American Journal of Applied Chemistry
2023; 11(5): 130-136
http://www.sciencepublishinggroup.com/j/ajac
doi: 10.11648/j.ajac.20231105.13
ISSN: 2330-8753 (Print); ISSN: 2330-8745 (Online)

SciencePG
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Dissolution of Trace Metal Elements in Water by Permeation: The Case of the Drinking Water Network of the City of Bangui in the Central African Republic

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To cite this article:
Eric Foto, Oscar Allahdin, Olga Biteman, Nicole Poumaye. Dissolution of Trace Metal Elements in Water by Permeation: The Case of the Drinking Water Network of the City of Bangui in the Central African Republic. *American Journal of Applied Chemistry*.
Vol. 11, No. 5, 2023, pp. 130-136. doi: 10.11648/j.ajac.20231105.13

Received: September 24, 2023; **Accepted**: October 10, 2023; **Published**: October 28, 2023

Abstract: Assessment heavy metal concentrations is particularly important, given their toxicity and capacity to bioaccumulate along food chains. Unlike organic pollutants, metals cannot be biologically or chemically degraded. The aim of this study is to characterize the spatio-temporal variation in contamination by trace metal elements (TMEs), in particular Zn, Fe, Cu, Pb, Cd, Cr, Hg and Ni, in public water supplies in the city of Bangui, Central African Republic. Thirteen sampling points were selected on the production company's distribution network to determine the water's physico-chemical parameters and assess the level of trace metal contamination. The results obtained established the following quantitative order: Pb (0,002 – 0,07 ppm) > Fe (0,03 – 0,597 ppm) > Ni (0,001 – 0,036 ppm) > Cu (0,01 – 0,06 ppm) > Zn (0,001 – 0,438 ppm) > Cd = Cr = Hg = 0 ppm, lead levels are 7 times higher than WHO standards, while iron levels are two to three times normal. Contamination is influenced by the physico-chemical conditions of the environment. Indeed, the alkaline pH of the water and the rise in temperature during the dry season have favored the precipitation of TMEs from the materials used to manufacture the network's pipes, and their release into the water through permeation phenomena.

Keywords: Toxicity, Traces Elements, Precipitation, Bioaccumulation, Pollutants, Foods Chains

1. Introduction

The availability of fresh water is one of the major issues facing mankind today in a most important sense - because the problems associated with it affect the lives of many millions of people [1, 2]. Rapid population growth coupled with steadily increasing demand for water for agricultural and industrial development have imposed severe stress on available freshwater resources in terms of both quantity and quality, requiring constant and careful assessment and management of said resources for sustainable development [2]. Excess or deficiency of some essential metals can cause adverse effects on human health; on the other hand, non-essential metals such as lead or cadmium can be toxic to health even at very low concentrations. [2, 18]. One of the characteristics of metal toxicity is their ability to form an element carrying functional groups enabling it to bond to one or more atoms (ligands). Availability and toxicity depend on the concentration of free ions of the element, as well as on the total concentration of the metal or that of the metal complex [2]. TMEs can be absorbed by humans through the skin, by ingestion or inhalation [3-5].

The city of Bangui, capital of the Central African Republic, is bounded by the commune of Begoua to the north, Bimbo to the west and Zongo on the south bank of the Oubangui River in the DRC Congo. The city is located at 04°21'41" North Latitude and 018°33'19" East Longitude. It covers an area of 59.72 km^2. The city's population is estimated at 1,145,280, a quarter of the country’s total. It has eight (8) arrondissements. SODECA has three water supply distribution networks fed by two large reservoirs with respective capacities of 600 m^3 and 900 m^3. The system is composed as follows: (i) A primary network comprising around 170 km of water distribution pipes, with diameters ranging from 100 mm to 500 mm; (ii) A secondary network of around 220 km of pipes, with diameters ranging from 63 mm to 90 mm, and (iii) The tertiary network, with around 600 km of pipe, features pipes with diameters ranging from 32 mm to 50 mm The city of Bangui's water distribution is provided by The Société de Distribution d'Eau (SODECA). SODECA drinking water distribution network is made up of the following materials: asbestos cement, cast iron, galva steel, polyvinyl chloride (PVC) and high-density polyethylene (HDPE) pipes.

