Dissolved Trace Elements in the Chari–Logone Rivers from N'Djamena to the Chari Mouth (Chad Republique). An Early-2000s Baseline for Assessing Anthropogenic Impacts

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Abstract— *This study presents one of the earliest multi-element assessments of dissolved trace elements (<0.22 μm) in the Chari and Logone rivers, based on ten samples collected between N'Djamena and the Chari mouth during three field campaigns in 2003–2005. Concentrations of 20 elements, determined by ICP-MS, were compared with global riverine averages and international guideline values. Concentrations of Li, B, Mn, As, and U were below global averages; Cr, Sr, Mo, and Cs were comparable; Ni, Cu, Cd, and Pb were occasionally higher; Al, V, and Co were generally higher; and Zn, Rb, and Ba consistently exceeded global averages. Soluble elements (Li, B, V, Rb, Sr, Mo, Cs, Ba) occurred at low levels, well below thresholds for drinking water, irrigation, livestock watering, and aquatic life protection. The other analyzed elements are prone to colloidal or particulate association, among which Co, Cu, Zn, and Cd exceeded some guideline thresholds, whereas the others remained below. However, actual levels are likely underestimated due to fine filtration, as reported in the literature for Cr, Mn, Ni, Cu, Zn, As, Cd, and Pb. Overall, the results suggest predominantly anthropogenic contamination and provide a valuable early-2000s baseline for evaluating changes associated with urban growth and agricultural intensification in the N'Djamena–Lake Chad region*

Keywords— *Chari-Logone Rivers, Trace elements, Dissolved fraction, Colloids and particulates, Water quality, Anthropogenic contamination.*

I. Introduction

Trace elements in surface waters derive from two main sources: natural processes, predominantly rock and soil weathering, and anthropogenic activities, including agricultural practices, urban runoff, and industrial effluents. Many trace elements are environmentally significant due to their persistence, mobility, and potential toxicity and are recognized as key indicators of water quality (Ayer and Westcot, 1985; ANZECC and ARMCANZ, 2000; WHO, 2022). They can affect human health through drinking water, reduce crop productivity through irrigation, accumulate in livestock, or disrupt aquatic ecosystems even at trace levels.

In Central Africa, the Chari and Logone Rivers form the main hydrological system supplying Lake Chad and provide essential water resources for domestic use, agriculture, and fisheries. They drain N'Djamena, Chad's capital, where the population has surged from approximately 700,000 in the early 2000s to nearly 1.7 million in 2025. This rapid growth, combined with unregulated urbanization, industrial activity, peri-urban agriculture, and inadequate wastewater management, exacerbates contamination risks (Kadjangaba, 2007).

Despite numerous studies on the major ions, few have focused on trace elements in surface water between N'Djamena and Lake Chad. The earliest analyses of trace elements in the Chari River (Roche, 1967), based on photometric techniques, suffered from limited analytical precision. In the present study, we report concentrations of dissolved trace elements, operationally defined as the <0.22 μm fraction, from ten surface water samples collected from the Logone and Chari rivers. Although the samples were collected in 2003–2005, these datasets remain highly relevant because surveys of dissolved trace elements in the Chari–Logone system are extremely scarce. The rare recent studies have focused on a limited set of trace elements (Nambatingar et al., 2017; Mahamat Nour et al., 2020; Dorim et al., 2022). These investigations, based on 0.45 μm filtration, included small colloids, thereby leaving the truly dissolved fraction insufficiently characterized.

Twenty trace elements were analyzed, including alkali and alkaline earth elements, transition metals, metalloids, and uranium, using inductively coupled plasma mass spectrometry (ICP-MS). The objectives of this study are threefold: (1) to document the concentrations and spatial distribution of dissolved trace elements in the surface waters of the Chari and Logone rivers; (2) to compare the measured values with global river water averages and with international guidelines for drinking water, irrigation, livestock watering, and aquatic life protection; and (3) to assess the potential underestimation of total environmental exposure resulting from the use of 0.22 μm filtration, particularly for elements known to associate with colloids and particulates.

This study constitutes one of the first multi-element assessments of dissolved trace metal contamination in the Chari-Logone rivers and provides a valuable reference for future studies aiming to monitor the impact of rapid demographic growth and intensifying agricultural and urban activities on surface water quality in the Lake Chad basin.

II. Material And Methods

In October 2003, May 2004, and April 2005, ten surface water samples were collected along a transect from the Logone and Chari rivers at N'Djamena to Lake Chad. Sampling locations included: the Logone (three samples) and the Chari rivers within the city of N'Djamena (four samples), the Chari River downstream at Douguia (two samples), and the Chari mouth approximately 1 km upstream of Lake Chad (one sample); see Fig. 1 for coordinates.
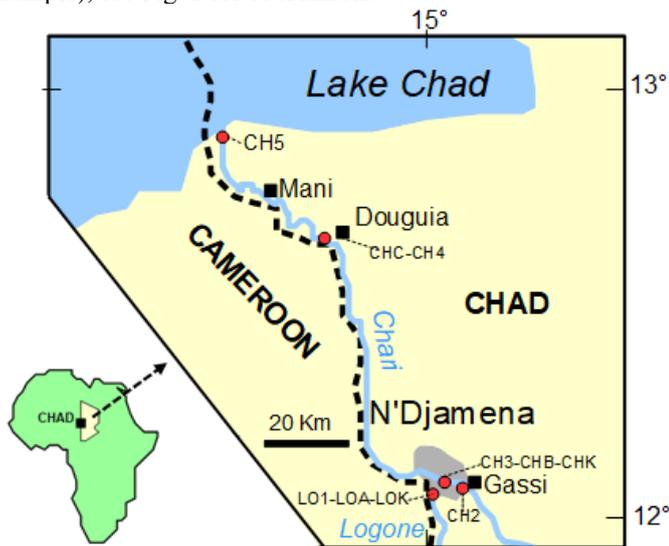

Fig. 1. Location of the analyzed samples. LO1, LOA, LOK: Logone upstream of N'Djamena (12°04'03.80" N; 15°02'09.09" E). CH2: Chari at Gassi (12°04'08.64" N; 15°08'24.59" E). CHB, CH3, CHK: Chari at the double-lane bridge in N'Djamena (12°05'05.26" N; 15°06'20.10" E). CHC, CH4: Chari at Douguia (12°37'08.37" N; 14°50'12.67" E). CH5: Chari mouth, 1 km upstream of Lake Chad (12°52'03.48" N; 14°31'29.48" E).

