



## Occurrence and Health Risk Assessment of Trace Metals in Groundwater from the Ouémé Delta

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**Abstract:** This study aims to assess the level of metallic contamination of groundwater from the Oueme Delta as well as the potential health risks associated with their consumption. It is part of a context where anthropogenic pressures, including agriculture, urbanization and population growth exert an increasing influence on the quality of water resources in the Oueme Delta. The chemical analysis focused on four traces metals elements (TMEs): lead (Pb), cadmium (Cd), zinc (Zn) and iron (Fe), chosen because of their toxicity and their frequent presence in the groundwater. Metal analyzes were carried out at the flame atomic absorption spectrophotometer. The results reveal that the lead concentrations (average = 0.054 mg/L) and cadmium (average = 0.022 mg/L) present non-conformities compared to the directives of the World Health Organization (WHO) for drinking water, while those of zinc remain below the admissible threshold. Iron, on the other hand, shows significant variability, with a notable reverse correlation with lead ( $r = -0.25$ ), suggesting distinct mobilization mechanisms. The correlations between the metallic traces analyzed are generally low ( $r < 0.50$ ), reflecting the multiplicity of sources and transfer processes. The average values of the degree of contamination (CI) are greater than 3 indicating a high level of contamination of groundwater. This trend is confirmed by the heavy metal assessment index (HEI) which reveals that around 80% of the collected samples have a high level of contamination high. On the health level, the assessment of non-carcinogenic risks through the HQ (Hazard Quotient) and HI (Hazard Index) indices indicates moderate to high risk levels, especially for lead and cadmium. Children appear to be the most vulnerable, due to their increased physiological sensitivity. Although chronic exposure doses (CDI) are relatively low, the lasting presence of these metals in drinking water remains worrying. Prolonged exposure to these contaminated waters could cause harmful effects on public health.

## 1. Introduction

Large African cities are experiencing rapid demographic growth, often causing unplanned and disorderly urbanization (Makinde *et al.*, 2012; Cobbinah *et al.*, 2015; Fayiga *et al.*, 2018; Adedini, 2023). This accelerated dynamic promotes the anarchic extension of urban areas and therefore

intensifies the rejection of pollutants in surface waters and groundwaters (WWAP, 2017; Zoro *et al.*, 2025). The groundwaters play a central role. They are the main source of water supply for populations, especially Beninese, today covering more than 70% of domestic and agricultural needs (WWAP, 2017). However, despite their vital importance, these resources are increasingly exposed to pressures of anthropogenic origin (Alaqarbeh *et al.*, 2022).

Galloping urbanization in large agglomerations such as Porto-Novo and Cotonou, the rise of intensive agriculture massively using chemical inputs, as well as the development of informal industrial activities (discharges, batteries recycling, etc.) contribute to the progressive degradation of water quality (Dovonou *et al.*, 2014). Among the worrying pollutants are the elements metallic traces (ETM) such as lead (Pb), cadmium (Cd), zinc (Zn) and iron (Fe) (N'Dri *et al.*, 2024a). Although naturally present in soils in the state of traces, these metals can be released in groundwater at high concentrations under the effect of human activities. Even in low doses, their persistent presence represents a major health risk (El Hammari *et al.*, 2022; Chowdhury *et al.*, 2024).

In Cotonou, the analysis of soils collected close to landfills highlighted alarming cadmium contamination (6.5 mg/kg) and lead (1,775 mg/kg) (Biaou *et al.*, 2019). These sites often house waste containing batteries, used batteries and electronic equipment, whose leaching under the effect of precipitation promotes the migration of metal traces to groundwater. In addition, the spreading of phosphate fertilizers represents a well-known source of cadmium pollution. The cultivated soil can thus receive additional Cd (up to several tens of mg/kg). Added to this are the uncontrolled discharges of wastewater, treatment sludge or urban streams (Houkpatin *et al.*, 2021). These contributions introduce Pb, Cd and Zn into groundwater.

According to the World Health Organization, exposure to lead is particularly worrying for children, in whom it can cause irreversible effects on the development of the central nervous system, with lasting cognitive disorders. In adults, chronic lead exposure is associated with an increase in the risk of high blood pressure, cardiovascular disease and renal dysfunctions (WHO, 2017). Cadmium, on the other hand, is classified as human carcinogenic in group 1 by the IARC, and it has been linked to several types of cancer, including lung, kidney, bladder and prostate cancers (Firmani *et al.*, 2024). It has the particularity of accumulating slowly in the body, in particular in the kidneys and the skeleton, where it can cause bone demineralization, spontaneous fractures and chronic renal failure. Conversely, zinc is an essential trace element, and its toxicity only manifests itself with strong concentrations (Ugokwe and Awobode, 2015). Its excess in drinking water can however alter the taste or cause a laxative effect, without representing a major health danger below several mg/l. WHO also fixes its guide value at 3 mg/L (WHO, 2017). Similarly, excess iron (> 0.3 mg/l) can harm water clarity and give it an unpleasant metallic odor (Kouyaté *et al.*, 2021).

Overall, the urban and industrial sites of the Beninese coast present the most intense sources of metal pollution (Houkpatin *et al.*, 2021). TMEs pollution indices are simple but effective tools to assess the overall level of metal contamination in the environment (Al-Hejuje, 2017). Several clues have been developed over the years to assess the overall contamination of water by TMEs. Among the most commonly used are the metal load (ML) (Zakir *et al.*, 2020), the degree of contamination index (CI) introduced by Backman *et al.* (1998) and the heavy metal assessment index (HEI) proposed by Edet and Offiong (2020). Groundwaters play a strategic role, not only for irrigation, but also for daily domestic uses. In this context, it is therefore essential to regularly monitor their quality in order to anticipate effective protective measures to limit the risk of metal contamination.