The quality of distributed water can change during transport between the production site and the consumer's tap [3]. This is due to interactions between the water and the materials used in drinking water distribution systems [6, 7]. The distribution of piped water requires the use of appropriate conduits [3, 6]. The aim of this study is to identify possible sources of trace metal pollution in public water supplies as the water passes through the pipes. In order to assess metal contamination in the distribution network for drinking water produced by the Société de Distribution d'Eau (SODECA), we chose as a sample city, the city of Bangui, capital of the Central African Republic.

2. Experimental

2.1. Materials

2.1.1. Sampling Points

In order to assess the concentration of metallic elements along the water distribution network, we chose 13 sampling points from the storage tank at the plant and on each avenue of the end, in the middle and at the end of the network. This enables us to assess the factors responsible for water contamination by trace metals. These sampling points are shown on the sampling map below (Figure 1).

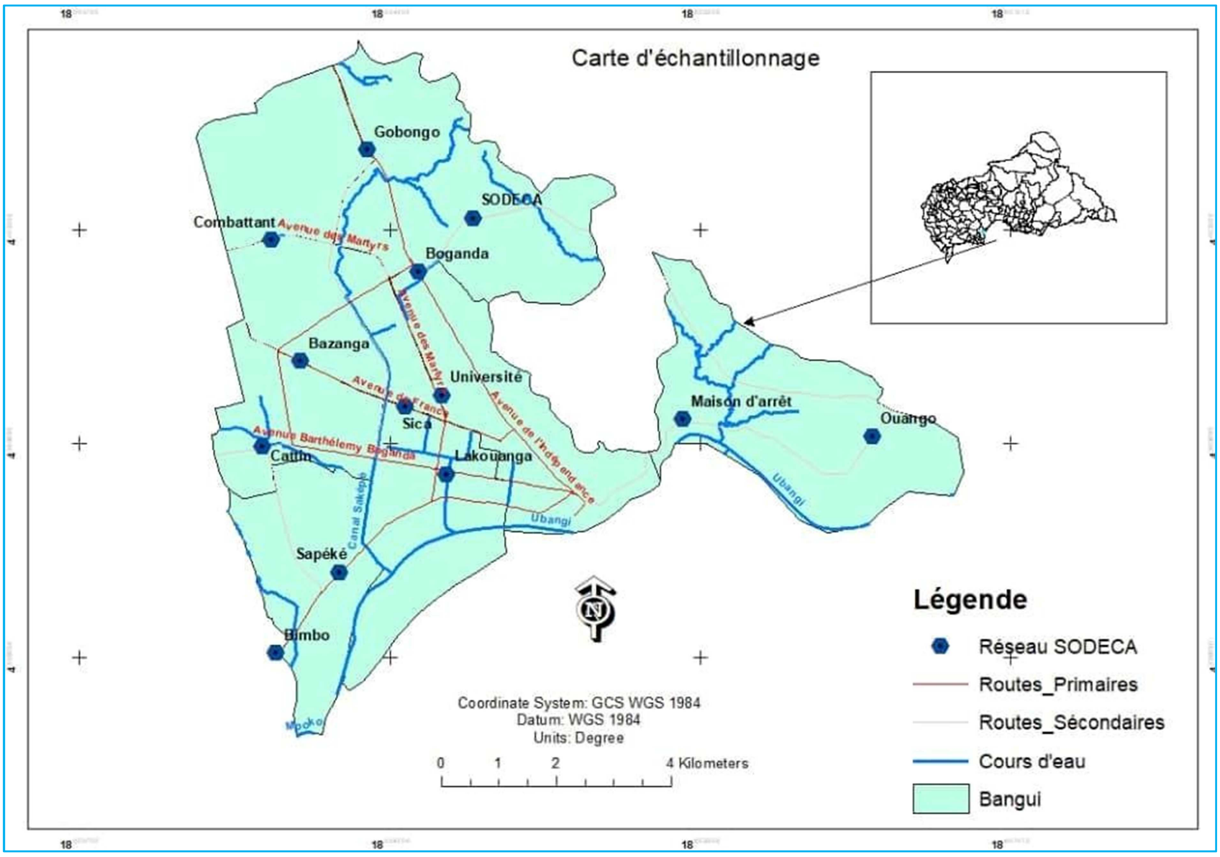

Figure 1. Sampling map.