The water samples were collected in plastic bottles that had been previously washed, rinsed with distilled water, and finally rinsed with water from the sampling site. Each water sample was immediately filtered in the field using 0.22 µm Millipore® membrane filters and acidified to pH <2 with ultrapure nitric acid (HNO_3, 1‰ v/v). Samples were stored in pre-cleaned high-density polyethylene bottles to minimize contamination.

Lithium (Li), boron (B), aluminium (Al), vanadium (V), chromium (Cr), manganese (Mn), cobalt (Co), nickel (Ni), copper (Cu), zinc (Zn), arsenic (As), rubidium (Rb), strontium (Sr), molybdenum (Mo), cadmium (Cd), cesium (Cs), barium (Ba), lead (Pb), and uranium (U) concentrations were determined at the HydroSciences Laboratory in Montpellier, France, using inductively coupled plasma mass spectrometry (ICP-MS). The instrument used was a VG PlasmaQuad PQ2 Turbo+. The accuracy and reproducibility of the analyses were ensured through calibration with certified standards and blank controls.

III. Results And Discussion

The trace element concentrations are presented in Table 1. The maximum concentrations of Li, As, Cd, Cs, Pb, and U are all below 1 µg/L. Most other elements have maximum concentrations that do not exceed 5 µg/L, with the exception of

B (7.176 µg/L), Zn (13.668 µg/L), and Rb (10.558 µg/L). In contrast, Al, Sr, and Ba display both minimum concentrations above 10 µg/L and high maximum values, 280.083, 85.275, and 65.54 µg/L, respectively (Table 1).

The coefficient of variation is low (20 < CV < 40%) for B, Cu, Sr, and Ba; moderate (40 < CV < 70%) for Li, V, Cr, Mn, Ni, Zn, As, Rb, Cs, Pb, and U; and high (70 < CV < 100%) for Al. It is very high (CV > 100%) for Co, Mo, and Cd (Table 1). No systematic increase in concentrations is observed during low-flow conditions (April–May) compared to high-flow conditions (October) (Table 1). Concentrations in the Chari River show no consistent increase from upstream to downstream (Table 1).

The waters of the Chari and Logone rivers are weakly basic (mean pH ~8) with low mean hardness (<22 mg/L as $CaCO_3$) (Kadjangaba, 2007; Mahamat Nour et al., 2019). Under these conditions, soluble elements such as Li, B, V, Rb, Sr, Mo, Cs, and Ba are predominantly present in dissolved form (Hem, 1985; Langmuir, 1997; Gaillardet et al., 2003). The other analyzed elements (Table 1) are known to associate with particulate or colloidal phases, or to exhibit variable partitioning among dissolved, colloidal, and particulate forms depending on redox conditions and organic matter content (Elder, 1988; Gaillardet et al., 1997; Sigg et al., 2014; Bergen et al., 2023). Based on turbidity and suspended solids measurements, the waters of the Chari and Logone rivers contain moderate to high levels of particulate and colloidal material (Nambatingar, 2011; Sorlini et al., 2013; Hissein et al., 2015; Tchoroun et al., 2015; Dorim, 2022).

Trace element concentrations reported in this study correspond to the dissolved fraction, operationally defined as the portion passing through a 0.22 µm filter. These values are compared with the global average concentrations of the dissolved load in rivers (Gaillardet et al., 2003), determined using the same filtration cutoff, and with international water quality guidelines for drinking water, irrigation, livestock watering, and aquatic life protection (Table 2), which are generally established for unfiltered or 0.45 µm filtered water. The World Health Organization (WHO) drinking-water guidelines (WHO, 2022) refer to water as consumed. Guideline values for livestock drinking water and irrigation usually refer to unfiltered water, representing the total concentration (dissolved, colloidal, and particulate) to which animals or crops may be exposed. Environmental guidelines for the protection of aquatic life are generally based on concentrations, measured after 0.45 µm filtration, which includes both true solutes and small colloids. As a result, while the concentrations reported here can be directly compared with the global average concentrations in rivers, comparison with guideline values may, except for predominantly soluble elements, underestimate total trace element exposure.

Lithium. Dissolved Li concentrations range between 0.036 and 0.258 µg/L (Table 1), which are low compared to the global average composition of river water (Fig. 2), estimated at 1.84 µg/L (Gaillardet et al., 2003). These levels indicate a predominantly natural origin, most likely controlled by the weathering of lithogenic sources, with no evidence of significant anthropogenic enrichment.

TABLE 1. Surface water concentrations in μg/L. Legend as in Fig. 1. MIN : Minimum. MAX : maximum. CV: Coefficient of variation (CV = (σ/μ) × 100, where σ is the standard deviation and μ the mean).