These works were chosen for their good spatial coverage and their proximity to the likely sources of contamination. During these campaigns, polyethylene bottles of 1.5 L, previously washed and sterilized were used for water sampling. The samples thus taken were labeled, hermetically closed and then placed in a refrigerated cooler and quickly transported to the National Water Quality Control Laboratory and Food (ANCQ) in Cotonou in Benin, for chemical analyzes. A few drops of concentrated hydrochloric acid were previously added to the samples for the conservation of ETMs. Metal traces (Pb, Cd, Zn, Fe) in the underground water samples have been dosed using an atomic absorption spectrophotometer (AAS) of the Agilent brand with a detection limit of 0.002 mg/L.

### 2.3 Evaluation of metallic contamination of groundwater

When assessing water quality, various indices are used to assess the level of contamination and the potential risks associated with metal traces. Among the commonly used indices, they are metal load (ML), the degree of contamination (CI) and the heavy metal assessment index (HEI).

#### 2.3.1. Metal load

Metal load (ML) is the arithmetic sum of the concentration of all the metals dosed in the water sample (Sanou *et al.* 2022a, N'Dri *et al.*, 2024b). The ML (mg/L) was calculated using the mathematical relationship given by Eqn. 1 (Zakir *et al.*, 2020):

$$ML = \sum_{i=1}^n C_i = C_{Cd} + C_{Fe} + C_{Pb} + C_{Zn} \quad \text{Eqn. 1}$$

#### 2.3.2. Heavy Metal Evaluation Index

The heavy metal evaluation index (HEI) is a method of estimating water quality by emphasizing metal traces in consumer water (Sobhanardakani, 2016). HEI was calculated according to the formula given by Eqn. 2 (Edet and Offiong, 2020, Rajkumar *et al.*, 2020):

$$HEI = \sum_{n=1}^n \frac{Hc}{Hmac} \quad \text{Eqn. 2}$$

Where: Hc represents the measured concentration of metal in the sample, Hmac corresponds to the maximum admissible concentration of this metal in drinking water and n the number of metals considered in the analysis. HEI may classify into three categories of pollution levels: low (HEI < 10), moderate (10 ≤ HEI ≤ 20) and high (HEI > 20) (Boateng *et al.*, 2015; Ghaderpoori *et al.*, 2018; Saleh *et al.*, 2019). The maximum concentrations used in this study have been obtained from WHO guidelines (WHO, 2017) (Table 1).

**Table 1.** WHO guidelines for the trace metals studied

	Traces metals elements (mg/L)			
	Cd	Fe	Pb	Zn
WHO (2017)	0.003	0.3	0.01	3.00

#### 2.3.3. Contamination degree index

The contamination degree index (CI) makes it possible to assess the degree of contamination or the cumulative effects of different quality parameters, which are considered harmful to domestic water (Backman *et al.*, 1998; Rajkumar *et al.*, 2020). It is generally used to assess the cumulative effect of the metal content in consumer waters compared to recommended international standards (Sanou *et al.*, 2022a; Badeenezhad *et al.*, 2023). The CI is calculated using Eqn. 3 and Eqn. 4:

$$CI = \sum_{i=1}^n CF_i \quad \text{Eqn. 3}$$

$$CF_i = \frac{C_{Ai}}{C_{Ni}} - 1 \quad \text{Eqn. 4}$$

Where  $CF_i$  is the metal contamination factor,  $C_{Ai}$  is the concentration of metal analyzed in the water sample and  $C_{Ni}$  designates the maximum authorized for metal in consumption water (Table 1).

CI values are generally classified into three categories: low contamination ( $CI < 1$ ), average contamination ( $1 < CI < 3$ ) and high contamination ( $CI > 3$ ) (Rajkumar *et al.*, 2020).

#### 2.4. Population health risk assessment

Chronic ingestion of trace metallic elements, beyond the tolerance threshold in humans, can cause harmful effects on health (Sanou *et al.*, 2021a; Maliehe *et al.*, 2024). In this study, we evaluated non-carcinogenic health risks. The non-carcinogenic risk refers to the potential for toxic effects caused by exposure to ingestion to non-carcinogenic metals of concern (Maliehe *et al.*, 2024). The non-carcinogenic health risk has been evaluated using chronic daily intake (CDI), danger quotient (HQ) and danger index (HI).

##### 2.4.1. Chronic Daily Intake

The chronic daily intake (CDI) is the estimate of the quantity of a toxic substance in a food, based on body weight, which is daily ingested by the consumer (Sanou *et al.*, 2021a). The chronic daily intake of metal traces elements, expressed in milligram per kilogram per day (mg/kg/day), was calculated using Eqn. 5 (Alimahammadi *et al.*, 2018; Saleh *et al.*, 2019):

$$CDI = \frac{C \times IR}{BW} \quad \text{Eqn. 5}$$

Where C designates the concentration of metal in water (in mg/L), IR is the ingestion rate (in L/day), BW is the average body weight (in kg) (Table 2).

**Table 2.** Parameters used to assess the risk for the health of groundwater

Parameters	Units	Values		References
		Adults	Children	
Concentration of TME	mg/L	–	–	This study
Ingestion rate (IR)	L/jour	2.5	0.78	USEPA (2014)
Body weight (BW)	kg	65	15	Rajmohan (2022)

##### 2.4.2. Hazard Quotient

Risk assessment provides a rapid and essential method for measuring the effect of trace metal elements on human health. The non-carcinogenic effects of each metal were evaluated by the hazard quotient (HQ). It is a term commonly used to assess the risk of consuming a food. The HQ is the simplest tool for assessing risk and it allows the risk associated with a single metal to be assessed (Sanou *et al.*, 2021a). HQ is defined as the report of the chronic daily dose at the reference dose (Wei *et al.*, 2015). The values of HQ are estimated from Eqn. 6 (Saleh *et al.*, 2019; Soleimani *et al.*, 2022):

$$HQ = \frac{CDI}{RfD} \quad \text{Eqn. 6}$$

Where RfD is the reference oral dose (mg/kg/day) of the metal (Table 3). For HQ values  $\leq 1$ , there are no harmful effects on health and HQ values  $> 1$  indicates that there are probably harmful effects on health (Wei *et al.*, 2015; Sanou *et al.*, 2021a).