2.1.2. Sampling and Storage

Water samples were taken in March (dry season) and July (high water) of 2022. Samples were collected in polyethylene bottles for heavy metals, with the exception of mercury, which was collected in borosilicate glass. Samples were stored in PET bottles previously rinsed with 1% nitric acid.

The following in situ analyses were carried out at each water sampling point performed:

1. pH (WTW 340i pH meter)
2. Electrical conductivity and temperature (WTW 340i conductivity meter)
3. Alkalinity (HACH Alkalinity kit)

For the Elements Traces Metalliques, the samples were preserved by adding nitric acid (HNO_3) to bring the pH < 2 [23]. They were then transported to the laboratory using a cooler containing ice baths to maintain the temperature at around 4°C. For mercury, samples were taken in borosilicate glass and 10 ml of mercury stabilizing solution (Dissolve 5 g potassium dichromate ($K_2Cr_2O_7$) in 500 ml nitric acid, then make up to 1 liter with distilled water.) were added [AFNOR, NF-T 90-10).] stabilizing solution to bring the pH of the samples to 1 or less, to fix the mercury in the sample.

2.2. Analytical Methods

Trace metals (Cu, Zn, Mn, Ni, Cd, Fe, Hg and Pb) were analyzed at the Laboratory d'Hydrosciences Lavoisier using a Varian SpectrAA 20 Inductively Coupled Plasma Atomic Emission Spectrophotometer (ICP-AES).

Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES) is an emission spectroscopy that quantifies the mass percentage of metals in metal/polymer nanocomposites. ICP-AES is based on the excitation of metal atoms/ions in metal/polymer nanocomposites using a plasma and analysis of the emission wavelength of electromagnetic radiation, which is typical of that particular metal. The determination of a given element requires a number of specific characteristics in order to obtain a reliable result. According to our analyses, the characteristics of each element are presented in Table 1.

Table 1. *Measurement parameters.*

Elements	Wavelength, nm	Slit width, nm	Concentration range (ppm) for standard solutions	Analysis range (µg/mL)
Cadmium, Cd	228.8	0.5	0.25, 0.5, 1, 2, 3	0.02 - 3.00
Copper, Cu	324.7	0.5	0.5, 1, 2, 4, 8	0.03 - 10
Chromium, Cr	357.9	0.2	0.5, 1, 2, 4, 8	0.06 - 15
Iron, Fe	248.3	0.2	0.25, 1, 3, 7, 10	0.06 - 15
Mercury, Hg	253.7	0.5	0.1, 0.2, 0.3, 0.4, 0.5	2 - 400
Nickel, Ni	232.0	0.2	0.5, 2, 4, 8	0.1 - 20
Lead, Pb	217.0	1.0	0.5, 1, 2, 4, 8	0.1 - 30
Zinc, Zn	213.9	1.0	0.25, 0.5, 1, 2	0.01 - 2

Table 2. *WHO limits pH, conductivity, temperature, turbidity and heavy metal concentrations.*

Location	pH	Conduct., µS/cm	Temp., °C	Turbidity, NTU	Heavy metal concentration, µg/mL							
					Cd	Cu	Cr	Fe	Hg	Ni	Pb	Zn
WHO limits	6,5 – 8,5	< 400	< 25	< 2	0,005	2	0, 05	0, 3	0,001	0, 02	< 0, 05	3

3. Results and Discussion

This section presents and interprets the results of physicochemical analyses of water taken from the distribution network.

3.1. Temperature

The average water temperature in the network varies between 25.00 and 29.69°C during the dry season and between 25.7 and 29.3°C during the rainy season (Table 3), compared with Brazzaville in Congo, where the average temperature varies between 27.20 and 29.77°C. These values do not comply with the WHO guide value of 25°C [2, 8]. The increase in tap water temperature could be due to the rise in ambient temperature over the study period.