μg/L	LOA Oct. 03	CHB Oct. 03	CHC Oct. 03	LO1 Apr. 05	LOK May 04	CH2 Apr. 05	CH3 Apr. 05	CHK May 04	CH4 Apr. 05	CH5 Apr. 05	MIN	MAX	CV
Li	0.095	0.086	0.104	*0.119*	0.036	0.163	0.258	0.081	0.133	0.202	0.036	0.258	51
B	2.924	6.001	3.439	*3.104*	2.275	6.577	7.176	7.114	4.968	5.238	2.275	7.176	38
Al	95.054	11.638	91.281	*58.768*	30.697	81.782	64.151	24.901	118.259	280.083	11.638	280.083	89
V				3.645	3.09	*0.490*	2.032	3.741	1.214	2.241	0.490	3.741	52
Cr				1.143	0.364	0.493	0.468	0.237	0.453	0.654	0.237	1.143	54
Mn	2.759	3.403	2.113	*0.248*	0.328	3.168	1.846	0.395	2.381	1.392	0.248	3.403	65
Co	0.082	0.082	0.085	0.868	0.038	3.022	0.142	0.072	0.302	0.182	0.038	3.022	189
Ni	0.669	0.476	0.536	1.489	0.432	2.639	1.743	0.693	0.968	1.202	0.432	2.639	65
Cu	2.131	2.013	1.726	1.214	0.751	2.516	1.550	1.001	1.419	1.597	0.751	2.516	34
Zn	7.164	5.544	5.468	10.135	3.462	13.668	13.103	3.832	10.463	11.206	3.462	13.668	45
As	0.115	0.371	0.171	0.210	0.057	0.141	0.101	0.361	0.274	0.147	0.057	0.371	55
Rb	2.356	7.548	3.524	4.509	3.548	10.094	10.168	10.558	7.765	7.277	2.356	10.558	45
Sr	43.517	62.088	45.057	83.821	53.914	81.957	84.345	72.976	85.275	84.904	43.517	85.275	25
Mo	4.616	0.425	0.503	0.295	0.232	0.409	0.426	0.396	0.350	0.329	0.232	4.616	168
Cd	0.098	0.029	0.184	0.667		0.106	0.089		0.225	0.065	0.029	0.667	112
Cs	0.005	0.009	0.005	0.004		0.014	0.012		0.007	0.013	0.004	0.014	45
Ba	38.195	45.566	36.250	52.470	36.052	62.927	60.693	51.319	62.511	63.542	36.052	63.542	22
Pb	0.273	0.126	0.267	0.034	0.038	0.241	0.151	0.019	0.124	0.162	0.019	0.273	66
U	0.058	0.386	0.086	0.097	0.047	0.355	0.353	0.424	0.250	0.192	0.047	0.424	66

TABLE 2. World average river water composition and international water quality guidelines. World average river water composition from Gaillardet et al. (2003). References for international guideline values are provided in the text. NG = no guideline available

μg/L	Global average river water composition (μg/L)	International guidelines			
		Drinking water (μg/L)	Irrigation (mg/L)	Livestock drinking water (mg/L)	Aquatic life (μg/L)
Li	1.84	10	2.5	NG	240
B	10.2	2400	5	5	370
Al	32	900	5	5	400
V	0.71	15	0.1	1	120
Cr	0.7	50	0.1	1	1
Mn	34	80	0.2	10	270
Co	0.148	70	0.05	1	0.78
Ni	0.801	70	2	1	8
Cu	1.48	2000	0.2	5	1.4
Zn	0.6	3000	2	20	7
As	0.62	10	0.5	0.1	5
Rb	1.63	NG	NG	NG	NG
Sr	60	400	NG	NG	530
Mo	0.42	50	0.01	0.15	34
Cd	0.08	3	0.01	0.01	0.06
Cs	0.011	NG	NG	NG	NG
Ba	23	1300	50	6.5	140
Pb	0.079	10	0.2	0.1	1
U	0.372	30	0.01	0.02	0.5

have shown that oral doses of 250 mg/kg can cause intoxication in mature animals, and doses of 500–700 mg/kg may be toxic or lethal (Johnson et al., 1980); such doses cannot be reached through drinking water exposure.
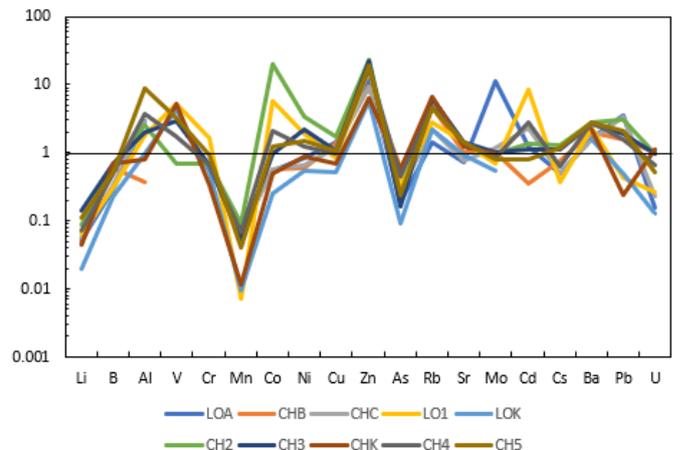

Fig. 2. Profiles of trace element concentrations normalized to the world average river water composition. Normalization values are from Gaillardet et al., (2003). Legend as in Fig. 1

In aquatic ecosystems, Li toxicity has been observed at concentrations exceeding 150 μg/L in waters with very low sodium content (Kszos et al., 2003), and the tolerance of aquatic fauna to Li increases with sodium concentrations. For the Chari and Logone Rivers, which have an average sodium content of about 4 mg/L (Kadjangaba, 2007; Nour et al., 2019), a higher Li concentration (around 240 μg/L) may therefore be tolerated, according to Kszos et al., (2003).

The Li concentrations measured in this study do not raise toxicological or environmental concerns. Given that Li is predominantly present in dissolved form, the measured concentrations likely reflect total exposure.

The WHO does not define a health-based guideline value for Li in drinking water. The U.S. Environmental Protection Agency has proposed a non-regulatory health-based screening level of 10 μg/L for Li in drinking water (EPA, 2023). The Li concentrations remain below the trigger value of 2.5 mg/L for irrigation waters (ANZECC AND ARMCANZ, 2000). While Li is not considered an essential nutrient for livestock, it is generally well-tolerated at low doses. No formal guideline exists for Li in drinking water for cattle. Experimental studies

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Boron. Dissolved B concentrations range from 2.275 to 7.176 µg/L (Table 1). These values are low compared to the global average composition of river water (Fig. 2), estimated at 10.2 µg/L (Gaillardet et al., 2003). These levels indicate that B is largely of natural origin, most likely controlled by lithogenic weathering within the basin. However, minor anthropogenic inputs, such as those related to agricultural practices or domestic wastewater, cannot be entirely excluded.