**Table 3.** References doses (RfD) of TMEs studied

Traces metals elements	RfD (mg/kg/day)	References
Cd	0.001	
Fe	0.3	USEPA (2003)
Pb	0.0014	USEPA IRIS (2011)
Zn	0.3	

### 2.4.3. Hazard Index

The non-carcinogenic effects due to all TMEs were evaluated using the danger index (HI). The HI was calculated from [Eqn. 7](#) ([Shahsavani et al., 2022](#)):

$$HI = HQ_{Cd} + HQ_{Fe} + HQ_{Pb} + HQ_{Zn} \quad \text{Eqn. 7}$$

If the value of  $HI \leq 1$ , no significant risk of non-carcinogenic effects is supposed to occur. However, if  $HI > 1$ , there is a possibility of non -carcinogenic effects, and this probability increases with HI value ([Wei et al., 2015](#)).

### 2.5. Statistical analysis

In order to establish a relationship between the metallic traces analyzed in the waters, the Bravais-Pearson correlation test was carried out using the R version 4.3.2 software. The linear correlation coefficient R of Bravais-Pearson varies from -1 to +1. The value -1 translates a perfect negative correlation and the +1 value indicates a perfect positive correlation. As for value 0, it shows an absence of correlation between the parameters studied ([Sanou et al., 2022b](#); [N'Dri et al., 2024b](#); [Traoré et al., 2024](#); [Alassane Zakari et al., 2026](#)). The graphics were made with the Origin Lab statistical software.

## 3. Results and Discussion

### 3.1 Heavy Metal Content and Metal Load in groundwater

The results of the statistical analysis of the metal traces elements dosed in the underground water samples are recorded in [Table 4](#). The table presents the minimum, maximum and average concentrations of Pb, Cd, Zn and Fe measured in the waters. The concentrations varied from 0.002 to 0.189 mg/L for Pb, from 0.001 to 0.052 mg/L for Cd, from 0.070 to 1,400 mg/L for Zn and from 0,000 to 5.603 mg/L. The average concentrations of Pb, Cd, Zn and Fe are respectively 0.054; 0.022; 0.238 and 0.484 mg/L in the wells of the Oueme Delta. The elements are abundant in the waters according to the following order:  $Fe > Zn > Pb > Cd$  ([Figure 2](#)).

**Table 4.** Descriptive statistics of metal traces elements in groundwater

	Traces metals elements content (mg/L)				ML (mg/L)
	Lead (Pb)	Cadmium (Cd)	Zinc (Zn)	Iron (Fe)	
<b>Min</b>	0.002	0.001	0.070	0.000	0.168
<b>Max</b>	0.189	0.052	1.400	5.603	5.997
<b>Mean</b>	0.054	0.022	0.238	0.484	0.797
<b>SD</b>	0.040	0.010	0.209	0.889	0.939
<b>WHO (2017)</b>	<b>0.010</b>	<b>0.003</b>	<b>3.000</b>	<b>0.300</b>	-

The results of descriptive statistics on analysis data in metal trace elements ([Table 4](#)) reveal that the majority of TMEs concentrations obtained in the wells, except for Zn have non-conformities by

referring to the WHO guidelines values for drinking waters (WHO, 2017). Indeed, 46 samples (86.79%) for Pb, 48 samples (90.56%) for Cd and 36 samples (67.92%) for Fe have contents above the WHO guide values relating to standard recommended for drinking water (Table 4).

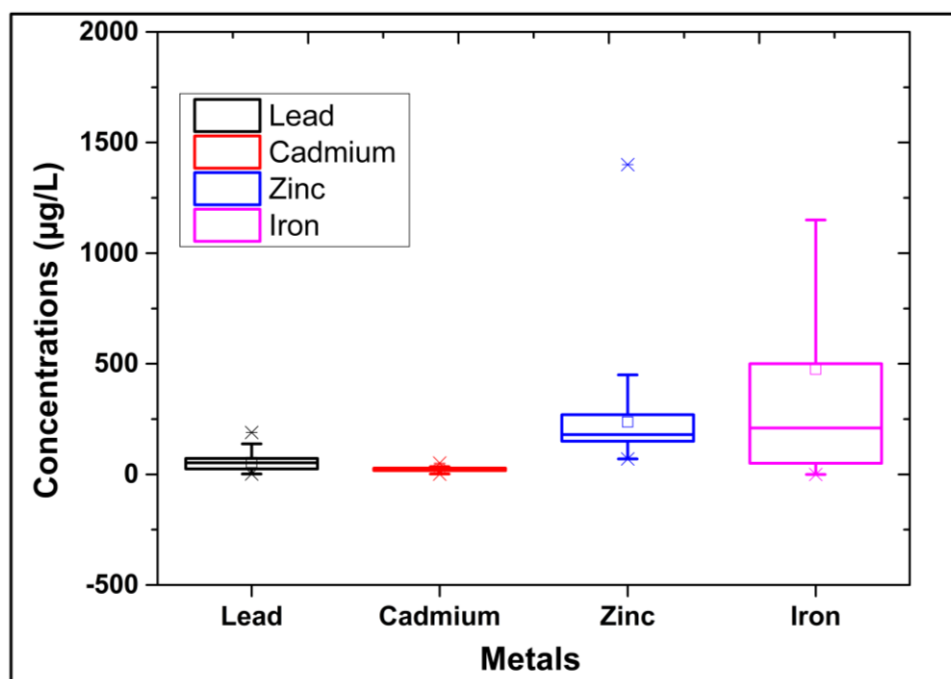


Figure 2. Comparative analysis of TMEs levels detected

The results obtained show contamination of water samples by at least one of the TMEs studied, except Zn. These high concentrations of trace metals in these waters can cause health damage such as cancer, hypertension, pulmonary diseases, gastrointestinal bleeding, kidney disease, neurological disorders and effects on reproduction (Bhan and Sarkar, 2005; Sanou *et al.*, 2020). This is due to their tendency to accumulate in living organisms and concentrate along food chains (Gazi Hasan *et al.*, 2025; Zinsou *et al.*, 2026).