3.2. Hydrogen Potential

Table 4 shows average pH values at 13 sampling points. It shows that pH fluctuates between 6.74 and 7.81 during the wet season, acceptable values for water intended for human consumption according to WHO guidelines (6.5 to 8.5) [8]. In contrast, it varies between 6.05 and 7.12 during the dry season. This acidity could be due to the increase in temperature in drinking water distribution pipes, as data in the literature show that increasing water temperature increases water dissociation, which in turn decreases pH [9]. pH is a crucial factor in the mobility of metal ions, as it influences the number of negative charges that can be brought into solution [9, 10]. These values are acceptable compared to those obtained in the drinking water network of the city of Brazzaville, where the pH ranges between 5.23 and 5.68, below the lower limit of the WHO guide, reflecting the acidity of these waters at this time of year, with a 100% non-compliance rate [3].

It should be pointed out in this respect that the solubility of corrosion by-products usually decreases as the pH of the water increases, thus raising the temperature [9, 11, 12]. However, water with a lower pH (approximately pH 7 or less) is likely to be more corrosive. The pH of water entering the distribution system must be regulated to minimize corrosion of water mains and pipes in domestic water distribution systems [8]. In particular, low pH levels (acidic water) increase the risk of metals being present in a more toxic ionic form.

Table 3. *Temperature for two season.*

Season	Bâche	Maison d'arrêt	Ouango	Boganda	Gobongo	Université	Combattant	Sica	Bazanga	Lakouanga	Cattin	Sapéké	Bimbo
March	25	29,66	30,82	27,75	27,75	27,96	28,15	27,45	29,69	28,2	27,33	28,12	29,33
July	29,3	28,97	28,25	25,76	26,9	26,8	26,2	26,7	28,09	27,59	26,2	27,4	27

Table 4. *pH variation.*

Season	Bâche	Maison d'arrêt	Ouango	Boganda	Gobongo	Université	Combattant	Sica	Bazanga	Lakouanga	Cattin	Sapéké	Bimbo
March	6,5	6,05	6,14	7,12	6,11	6,3	6,32	6,29	6,25	6,4	6,32	6,66	6,3
July	6,74	7,45	7,81	7,42	7,6	7,53	7,51	7,3	7,66	7,46	7,28	7,44	7,5

3.3. Conductivity

Average conductivity values range from 30.3 to 59 µs/cm in the rainy season and 45 to 83.85 in the dry season,. All these values comply with the WHO guide value (≤ 400 µs/cm) [8] Conductivity values are homogeneous, except for the very low mineralization of Bangui city water. The water quality studied is therefore moderately hard [13-15]. Soft water, with a low pH, can, by its corrosive nature, corrode water distribution materials and allow metals to be released; however, some hard water with a pH often below 7.5 and a high bicarbonate content can also be responsible for corrosion [15, 16].

Table 5. *Conductivity.*

Season	Bâche	Maison d'arrêt	Ouango	Boganda	Gobongo	Université	Combattant	Sica	Bazanga	Lakouanga	Cattin	Sapéké	Bimbo
March	45	83,85	80	63,6	67,5	62,2	61,6	53,5	59,55	63,6	65,6	64,4	69,5
July	30,3	51	53	48s	45	51	56	52	59	49	54	50	52

3.4. Turbidity

The turbidity of our samples ranged from 0.36 to 3.29 NTU during low-water periods and 0.85 to 2.92 NTU during high-water periods. For water intended for human consumption, the WHO recommends that turbidity should not exceed 2 NTU [8]. This was not the case for some of our samples. During the first campaign, all samples showed values above the norm. This increase could be due to the change in water flow velocity in the pipes, which can lead to the deposition of particles, thus increasing turbidity. Turbidity values are acceptably low compared with the Central African sub-region.

Table 6. *Turbidity.*

Season	Bâche	Maison d'arrêt	Ouango	Boganda	Gobongo	Université	Combattant	Sica	Bazanga	Lakouanga	Cattin	Sapéké	Bimbo
March	0,3	2,45	0,36	2,35	2,5	2,28	3,01	3,29	0,98	0,74	2,6	1,79	0,96
July	0,8	2,66	2,92	2,1	2,87	1,18	1,21	2,85	2,87	1,94	2,7	0,85	1,59

3.5. Metallic Trace Elements

TME analyses focused on the following elements: Zn, Fe, Cu, Pb, Cd, Cr, Hg and Ni. The results showed the absence of the following elements in the network water. These were cadmium, chromium and mercury.