All measured concentrations remain well below established guideline values for different water uses. The WHO sets a health-based guideline value of 2.4 mg/L for drinking water (WHO, 2022). For irrigation water, the trigger value is 0.5 mg/L, and for livestock drinking water, concentrations up to 5 mg/L are considered safe for most animals (ANZECC and ARMCANZ, 2000).

Regarding aquatic ecosystems, toxicity thresholds for B vary by country. The Canadian Water Quality Guidelines (CWQ Guidelines) propose a long-term exposure guideline of 1.5 mg/L to protect aquatic life (CCME, 2009), while Australian and New Zealand guidelines (ANZ guidelines) suggest a more conservative threshold of 0.37 mg/L for 95% species protection (ANZECC and ARMCANZ, 2000).

The B concentrations recorded in this study pose no health or environmental risk under current international guidelines. As B is predominantly present in dissolved form in natural waters, the measured values are likely representative of total bioavailable exposure.

Aluminium. Concentrations of dissolved Al range from 11.638 to 280.083 µg/L (Table 1), exceeding for the most part the global average composition of river water (Fig. 2) of 32 µg/L (Gaillardet et al., 2003). The highest concentration was recorded at the Chari River Mouth (280.083 µg/L). The elevated Al concentrations in the Chari River likely reflect the presence of aluminosilicate colloids resulting from natural weathering and erosion processes in the basin, potentially exacerbated by industrial discharges in the N'Djamena area (Nambatingar et al., 2017; Kadjangaba et al., 2007).

Although no formal guideline exists for Al in drinking water, the WHO proposes a health-based value of 0.9 mg/L for untreated water (WHO, 2022). The concentrations measured in this study remain well below this threshold and are therefore not of toxicological concern. The Al concentrations remain below the recommended threshold of 5 mg/L for irrigation waters with neutral to alkaline pH, as well as below the same value proposed for livestock drinking water (ANZECC/ARMCANZ, 2000).

The guideline values for aquatic life are pH-dependent (ANZECC/ARMCANZ, 2000). For slightly alkaline waters such as those of the Logone and Chari rivers, the relevant threshold for the protection of 99% of aquatic species is 27 µg/L. Most concentrations measured in this study exceed this value, suggesting a potential risk to sensitive aquatic species. Notably, Al toxicity depends on pH and also of dissolved organic carbon (DOC) and water hardness, which influence its speciation and bioavailability. According to the updated Canadian guidelines (ECCC, 2022), the 27 µg/L threshold corresponds to highly sensitive conditions (pH 6.5, hardness 10 mg/L as CaCO₃, DOC 1 mg/L). Under the physicochemical

conditions observed in this study, the guideline value would be ≥ 400 µg/L, regardless of DOC. Therefore, Al concentrations remain environmentally acceptable when using more recent bioavailability-based criteria.

However, aluminium is strongly associated with particulate and colloidal phases, so the measured concentrations may underestimate actual exposure in unfiltered waters.

Vanadium. Dissolved V concentrations range from 0.490 to 3.741 µg/L (Table 1). Except for the Chari at Gassi these values are slightly above the global average composition of river water (Fig. 2), estimated at 0.71 µg/L (Gaillardet et al., 2003). The enrichment in V is most plausibly attributable to inputs from urban runoff and atmospheric deposition related to fuel combustion, in agreement with the lowest concentration (0.490 µg/L) recorded at Gassi, upstream of N'Djamena.

No health-based guideline value for V has been established by the WHO for drinking water (WHO, 2022). However, the California Office of Environmental Health Hazard Assessment has proposed a notification level of 15 µg/L, based on developmental toxicity studies (OEHHA, 2021). For irrigation purposes, the recommended threshold to protect sensitive crops is 100 µg/L, while for livestock drinking water, concentrations up to 100 µg/L are generally considered safe (ANZECC/ARMCANZ, 2000).

Regarding aquatic life, the European Chemicals Agency reports a chronic effect threshold of 50 µg/L in sensitive invertebrates (ECHA, 2023), and the CWQ Guideline is 120 µg/L for total vanadium (CCME, 2016). All concentrations measured in this study are well below these thresholds, indicating no environmental or toxicological concern.

V is generally present in dissolved form, and the measured values likely reflect total exposure.

Chromium. Concentrations of dissolved Cr range from 0.237 to 1.143 µg/L (Table 1). These values are comparable to the global average composition of river water (Fig. 2), estimated at 0.7 µg/L (Gaillardet et al., 2003). Because the Chari–Logone basin is constituted by granitoids and sedimentary formations without ultrabasic rocks (Wolff, 1964), the natural contribution of dissolved chromium is expected to be limited. The measured concentrations, therefore, likely reflect a combination of natural background and anthropogenic inputs, with industrial effluents identified as a source in recent studies (Nambatingar et al., 2017; Dorim et al., 2022).

For drinking water, the WHO sets a health-based guideline value of 50 µg/L for total Cr (WHO, 2022). In agricultural contexts, concentrations below 100 µg/L are generally considered safe for irrigation, while up to 1 mg/L is tolerated in livestock drinking water (ANZECC/ARMCANZ, 2000).

For the protection of aquatic life, the CWQ Guidelines set threshold values of 1 µg/L for Cr(VI), the highly toxic and mobile form, and 8.9 µg/L for Cr(III), which is less toxic (CCME, 1999a). The concentrations reported in this study refer to total dissolved chromium. However, because Cr(III) has a strong tendency to bind to colloids and particulate matter, dissolved chromium in natural waters is generally dominated by the more soluble Cr(VI) species (Stumm and Morgan, 1996). The Cr levels measured in this study are, for the most part, below guideline thresholds and do not pose environmental or

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toxicological concern. In contrast, analyses conducted in 2008 using 0.45 µm filtration reported a mean Cr concentration of 50 µg/L in the Chari River at N'Djamena (Nambatingar et al., 2017), while recent data from 2022 indicate a similar average of 47 µg/L at the river's mouth (Dorim et al., 2022). These elevated values suggest that a significant fraction of chromium may occur in colloidal or fine particulate form, predominantly as Cr(III). Reported peak concentrations, ranging from 10 to 130 µg/L (Nambatingar et al., 2017) and 20 to 70 µg/L (Dorim et al., 2022), exceed the CWQ Guidelines. However, because Cr(III) is far less bioavailable and toxic than Cr(VI), these exceedances are unlikely to pose substantial adverse effects on aquatic biota (Pawlisz et al., 1997 ; CCME, 1999a).