Iron is an essential element for the human body, including the blood system. However, high concentrations affect the organoleptic properties of water and also color laundry (Kouyaté *et al.*, 2021). The moderate presence of zinc in samples may be considered an advantage because zinc is an essential metal contained in the cells of living organisms as one of the main components of various enzymes (Sanou *et al.*, 2022a).

The variability of the metal trace elements differs from one metal to another. Indeed, lead and cadmium have recorded standard deviations lower than average values while the average iron value is lower than the standard deviation and that of zinc is very close to its standard deviation (Table 4). According to the literature, the standard deviations lower than the average values indicate the low variability of the parameters (Sanou *et al.*, 2024a), while the values of the standard deviations higher than the average values suggest the variability of the parameters (Yao *et al.*, 2020).

Anthropic activities are generally responsible for the presence of high ETM concentrations in the environment. Indeed, the contributions of zinc in the natural environment are particularly due to metallurgy (production of non-ferrous metals, iron and steel industry) and the combustion of wood and coals (Sarkar, 2002), but also to cosmetic products (creams, shampoos), batteries, pigments and paintings. Cadmium intake in the environment is linked to the zinc industry, the combustion of coal, the steel industry and the manufacture and the use of phosphate fertilizers (Crinoleau, 2001). Lead

paintings constitute craft sources (Rodier, 1996; Crinoleau, 2001; Sarkar, 2002). In addition, lead is also used as an adjuvant in PVCs and it is found in consumer water (Al-Malack, 2001; Lasheen *et al.*, 2008).

The high concentration of iron observed is probably attributable on the one hand to the dissolution and leachage of ferrallitic soil (bar earth) which cover most of the area (Boukari, 1998). On the other hand, they can come from activities anthropic which includes artisanal gold panning, the deposit of general waste and the use of prohibited fishing machines which can release iron in the environment, especially in the coastal area.

In our study area, we note the presence of activities such as dyeing, metallurgy, coal production, breeding, agricultural activities with the use of nitrogen fertilizers and phosphates as well as the use of manure as fertilizers. We also have industrial water discharges. This observation confirms the impact of anthropogenic activities on metal pollution in the study area. It is known that strong pollution of water by TMEs can pose health problems for the population (Sanou *et al.*, 2024b; Fort *et al.*, 2024).

### 3.2 Metal load of groundwater

The metal load (ML) translates the sum of the concentrations of the metallic trace elements analyzed in the water samples (Sanou *et al.*, 2022a). The metal load is between 0.168 and 5.997 mg/L with an average of 0.797 mg/L (Table 4). Figure 3 shows the variation in ML values by sample. It is higher at P42 (5.997 mg/L) in Hevie-Hessa, located in the Hevie district and lower at P22 (0.168 mg/L) in Affame in the town of Bonou.

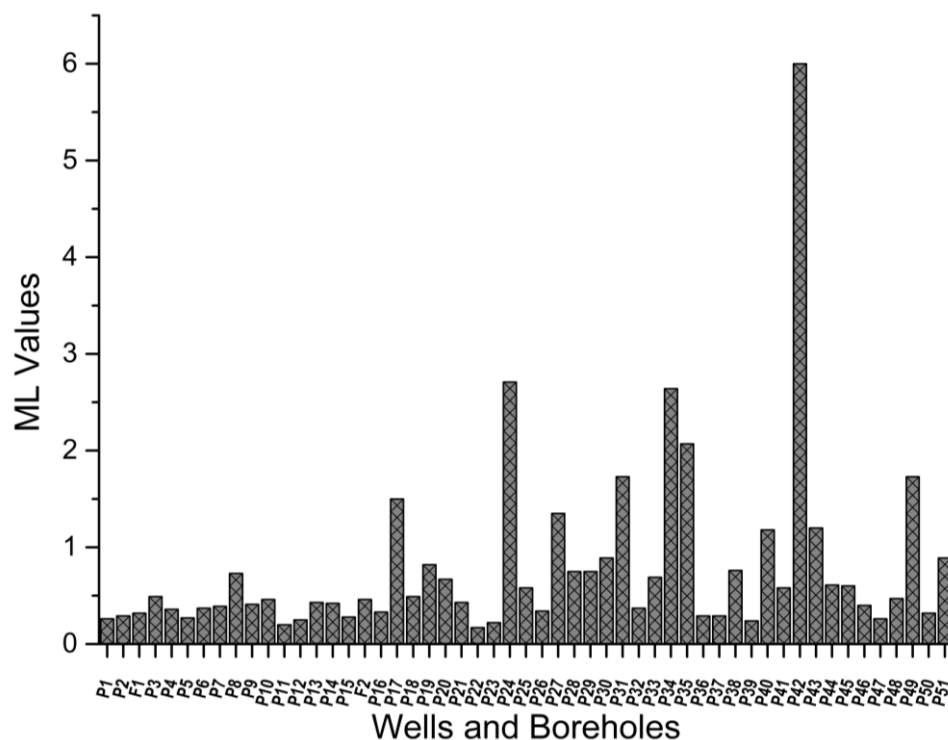


Figure 3. Variation of ML values

### 3.3 Heavy Metal Evaluation Index

The heavy metal assessment index gives the global status of water quality with regard to the content of metal traces (Edet and Offiong, 2002; Rajkumar *et al.*, 2020). This index is useful for the interpretation of the level of pollution and is mainly used for easy calculation steps. The values of the

calculated HEI index vary between 1.47 and 36.19 with an average of 14.28 (**Table 5**). A total of 11 water points (21%) have a HEI less than 10 ( $HEI < 10$ ); 35 water points (66%) with HEIs between 10 and 20 ( $10 < HEI < 20$ ) and 7 others (13%) whose HEIs are greater than 20 ( $HEI > 20$ ). It appears from these results that 21% of the samples of withdrawn groundwater present a low level of pollution while 66% of these samples have a level of medium pollution and 13% have a high level of pollution. Among the metallic traces analyzed, the contributions most marked to overall pollution were observed for lead (Pb) and cadmium (Cd). These metals are classified among the most toxic by WHO and could therefore have an impact on user health (*Sanou et al., 2021b*).