3.5.1. Copper Concentrations

None of our analyzed samples contained concentrations in excess of WHO recommended limits (2 mg/l) [8]. However, there was a significant difference between sample concentrations in different periods. Copper concentrations during low-water periods were higher than during high-water periods. Copper levels in water are influenced by water hardness, pH, anion concentration, dissolved oxygen content and temperature [2]. High copper concentrations can be attributed to the corrosive nature of tap water and the age of pipes [6]. The release of copper into drinking water depends largely on the type of incrustations formed by corrosion in the plumbing system [7, 11]. The given age of the pipes, a by-product of corrosion, will determine the concentrations of copper released into the system [9].

Table 7. *Copper concentrations.*

Season	Bâche	Maison d'arrêt	Ouango	Boganda	Gobongo	Université	Combattant	Sica	Bazanga	Lakouanga	Cattin	Sapéké	Bimbo
March		0,009	0,01	0,001	0,014	0,015	0,011	0,045	0,018	0,016	0,028	0,007	0,035
July	0,06	0,007	0,008	0,001	0,004	0,012	0,007	0,008	0,005	0,005	0,008	0,002	0,004

3.5.2. Iron Concentrations

The results show that iron levels in the distribution network exceed the WHO standard of 0.3 mg/L [8]. Concentrations ranged from 0.301 mg/L to 0.597 mg/L in the first sampling, and 0.026 to 0.45 mg/L in the second (Table 8). Iron in tap water comes from the release of this element by pipe materials made of iron [12]. In fact, pipes made of ferrous materials corrode and release iron. Variations in iron content in water are controlled by oxidation-reduction phenomena and the acid/alkalinity balance [17]. An increase in temperature at low water pH is accompanied by an increase in dissolved metal concentrations [17-19]. This is in line with the data reported in our study, where points with high iron concentrations (Bimbo = 0.597 mg/L; Cattin = 0.59 mg/L) have a pH of 6.30 at Bimbo and pH= 6.32 at Cattin, respectively. Corrosion also plays an important role in the release and increase of iron concentrations in water. Corrosion is influenced by a number of factors, including the age of the pipes, the period of stagnation of the water, pH, alkalinity and dissolved oxygen [18, 20, 21]. Excess iron is responsible for the metallic taste of water, irritability and sometimes heart failure in adult subjects [15, 9, 22].

Table 8. *Iron concentrations.*

Season	Bâche	Maison d'arrêt	Ouango	Boganda	Gobongo	Université	Combattant	Sica	Bazanga	Lakouanga	Cattin	Sapéké	Bimbo
March	0,0001	0,41	0,301	0,309	0,312	0,52	0,32	0,42	0,432	0,36	0,59	0,582	0,597
July	0,032	0,234	0,04	0,18	0,429	0,45	0,22	0,35	0,16	0,12	0,317	0,15	0,25

3.5.3. Nickel Concentrations

Table 9 shows the evolution of Nickel content in the distribution network. The values obtained are not in line with the WHO standard for Nickel in drinking water (20 μg/L or 0.02 mg/L) [6, 7].

Table 9. *Nickel concentrations.*

Season	Bâche	Maison d'arrêt	Ouango	Boganda	Gobongo	Université	Combattant	Sica	Bazanga	Lakouanga	Cattin	Sapéké	Bimbo
March	0	0,018	0,021	0,032	0,014	0,011	0,012	0,02	0,001	0,019	0,012	0,006	0,025
July	0	0,013	0,02	0,032	0,012	0,003	0,02	0,036	0	0,018	0,013	0,007	0,021

3.5.4. Lead Concentrations

Lead concentrations differ between the two types of sampling and are fairly high. Concentrations ranged from 0.01 to 0.075 mg/L in the first sampling, and from 0.002 to 0.07 mg/L in the second (table 10). The values obtained for lead concentration in the network during the first campaign do not comply with WHO recommendations, i e. 0.01 mg/L in force [8]. In our study, lead levels varied according to the two seasons and therefore temperature. Lead in tap water results from the dissolution of lead-containing lining materials, joints and brass [9]. Galvanized steel used in the distribution network is believed to be the source of lead in tap water [9]. Lead is dangerous to the human organism, [2, 6, 17].