Manganese. Dissolved Mn concentrations range from 0.248 to 3.403 µg/L (Table 1), well below the global average (Fig.2) of 34 µg/L reported for world rivers (Gaillardet et al., 2003). The low Mn levels likely reflect natural inputs, though colloidal and particulate associations may lead to underestimation of total exposure.

For drinking water, the WHO sets a health-based guideline of 80 µg/L, mainly to prevent neurological effects from long-term exposure (WHO, 2022).

In agricultural contexts, Mn concentrations below 200 µg/L are considered safe for most crops (ANZECC/ARMCANZ, 2000), and values up to 10 mg/L are tolerated in livestock drinking water (DWAF,1996). Regarding aquatic ecosystems, Mn toxicity is influenced by pH and water hardness. Under the conditions of this study, the CWQ Guidelines establish a chronic threshold above 270 µg/L (CCME, 2019).

The manganese concentrations measured in this study fall well below all international thresholds for human health and environmental protection. However, an elevated mean concentration of 355 µg/L is reported in the Chari River at N'Djamena in 2008, measured using 0.45 µm filtration (Nambatingar et al., 2017). Except for livestock drinking water, the reported range (180–550 µg/L), attributed to anthropogenic inputs (Nambatingar et al., 2017), frequently exceeds international thresholds.

Cobalt. Dissolved Co concentrations range from 0.038 to 3.022 µg/L (Table 1), with the highest value observed in the upper Chari River at Ngassi. Most of these values exceed the global average composition of river water (Fig. 2) estimated at 0.148 µg/L (Gaillardet et al., 2003), indicating localized enrichment, likely associated with industrial runoff, as previously reported (Kadjangaba, 2007; Nambatingar et al., 2017; Dorim et al., 2022)

The World Health Organization (WHO, 2022) does not provide a guideline value for Co in drinking water due to insufficient evidence for adverse health effects at typical environmental levels. However, a health-based screening level of 70 µg/L has been referenced by the Environmental Working Group (EWG, 2023). For irrigation, the water long-term value is 50 µg/L, and for livestock drinking water , levels up to 1 mg/L are considered safe (ANZESS AND ARMCANZ, 2000).

For aquatic ecosystems, the chronic toxicity of Co depends on water hardness. Under the conditions observed in this study, a chronic threshold of 0.78 µg/L was proposed (ECCC, 2017).

The value measured in the Logone River (0.868 µg/L) is close to the ecological effect threshold, while the concentration recorded at Gassi on the Chari River (3.022 µg/L) exceeds it, suggesting a localized risk to sensitive aquatic organisms. Therefore, while cobalt levels in this study remain low in absolute terms, they may warrant attention for potential ecological effects. Moreover, a portion of Co may occur in colloidal form, indicating a likely underestimation of total exposure in unfiltered water.

Nickel. Concentrations of dissolved Ni range from 0.432 to 2.639 µg/L (Table 1), with the highest value observed in the upper Chari River at Gassi. These values are sometimes slightly above the global average composition of river water (Fig. 2), estimated at 0.801 µg/L (Gaillardet et al., 2003). This slight enrichment suggests a combined natural and anthropogenic origin, with the natural background being supplemented by well-documented contributions from agricultural runoff and urban/industrial wastewater discharges (Kadjangaba, 2007; Nambatingar et al., 2017 ; Dorim et al., 2022).

The WHO has established a health-based guideline of 70 µg/L for drinking water (WHO, 2022). For irrigation, concentrations below 200 µg/L are generally considered safe for most crops (ANZECC and ARMCANZ, 2000). For livestock drinking water, no specific guideline exists; however, levels up to 1 mg/L are not expected to pose a risk to animal health (ANZECC and ARMCANZ, 2000). Regarding aquatic ecosystems, a trigger value of 8 µg/L has been established for the protection of 99% of aquatic species (ANZECC and ARMCANZ, 2000).

The Ni concentrations measured in this study do not pose a concern for human, agricultural, or ecological use. However, as Ni can partially occur in colloidal form, measured values may slightly underestimate total exposure. This is consistent with a mean concentration of 326 µg/L reported in the Chari River at N'Djamena in 2008 using 0.45 µm filtration (Nambatingar et al., 2017). The reported values (ranging from 80 to 650 µg/L), attributed to industrial discharge, mostly exceed international thresholds for drinking water, irrigation, and aquatic life protection.

Copper. Dissolved Cu concentrations range from 0.751 to 2.516 µg/L (Table 1), sometimes higher than the global average composition of river water (Fig. 2), estimated at 1.48 µg/L (Gaillardet et al., 2003). This low-level enrichment suggests a dual origin, both natural and anthropogenic. The natural background is amplified by inputs from agricultural and urban/industrial sources observed in N'Djamena (Kadjangaba, 2007; Nambatingar et al., 2017; Dorim et al., 2022).

For drinking water, the WHO sets a health-based guideline value of 2 mg/L (WHO, 2022). For irrigation, concentrations below 200 µg/L are considered safe for most crops, and up to 0.4–5 mg/L is tolerated in livestock drinking water depending on species (ANZECC/ARMCANZ, 2000). Copper is highly toxic to aquatic life at relatively low concentrations. The CWQ Guidelines recommend a chronic guideline of 2 µg/L for the protection of aquatic life (CCME, 1987), while the ANZ Guidelines establish a trigger value of 1.4 µg/L for 95% species protection (ANZECC/ARMCANZ, 2000). In this study, Cu concentrations occasionally exceed these ecological thresholds

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for aquatic life. Moreover, copper binds strongly to colloids and particles; thus, measured concentrations may slightly underestimate total exposure. This is in agreement with a mean concentration of 113 µg/L reported in the Chari River at N'Djamena in 2008 using 0.45 µm filtration (Nambatingar et al., 2017). The reported values (ranging from 70 to 190 µg/L) largely exceed thresholds for aquatic life protection.