**Table 5.** Statistical values of HEIs

Parameters	Min	Max	Mean	Standard deviation	Critical value
HEI	1.47	36.19	14.28	6.46	10

### 3.4 Degree of contamination index

The degree of contamination index (CI) was used to assess the cumulative effect of the content of traces metals in the underground waters studied. **Table 6** presents the values (minimum, maximum and average) of the index of the degree of contamination for all groundwater samples. The results show that the Cd varied from - 2.53 to 32.18 with an average of 10.28. The CI of groundwater in 3.77%, 7.55% and 88.68% of the Oueme Delta show low contamination ( $CI < 1$ ), average ( $1 < CI < 3$ ), and high ( $CI > 3$ ) (*Rajkumar et al., 2020*). In addition, the average CI value is greater than 3. This suggests that the consumption of these waters is therefore not recommended.

**Table 6.** Statistical values of CI

Parameters	CF				CI
	Pb	Cd	Zn	Fe	
Min	-0.80	-0.53	-0.98	-1.00	-2.53
Max	17.93	16.19	-0.53	17.68	32.18
Mean	4.36	6.25	-0.92	0.58	10.28
SD	4.01	3.45	0.07	2.94	6.46

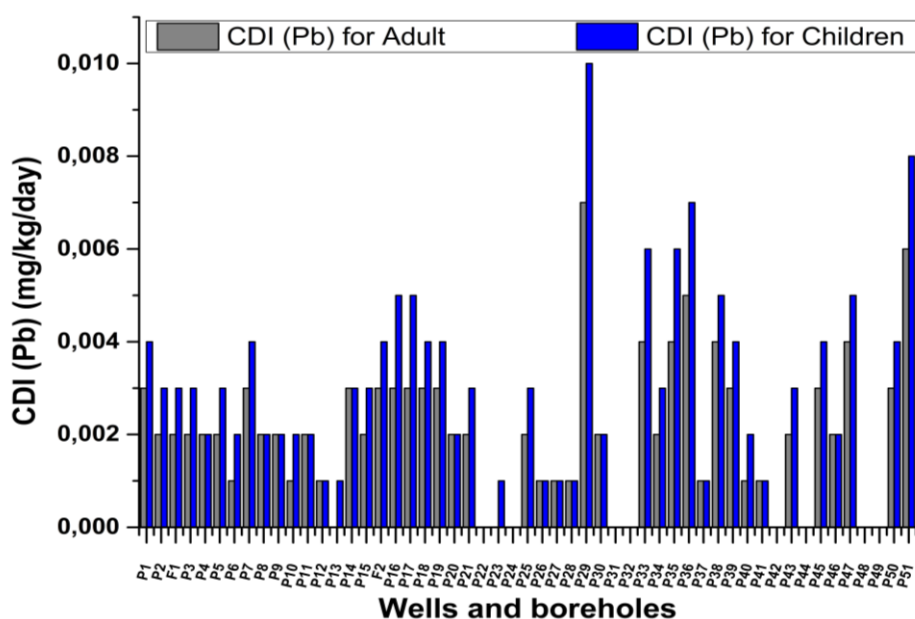
### 3.5 Evaluation of health risks

#### 3.5.1. Chronic daily intake

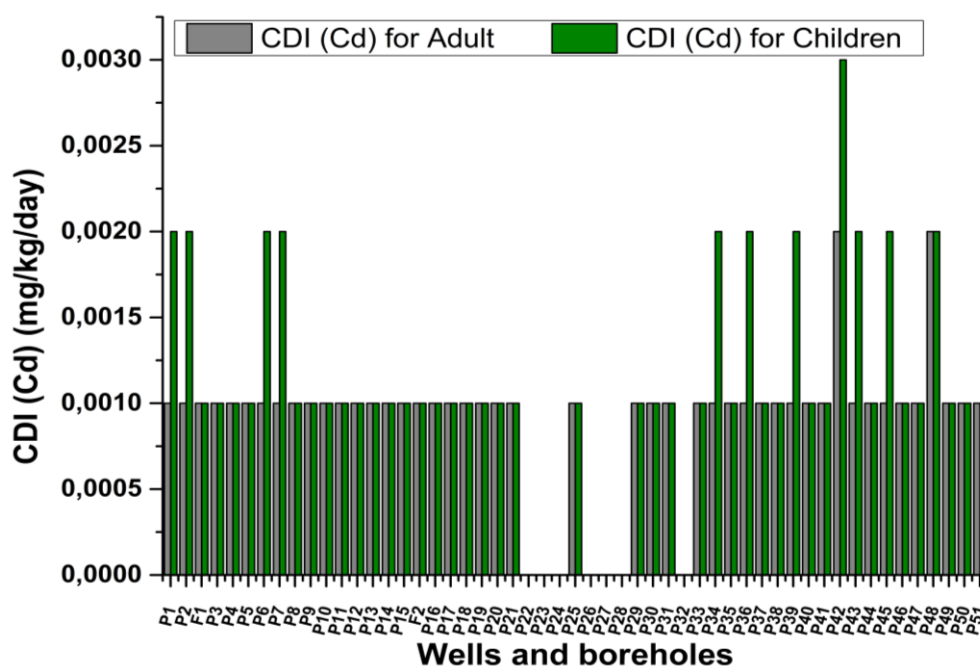
The potential effects of these traces metallic on health during the consumption of groundwater was evaluated by relying on the parameters of the Chronic daily intake (CDI) (*Chowdhury et al., 2024*). This evaluation is made according to the method recommended by the American Environmental Protection Agency (USEPA). These chronic exposure doses (CDI) of the metals studied vary between 0 and 0.216 mg/kg/day in adults and between 0 and 0.291 mg/kg/day in children as indicated by **Table 7**. All these CDI values remain less than 1 ( $CDI < 1$ ). This reflects a moderate chronic exposure to the metals concerned, not exceeding the tolerance thresholds defined for non-carcinogenic effects (*Rajmohan, 2022; Sanou et al., 2022a*). **Figures 4, 5, 6 and 7** have a comparative analysis of exposure to lead, cadmium, zinc and iron in adults and children, respectively. In general, the CDIs of Pb (**Figure 4**), Cd (**Figure 5**), Zn (**Figure 6**) and Fe (**Figure 7**) are more important in children than in adults. This reflects a stronger health risk sensitivity in children. It is therefore essential to protect children from exposure to metallic traces, because their developing body and their small size, make them more vulnerable to the toxic effects of TMEs than adults.

