this study were compared to EF calculated levels of metals in the sediments of Lake Bakhtegan, Iran (Figure 2). The values of this study as well as the Lake Bakhtegan study (Shakeri et al, 2014), with the exception of the level for Cd in the sediment from Lake Bakhtegan, were EF<2, which indicates that the metals in the sediments originate basically from natural processes.
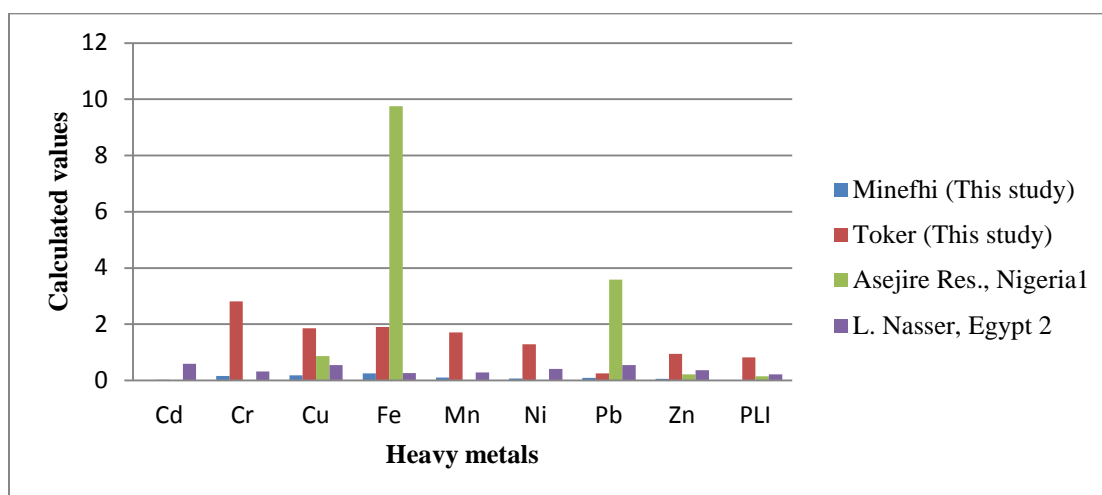
Contamination Factor (*CF*), Contamination Degree (*CD*) and Pollution Load Index (PLI)

In the present study the contamination factor (*CF*) and contamination degree (*CD*) are used to assess the contamination status of sediments in the reservoirs. Håkanson (1980) described *CF* as a ratio of the concentration of the element in samples to the pre-industrial reference value for the element. In this study, the world surface rock average values (Martin and Maybeck, 1979) are used for the calculation of *CF* as reference baselines. The degree of contamination (*CD*) used in this study is also defined as the sum of all *CF* values of the heavy metals (Aksu et al, 1998). Both *CF* and *CD* are classified in five categories (Table 5) according to the definition by Håkanson (1980). Another powerful tool geochemical tool, the pollution load index (PLI), which was developed by Thomlinson et al. (1980), is also used in heavy metal pollution evaluation. Values of PLI > 1 imply that heavy metal pollution exists while PLI < 1 indicate no pollution (Thomlinson et al., 1980; Chakravarty and Patgiri, 2009).

Table 5: Contamination factor (*CF*) and contamination degree (*CD*) categories and terminologies

CF classes	*CF* and *Cd* terminologies	*Cd* classes
CF < 1	Low *CF* indicating low contamination / Low *Cd*	*Cd < 6*
1 ≤ CF < 3	Moderate *CF / Cd*	$6 \leq Cd < 12$
3 ≤ CF < 6	Considerable *CF / Cd*	$12 \leq Cd < 24$
CF ≥ 6	Very high *CF / Cd*	*Cd ≥ 24*

The calculated contamination factor (*CF*) results (Figure 3) indicated that Mainefhi sediment was not polluted (*CF*<1), while the Toker sediment was also not polluted for Cd, Pb and Zn, which have *CF*<1, whereas it was moderately contaminated for Co, Cr, Cu, Fe, Mn and Ni, where the values are *CF = 1-3*. Accordingly, metal contamination levels were in order of Cr >Fe > Cu > Mn > Co > Ni in Toker sediment. Similarly, the *CD* calculation also showed that Mainefhi sediment was not contaminated (*CD<1*), while Toker sediment was in the 'moderate contamination degree' (*CD = 6-12*).

1 = Assessment of heavy metal pollution and sediment quality of Asejire reservoir, southwest Nigeria. (Godwin et al., 2015)
2 = Metal assessment in the surface sediment of Lake Nasser, Egypt. (Goher et al., 2014)

Figure 3: Comparison of Contamination factor and Pollution load index values metals in this study with those of other studies.

A similar study of Lake Nasser sediments (Goher et al., 2014) the values of *CF* of the metals Cd, Cr, Cu, Fe, Mn, Ni, Pb and Zn agreed with that of Mainefhi sediment values, no contamination, in the current study (Figure 3). The study of Asegire reservoir sediments (Godwin et al., 2015)

also similar no contamination for Cr, Cu, Mn, Ni and Zn (*CF*<1), while it was considerable pollution for Pb (*CF*=3.6) and very high pollution for Fe (*CF*=9.8).

Calculated PLI values for the sediment of Mainefhi and Toker reservoirs was less than one, which implying that the sediment was unpolluted for the assessed metals (Figure 3). Similar results were also obtained for sediments of Asejire reservoir, Nigeria (Godwin et al., 2015) and Lake Nasser, Egypt (Goher et al., 2014), whereas the PLI level of > 1 was calculated for Lake Vembanad, India (Harikumar et al., 2009) suggesting presence of heavy metal contamination in its sediment.

Conclusion

The present study shows that the heavy metals levels in the sediment of the two reservoirs were within the recommended values of CSQGs, with the exception of Cr, Fe, Mn and Ni in Toker sediment, which were higher than the guidelines. The geochemical parameters, *Igeo, EF, CF*, *CD* and *PLI* applied on the sediment of both reservoirs, also indicated there was no to moderate pollution and little or no anthropogenic input of the studied metals. These results, therefore, reinforce the fact that both reservoirs and their catchment areas are not influenced so far by anthropogenic polluting activities. It is noteworthy to mention that this study can serve as baseline information for further research to help in the monitoring of the safety and quality of the reservoirs for domestic water use as it is the first survey of its kind. It is recommended that regular water quality monitoring surveys are essential to enable the evaluation of possible build-up of heavy metals and other hazardous chemicals in the sediment with the impending mining activities in the upper catchments.

Acknowledgements

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