Zinc. Concentrations of dissolved Zn range from 3.462 to 13.668 µg/L (Table 1), with the highest value recorded in the upper Chari River at Gassi. These levels are above the global average composition of river water (Fig. 2), estimated at 0.6 µg/L (Gaillardet et al., 2003). This pronounced enrichment indicates a clear anthropogenic influence from agricultural and urban/industrial sources (Nambatingar et al., 2017; Dorim et al., 2022), with urban runoff being highly enriched in Zn due to the widespread accumulation of used batteries in N'Djamena (Kadjangaba, 2007).

For drinking water, the WHO has not established a formal health-based guideline for zinc; however, concentrations above 3 mg/L may impair the aesthetic quality of water (WHO, 2022). For irrigation, concentrations below 2 mg/L are considered safe for most crops, and livestock drinking water can tolerate zinc levels up to 20 mg/L (ANZECC/ARMCANZ, 2000). In aquatic ecosystems, zinc is toxic to invertebrates and fish at relatively low concentrations. The CWQ Guidelines recommend a chronic threshold of 7 µg/L (CCME, 2018) while the ANZ Guidelines establish a trigger value of 8 µg/L for 95% species protection (ANZECC/ARMCANZ, 2000).

In this study, some values exceed these thresholds, suggesting a potential for localized sublethal effects in sensitive aquatic species. Moreover, Zn can associate with colloids and particles, which may lead to an underestimation of Zn concentrations in our samples. This is supported by a mean concentration of 161 µg/L reported in the Chari River at N'Djamena in 2008, using 0.45 µm filtration (Nambatingar et al., 2017). The reported range (60 to 250 µg/L), exceeds the thresholds established for aquatic life protection.

Arsenic. Dissolved As concentrations range from 0.057 to 0.371 µg/L (Table 1). These levels are significantly below the global average composition of river water (Fig. 2) estimated at 0.62 µg/L (Gaillardet et al., 2003). The source of As in the water is both natural and anthropogenic. The observed low dissolved concentrations likely reflect a primarily natural input. However, the association of As with colloidal and particulate matter suggests that the total As content is likely underestimated

As is a toxic metalloid and chronic exposure can lead to serious health effects. The WHO guideline for drinking water is 10 µg/L (WHO, 2022). The trigger value for livestock drinking water is 500 µg/L, while the long-term irrigation threshold is 100 µg/L (ANZECC and ARMCANZ, 2000). For aquatic ecosystems, the CWQ Guidelines recommend a chronic guideline of 5 µg/L (CCME, 1999b).

All concentrations measured in this study are well below these limits. However, arsenic can bind to iron oxides and colloids, suggesting that filtered concentrations may underestimate actual exposure. The underestimation of total As concentrations is supported by recent data reporting an exceptionally high mean concentration of 320 µg/L at Mani,

near the river's mouth (Dorim et al., 2022), with individual values ranging from 40 to 570 µg/L. These elevated concentrations, attributed to anthropogenic inputs, pose potential risks for all water uses

Rubidium. Concentrations of dissolved Rb range from 2.356 to 10.558 µg/L (Table 1), above the global average composition of river water (Fig. 2) estimated at 1.63 µg/L (Gaillardet et al., 2003). The average Rb content (6.735 µg/L) is higher than all the mean river values reported by Gaillardet et al. (2003), with a maximum of 6.16 µg/L in the Sanaga River, and is similar to that found in Lake Chad 1 km from the Chari River's mouth (6.558 µg/L) (Vicat et al., 2023). Rb is not commonly associated with industrial or urban pollution. Anthropogenic sources are rare and generally negligible compared to natural inputs. The dissolved Rb in the Chari and Logone rivers is primarily of natural origin, largely derived from the weathering of potassium-rich minerals within the granitic and metamorphic rocks of their drainage basin (Wolff, 1964).

Rb has no known essential biological function in humans, animals, or plants. No guideline values for drinking water, irrigation, livestock, or aquatic life have been established by international agencies. Given its low concentrations and low toxicity, Rb is not considered a risk to water quality. Rb is predominantly dissolved in natural waters; measured concentrations likely reflect total exposure.

Strontium. Dissolved Sr concentrations (43.5–85.3 µg/L) (Tabl. 1) are close to the global river water average of 60 µg/L (Gaillardet et al., 2003), as shown in Fig. 2. These levels indicate that Sr is largely of natural origin. The modest enrichments sometimes observed suggest additional inputs from urban and industrial sources, which have been documented in N'Djamena (Kadjangaba, 2007; Nambatingar et al., 2017; Dorim et al., 2022). Sr is naturally present in water and is not considered highly toxic. The WHO has not established a formal guideline value for Sr in drinking water. However, a health advisory level of 4000 µg/L for lifetime exposure has been proposed by the Minnesota Department of Health (MDH, 2019). Strontium is also unregulated for agricultural irrigation or livestock drinking water. For freshwater ecosystem protection, a chronic life benchmark of 530 µg/L was established by the Indiana Department of Environmental Management (IDEM, 1999).

All concentrations observed in this study remain well below these indicative thresholds. Given that strontium is predominantly present in dissolved form, the reported concentrations reflect total exposure and are consistent with 0.45 µm-filtered measurements in the Chari–Logone system (Mahamat Nour et al., 2019).

Molybdenum. Concentrations of dissolved Mo range from 0.0232 to 4.618 µg/L (Table 1). Except for the Logone in October 2003 (4.616 µg/L), the values (0.0232-0.503 µg/L) are close to the global average composition of river water (Fig. 2) estimated at 0.42 µg/L (Gaillardet et al., 2003). These concentrations indicate that Mo is largely of natural origin. The elevated Mo concentration in the Logone may result from localized contamination by Mo-bearing lubricants or fertilizers containing molybdate additives.