**Table 7.** Minimum, mean, and maximum values of chronic daily intake (CDI) for traces metals elements in the groundwaters of the study area

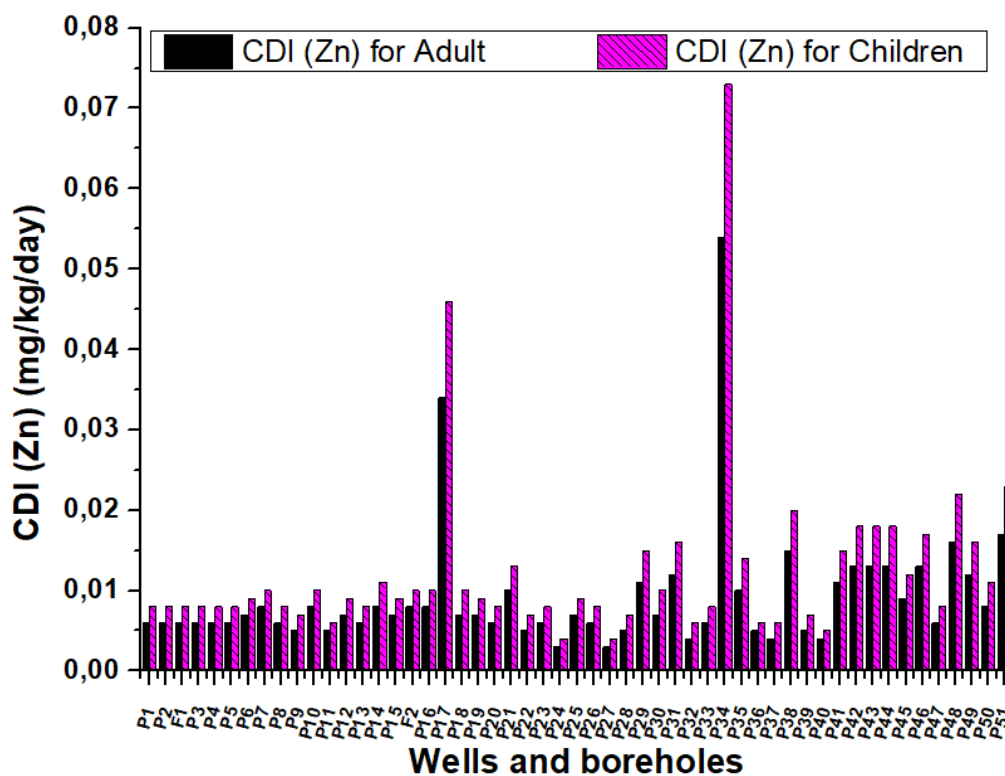
CDI (mg/kg/day)	Adults				Children			
	Min	Max	Mean	SD	Min	Max	Mean	SD
<b>Pb</b>	0.000	0.007	0.002	0.002	0.000	0.010	0.003	0.002
<b>Cd</b>	0.000	0.002	0.001	0.000	0.000	0.003	0.001	0.001
<b>Zn</b>	0.003	0.054	0.009	0.008	0.004	0.073	0.012	0.011
<b>Fe</b>	0.000	0.216	0.018	0.034	0.000	0.291	0.025	0.046



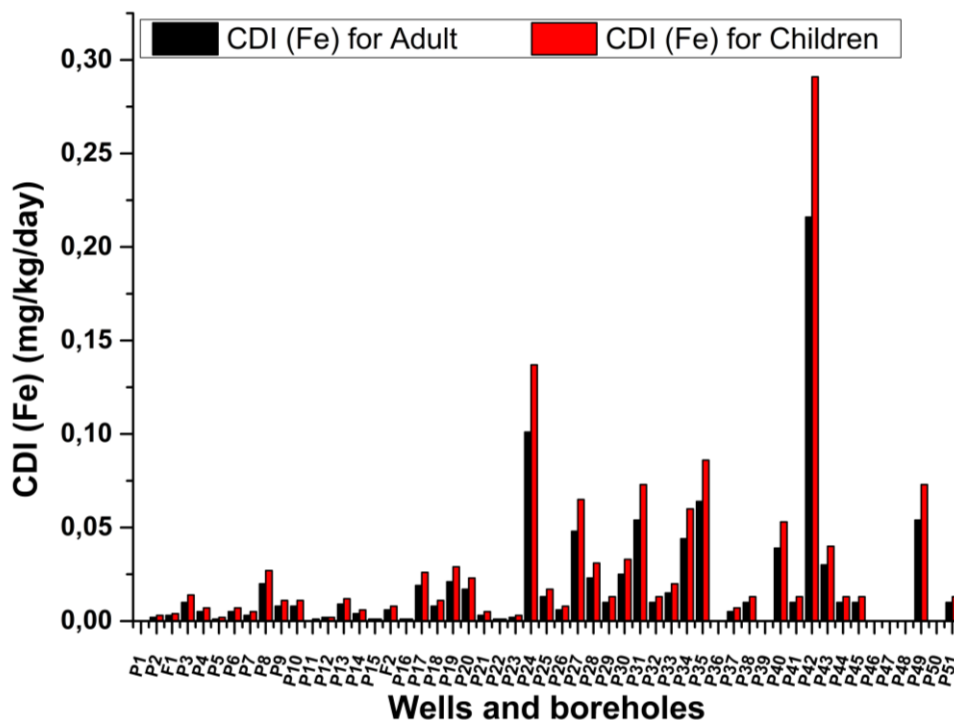
**Figure 4.** Comparative analysis of lead ingestion in adults and children



**Figure 5.** Comparative analysis of cadmium ingestion in adults and children



**Figure 6.** Comparative analysis of zinc ingestion in adults and children



**Figure 7.** Comparative analysis of iron ingestion in adults and children

### 3.5.2. Non-Carcinogenic Health Risk

In order to assess the non-carcinogenic risks linked to the consumption of groundwater, the risk indices (HQ) have been calculated for the metallic traces detected. The average values of estimated HQ and calculated HI are presented in **Table 8**. **Table 8** and **Figure 8** show that non-carcinogenic risk levels vary according to the metal traces studied and the different age groups.