Table 10. *Lead concentrations.*

Season	Bâche	Maison d'arrêt	Ouango	Boganda	Gobongo	Université	Combattant	Sica	Bazanga	Lakouanga	Cattin	Sapéké	Bimbo
March	0	0,015	0,07	0,01	0,038	0,02	0,03	0,07	0,07	0,054	0,075	0,068	0,064
July	0	0,01	0,03	0,003	0,028	0,058	0,05	0,05	0,059	0,039	0,07	0,03	0,002

3.5.5. Zinc Concentration

Zinc concentrations are in line with WHO recommendations (0.3 mg/L) [8], with the exception of the University point, which has a concentration of 0.438 mg/L (Table 11). Zinc levels in samples from the first sampling are quite high compared to samples from the second. This can be explained by the effect of temperature, which favours the dissolution of this metal in water [11]. Zinc in tap water comes from galvanized steel pipes [11, 17].

Table 11. *Zinc concentration.*

Season	Bâche	Maison d'arrêt	Ouango	Boganda	Gobongo	Université	Combattant	Sica	Bazanga	Lakouanga	Cattin	Sapéké	Bimbo
March	0	0,152	0,005	0,001	0,004	0,042	0,011	0,009	0,007	0,056	0,025	0,002	0,003
July	0,012	0,136	0,003	0,021	0,001	0,438	0,006	0,005	0,002	0,051	0,01	0	0,002

4. Conclusion

Contamination of SODECA's drinking water distribution networks by trace metals is a serious public health problem. The quality of tap water can be very different from that of water from wells or springs. Several factors are responsible for this difference in quality. In our study, trace metal elements such as cadmium, chromium, copper, iron, mercury, nickel, lead and zinc were analyzed, with levels in line with WHO guidelines. Lead levels are 7 times and iron 2 to 3 times higher than the WHO standard. The assessment showed that lead and iron contamination of the water came from the materials used to manufacture the network's pipes. Corrosion of pipes and water distribution accessories are the primary sources of pollution. However, other factors specific to the characteristics of the water, such as pH and temperature, have favored the dissolution of these metals in the distribution water. Heavy metals dissolve very well in acidic water (low pH), and the increase in lead and iron levels is due to the partial solubilization of tap water distribution materials and the nature of the latter [23]. Our study has shown that concentrations of these various trace elements vary from one network to another. This explains the important role played by temperature on materials, which causes them to expand, thus allowing these elements to be released into the pipes.

Disclosure Statement

Conflict of Interests

The authors declare that they have no conflict of interest.

Ethical Approval

All ethical guidelines have been adhered.

CRediT Authorship Contribution Statement

Conceptualization: Eric Foto;
Methodology: Eric Foto, Oscar Allahdin;
Validation: Eric Foto, Oscar Allahdin, Olga Biteman;
Formal Analysis: Olg Biteman, Eric Foto, Oscar Allahdin;
Investigation: Eric Foto, Oscar Allahdin;
Data Curation: Eric Foto, Oscar Allahdin;
Writing - Original Draft: Eric Foto, Oscar Allahdin, Olga Biteman, Nicole Poumaye;
Writing - Review and Editing: Eric Foto, Oscar Allahdin;
Visualization: Eric Foto, Oscar Allahdin, Olga Biteman, Nicole Poumaye;
Supervision: Eric Foto, Oscar Allahdin;
Project Administration: Eric Foto, Oscar Allahdin.

Acknowledgments

This work was initiated by International Agency Energy Atomic within the framework of the project Global Network of Isotopes in Precipitation / Global Network of Isotopes in River. Authors thank the International Atomic Energy Agency staff for the collection and analysis of the sample. The authors would like to thank the editor and anonymous reviewers for their constructive comments, which helped us significantly improve the quality of the manuscript.

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