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The WHO has not set a guideline, as natural water levels are well below health concerns (WHO, 2017, 2022). However, the Australian drinking water guideline is 50 µg/L (NHMRC, 2011). For agriculture, 10 µg/L is considered safe for irrigation, and 150 µg/L for livestock drinking water (ANZECC and ARMCANZ, 2000). Chronic aquatic toxicity is unlikely below 34 µg/L (ANZECC and ARMCANZ, 2000). The measured values, therefore, pose no environmental or toxicological risk. Molybdenum is mainly present in dissolved form; underestimation of exposure is unlikely.

Cadmium. Dissolved Cd concentrations range from 0.029 to 0.667 µg/L (Table 1). Several values exceed the global average composition of river water (Fig. 2) estimated at 0.08 µg/L (Gaillardet et al., 2003). Because the Chari–Logone watershed is dominated by granitoids and siliceous sedimentary rocks and lacks ultrabasic or sulfide-rich formations (Wolff, 1964), natural Cd inputs are expected to be negligible, as Cd is rare in silicates and mainly occurs in sulfides and carbonate minerals. The observed enrichment is most plausibly linked to urban, industrial, and agricultural sources reported in N'Djamena (Nambatingar et al., 2017; Dorim et al., 2022).

Cd is highly toxic even at low levels. The WHO sets a drinking water guideline of 3 µg/L (WHO, 2022). For irrigation and livestock drinking water, concentrations should remain below 10 µg/L (ANZECC and ARMCANZ, 2000). For aquatic life, the chronic threshold for 99% species protection is 0.06 µg/L (ANZECC and ARMCANZ, 2000). Most values (Table 1) exceed this guideline, indicating a potential risk. Moreover, Cd can associate with colloidal matter, suggesting that actual exposure may be underestimated. This is supported by a mean concentration of 37 µg/L reported for the Chari River at N'Djamena, in 2008, using 0.45 µm filtration (Nambatingar et al., 2017). These elevated levels, attributed to anthropogenic inputs, ranged from 10 to 50 µg/L. More recent data report an exceptionally high mean concentration of 490 µg/L at Mani, near the river's mouth (Dorim et al., 2022), with individual values between 240 and 710 µg/L. Such concentrations pose potential risks for all water uses.

Cesium. Concentrations of dissolved Cs range from 0.004 to 0.014 µg/L (Table 1), near the global average composition of river water (Fig. 2) estimated at 0.011 µg/L (Gaillardet et al., 2003) suggesting a predominantly natural origin derived from the weathering of K-feldspar and mica in the granitoid and metamorphic rocks of the Chari–Logone basin (Wolff, 1964), with negligible anthropogenic input.

Cs has no essential biological function and is not commonly regulated. No guideline values exist for drinking water, irrigation, livestock drinking water, or aquatic life. Due to its low toxicity and very low concentrations, Cs does not pose any known environmental concern in the studied samples. Cs is predominantly dissolved in surface waters; measured concentrations likely reflect total exposure.

Barium. Dissolved Ba concentrations range from 36.052 to 63.542 µg/L (Table 1). These values are above the global average composition of river water (Fig. 2) estimated at 23 µg/L (Gaillardet et al., 2003). The observed enrichment suggests a dual origin, combining natural contributions with a significant anthropogenic influence, likely from urban and industrial

sources well documented in N'Djamena (Nambatingar et al., 2017; Dorim et al., 2022).

The WHO guideline for drinking water is 1300 µg/L (WHO, 2022). No international guideline for Ba in irrigation or livestock drinking water exists. The Navajo Nation Water Quality Standards set a maximum of 50 mg/L for crop irrigation and note that livestock can generally tolerate levels under 6.5 mg/L (NNEPA, 2020). For aquatic life, the Indiana Department of Environmental Management provides a chronic value of 140 µg/L (IDEM, 2024). All measured concentrations are well below relevant thresholds for human health, agriculture, and ecological protection. Ba is predominantly present in dissolved form; the measured concentrations likely reflect total exposure.

Lead. Concentrations of dissolved Pb range from 0.019 to 0.273 µg/L (Table 1). Several values exceed the global average composition of river water (Fig. 2) estimated at 0.079 µg/L (Gaillardet et al., 2003). suggesting localized inputs, likely originating from industrial effluents, as reported in N'Djamena (Nambatingar et al., 2017; Dorim et al., 2022). Lead is a toxic metal with no biological function, and its effects are cumulative.

The WHO drinking water guideline is 10 µg/L (WHO, 2022). For irrigation, concentrations should not exceed 200 µg/L, and for livestock, drinking water levels up to 100 µg/L are tolerated (ANZECC and ARMCANZ, 2000). For aquatic life, the chronic threshold for 99% species protection is 1 µg/L (ANZECC and ARMCANZ, 2000).

All measured concentrations in this study are well below these thresholds. However, lead is known to strongly associate with colloids and particulates; therefore, our results may underestimate actual exposure. This is consistent with a mean concentration of 77 µg/L reported at Mani, near the river's mouth, in 2022 (Dorim et al., 2022), attributed to anthropogenic inputs. Reported values ranging from 10 to 150 µg/L exceed guideline limits for both drinking water and aquatic life protection.

Uranium. Dissolved U concentrations range from 0.047 to 0.424 µg/L (Table 1), for the most part below the global average composition of river water (Fig. 2) estimated at 0.372 µg/L (Gaillardet et al., 2003). These values indicate a predominantly natural origin from the weathering of uranium-bearing minerals such as uraninite and other minor accessory minerals in the granitoid and metamorphic rocks of the Chari–Logone basin (Wolff, 1964), although minor contributions from industrial and agricultural sources reported in N'Djamena (Nambatingar et al., 2017; Dorim et al., 2022) cannot be ruled out.