**Table 8.** Minimum, mean, and maximums values of non-carcinogenic human health risks posed by traces metals elements in the groundwaters of the study area

HQ	Adults				Children			
	Min	Max	Mean	SD	Min	Max	Mean	SD
Pb	0.055	5.201	1.473	1.101	0.074	7.031	1.992	1.489
Cd	0.055	1.983	0.837	0.398	0.074	2.682	1.131	0.539
Zn	0.009	0.179	0.030	0.027	0.012	0.243	0.041	0.036
Fe	0.000	0.718	0.061	0.113	0.000	0.971	0.082	0.153
HI	<b>0.179</b>	<b>5.904</b>	<b>2.401</b>	<b>1.257</b>	<b>0.242</b>	<b>7.982</b>	<b>3.246</b>	<b>1.700</b>

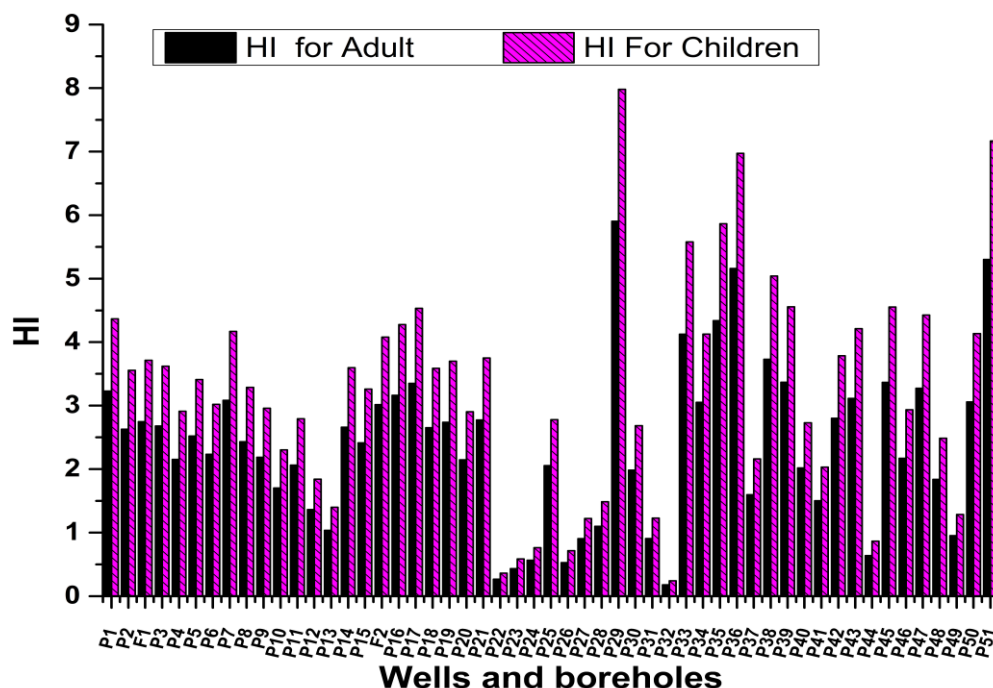
The non-carcinogenic risk indices (HQ) calculated for zinc (Zn) and iron (Fe) in the 53 water samples, remain less than 1 ( $HQ < 1$ ), both in adults and in children, indicating exposure without apparent danger for the two age groups (Wei *et al.*, 2015). On the other hand, lead (Pb) and cadmium (Cd) have higher non-carcinogenic risk levels, with HQ values of Pb above 1 ( $HQ > 1$ ) in 35 samples for adults and 37 for children as well as HQ values of Cd greater than 1 ( $HQ > 1$ ) in 18 samples for adults and 33 samples for children. These results suggest a potential health risk, especially in the youngest. In addition, lead and cadmium have a non-carcinogenic risk in more than two thirds of the water samples analyzed. HQ values for lead are higher than those of cadmium, zinc and iron. The order of contribution of metals to non-carcinogenic health risk is as follows:  $Pb > Cd > Zn > Fe$ , both in adults and in children. Although the HQ values of Zn and Fe are less than 1 ( $HQ < 1$ ), it is important to notify that long-term exposure to trace metallic elements, even at low concentration, can cause cumulative effects on health over time (Badeenezhad *et al.*, 2023). This shows a greater health problem, due to increased contamination of groundwater linked to urbanization and agricultural activities (Chowdhury *et al.*, 2024). Thus, the monitoring of TMEs contents in groundwater is imperative to guarantee the health of consumers (Soleimani *et al.*, 2023).

In addition, the danger index (HI) has been calculated in order to estimate the potential non-health cumulative effect of all TMEs on human health (Sanou *et al.*, 2022a, b). In general, the values of the danger index (HI) are greater than 1 ( $HI > 1$ ) both in adults and in children (Figure 8), suggesting a potential non-carcinogenic risk for exposed populations, with a risk that intensifies as the HI value increases (Wei *et al.*, 2015). In adults, only 9 out of 53 water points, or about 17.0%, have a HI less than 1 ( $HI < 1$ ). This observation is even more worrying in children, for whom only 6 water points, or 11.3%, show a HI less than 1 ( $HI < 1$ ), indicating a more generalized and potentially more critical exposure in this age group. The variations observed between the HI values of children and adults can be attributed to differences in sensitivity to exposure to metal traces and water consumption methods between the two age groups (Hou *et al.*, 2019).

### 3.6 Correlation between the traces metal elements and the indices

In environmental studies, results generally lead to a set of complex data. The use of statistical tests makes it possible to identify the existence or not of the effects of one parameter on another and to quantify these effects by a degree of meaning (Sanou, 2018; Sanou *et al.*, 2022c; Alassane Zakari *et al.*, 2024; N'Dri *et al.*, 2024).

In this study, the Bravais-Pearson correlation matrix was carried out to establish the relations between the metal traces dosed in the various underground water samples studied, the contamination indices and the danger index. The correlation coefficients are summarized in Table 9.



**Figure 8:** Comparative analysis of HI values in adults and children

**Table 9.** Correlation matrix between TMEs, ML, HEI, CI and HI

	Pb	Cd	Zn	Fe	ML	HEI	CI	HI Chil	HI Adu
Pb	1								
Cd	0,26	1							
Zn	0,12	0,26	1						
Fe	-0,25	0,17	0,15	1					
ML	-0,16	0,24	0,38	<b>0,97</b>	1				
HEI	<b>0,65</b>	<b>0,78</b>	0,30	0,39	0,48	1			
CI	<b>0,65</b>	<b>0,78</b>	0,30	0,39	0,48	<b>1</b>	<b>1</b>		
HI Chil	<b>0,94</b>	<b>0,57</b>	0,23	-0,07	0,03	<b>0,86</b>	<b>0,86</b>	1	
HI Adu	<b>0,94</b>	<b>0,57</b>	0,23	-0,07	0,03	<b>0,86</b>	<b>0,86</b>	<b>1</b>	1

The correlation coefficients obtained between the different metals are generally low ( $r < 0.5$ ), thus reflecting non-significant correlations between these metals (N'Dri *et al.*, 2024b). The correlation matrix indicates the existence of positive correlations between lead-cadmium couples ( $r = 0.26$ ), lead-zinc ( $r = 0.12$ ), cadmium-zinc ( $r = 0.26$ ), cadmium-iron ( $r = 0.15$ ) and a negative correlation between the lead-iron couple ( $r = -0.25$ ). The low correlations observed between the metal traces elements suggest that the absence or presence of one of these metals little influences the content of the other (Kam *et al.*, 2019; Kouakou *et al.*, 2022; Sanou *et al.*, 2022b). However, positive correlations could translate a possible common origin or similar behavior in the environment (Shetaia *et al.*, 2020; Shetaia *et al.*, 2023; Alassane Zakari *et al.*, 2024; Alassane Zakari *et al.*, 2026). On the other hand, the negative correlation between lead and iron could indicate an opposite relationship between these two elements thus reflecting the reduction of one with the increase in the other (Sanou *et al.*, 2021b; Sanou *et al.*, 2022a; Amon *et al.*, 2023). Furthermore, the weak or negative correlations observed between certain metals could indicate different sources of pollution (Li *et al.*, 2022; Shetaia *et al.*, 2022; Shetaia *et al.*, 2023).

Examination of the correlation matrix reveals a positive correlation between ML and all metal trace elements dosed with the exception of Pb ( $r = -0.16$ ). This correlation is significant between ML and Fe ( $r = 0.97$ ). This strong link between these two variables reflects the strong contribution of the

metal to the metal load of the water samples studied. All the metals studied have positive coefficients with HEI ( $r = 0.30 - 0.78$ ) and CI ( $r = 0.30 - 0.78$ ). These positive coefficients are significant between Pb-HEI ( $r = 0.65$ ), Pb-CI ( $r = 0.65$ ), Cd-HEI ( $r = 0.78$ ) and Cd-CI ( $r = 0.78$ ). These coefficients indicate a good correlation between these metals and the HEI and CI indices, thus confirming the strong contribution of Pb and Cd in the overall contamination of the groundwater of the Delta of Oueme.

To the analysis of the correlation matrix, the studied metals have the same HI correlation coefficients in children as well as in adults (Pb-HI ( $r = 0.94$ ), Cd-HI ( $r = 0.57$ ), Zn-HI ( $r = 0.23$ ), Fe-HI ( $r = -0.07$ )). The strong positive correlations observed between metals (Pb and Cd) and the danger index define the existence of a link between these elements. This shows that the increase in lead and cadmium in groundwater leads to an increase in the danger index. This represents an enormous risk to the health of consumers. The Bravais-Pearson correlation matrix indicates positive and significant coefficients between all the indices: ML-HEI ( $r = 0.48$ ), ML-CI ( $r = 0.48$ ), HEI-HI ( $r = 0.86$ ), CI-HI ( $r = 0.86$ ) and HEI-CI ( $r = 1$ ). These values indicate a good correlation between the clues and reflect coherence between them (Kouakou, 2017).

## Conclusion

The assessment of metallic contamination of groundwater in the Ouémé Delta underlines the presence of metal trace elements such as cadmium (Cd), lead (Pb), iron (Fe) and zinc (Zn) with variable levels. The analyzes show that, overall, the concentrations of the traces metals elements (TMEs) measured in the majority of wells (86.79% for Pb, 90.56% for Cd and 67.92% for Fe) exceeded the WHO guidelines values for drinking water, except zinc, whose contents remain conforming to WHO directives.

The calculation of metal contamination indices reveals a high degree of contamination of groundwater with an average CI value greater than 3. The cross-use of the various ML, HEI and CI indices has proven to be particularly effective to better assess the state of metal contamination in groundwater.

In addition, HEI shows low pollution with high pollution with 21%, 66% and 13% respectively low, medium and high. These wells which are close to the different probable sources of water pollution is contaminated by anthropogenic activities. Thus, it is indicated that they have a questionable drinking water quality, therefore remains unfit for human consumption.

Despite the chronic exposure doses (CDI) generally lower than the critical threshold of 1, the analysis of non-carcinogenic risk indices (HQ) and the cumulative danger index (HI) highlights worrying risk levels, especially for lead and cadmium. The situation is more worrying in children than in adults, whose physiological vulnerability increases the impact of repeated exhibitions. These results underline the need to assess the combined effects of contaminants rather than considering them in isolation.

It is therefore necessary to install and strengthen water quality monitoring devices, protect the areas of catchment, supervise the use of agricultural inputs and raise awareness of health risks linked to the consumption of contaminated water.

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