U is both chemically toxic and radioactive, though the latter is negligible at natural concentrations. The WHO guideline for drinking water is 30 µg/L (WHO, 2022). The ANZ Guidelines recommend a maximum of 10 µg/L for irrigation and 20 µg/L for livestock drinking water (ANZECC/ARMCANZ, 2000). For aquatic ecosystems, a trigger value of 0.5 µg/L has been proposed (ANZECC/ARMCANZ, 2000).

All measured concentrations are well below these thresholds, indicating no ecological or toxicological concern. However, U can bind to organic matter or colloids; measured values may slightly underestimate exposure.

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I. CONCLUSION

This study provides a rare baseline dataset on dissolved trace element concentrations in the Chari and Logone rivers, from N'Djamena to the mouth of the Chari during 2003–2005. It predates intensified agricultural and urban development and provides a valuable reference for future assessments. The results reveal localized anthropogenic contamination by several toxic elements. We emphasize the need for sustained monitoring of river water chemistry to track temporal trends in pollution. To mitigate contamination, we recommend expanding sewer and wastewater treatment infrastructure in N'Djamena, limiting the use of chemical fertilizers in favor of sustainable alternatives, and strengthening municipal waste collection. These measures, combined with continuous monitoring, are essential for preserving the water quality of the Chari–Logone system.

REFERENCES

[1] ANZECC and ARMCANZ (2000). *Australian and New Zealand guidelines for fresh and marine water quality. Volume 1: The guidelines; Volume 2: Aquatic ecosystems – Rationale and background information* (National Water Quality Management Strategy, Papers No. 4 and 4a). Canberra: Australian and New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand. https://www.waterquality.gov.au/anz-guidelines

[2] Ayers, R.S., and Westcot, D.W. (1985). *Water quality for agriculture* (FAO Irrigation and Drainage Paper No. 29, Rev.1). Rome: Food and Agriculture Organization of the United Nations. https://www.fao.org/3/t0234e/t0234e00.htm.

[3] Bergen, B., Moens, C., De Winter, A., Ricou, F., and Smolders, E. (2023). Colloids facilitate cadmium and uranium transport in an undisturbed soil: A comparison of soil solution isolation methods. *Sci Total Environ*, 10, 890:164419.

[4] CCME (1987). *Canadian water quality guidelines for the protection of aquatic life: Copper*. In *Canadian environmental quality guidelines.* Winnipeg, MB: Canadian Council of Ministers of the Environment.

[5] CCME (1999a). *Canadian water quality guidelines for the protection of aquatic life: Chromium*. In *Canadian environmental quality guidelines.* Winnipeg, MB: Canadian Council of Ministers of the Environment.

[6] CCME (1999b). *Canadian water quality guidelines for the protection of aquatic life: Arsenic*. In *Canadian environmental quality guidelines, 1999.* . Winnipeg, MB: Canadian Council of Ministers of the Environment.

[7] CCME (2009). *Scientific Criteria Document for the Development of the Canadian Water Quality Guidelines for Boron*. Winnipeg, MB: Canadian Council of Ministers of the Environment.

[8] CCME (2016). *Canadian water quality guidelines for the protection of aquatic life: Vanadium*. In *Canadian environmental quality guidelines.* Winnipeg, MB: Canadian Council of Ministers of the Environment.

[9] CCME (2018). *Canadian water quality guidelines for the protection of aquatic life: Zinc*. In *Canadian environmental quality guidelines*. Winnipeg, MB: Canadian Council of Ministers of the Environment.

[10] CCME (2019). *Canadian water quality guidelines for the protection of aquatic life: Manganese*. In *Canadian environmental quality guidelines, 1999*. Winnipeg, MB: Canadian Council of Ministers of the Environment.

[11] Dorim, N., Houkabe, E., Arabi, M., and Madi, A. (2022). Evaluation Of Water And Sediment Pollution Parameters Of The Chari River Before Its Discharge Into Lake Chad In The Mani Area (Chad). *Sahelian Journal of Engineering and Applied Sciences*, 1(1), pp. 76-92.

[12] DWAF (1996). *South African water quality guidelines*, 2nd edn, vol 5: Agricultural use: Livestock watering. CSIR. Environmental Services, Pretoria.

[13] ECCC (2017). *Federal environmental quality guidelines cobalt*. Environment and Climate Change Canada. Canadian Environmental Protection Act, 1999. Government Canada.

[14] ECCC (2022). *Federal environmental quality guidelines Aluminium*. Environment and Climate Change Canada. Canadian Environmental Protection Act, 1999. Government of Canada.

[15] ECHA (2023). *Vanadium pentoxide: Long-term toxicity to aquatic invertebrates.* European Chemicals Agency ECHA registration dossier. https://echa.europa.eu/registration-dossier/-/registered-dossier/15418/6/2/1

[16] Elder, J.F. (1988). *Metal Biogeochemistry in Surface-Water Systems: A Review*. U.S. Geological Survey Circular 1013.

[17] EPA (2023). *Technical Fact Sheet: Lithium in Drinking Water (UCMR5)*. U.S. Environmental Protection Agency. https://www.epa.gov/system/files/documents/2023-11/ucmr5-technical-fact-sheet-lithium-in-drinking-water.pdf

[18] EWG (2023). *Cobalt – Tap Water Database*. Environmental Working Group City of Ontario

[19] Gaillardet, J., Viers, J., and Dupré, B. (2003). *Trace elements in river waters*. In J. I. Drever (Ed.), Treatise on Geochemistry, (Vol. 5, pp. 225–272). Elsevier-Pergamon. https://doi.org/10.1016/B0-08-043751-6/05165-3

[20] Hem, J.D. (1985). *Study and interpretation of the chemical characteristics of natural water* (3rd ed.). U.S. Geological Survey Water-Supply Paper 2254.

[21] Hisseien, A.T., Kuate Kamga, R., and Mahamat, T.N. (2015). Physico-chemical analysis of Logone River water at Moundou City in Southern Chad. *International Journal of Biological and Chemical Sciences* 9(3):1654. https://doi.org/10.4314/ijbcs.v9i3.44

[22] IDEM (1999). Indiana Department of Environmental Management Office of Water Quality - Water Quality Standards Section. *Tier II Acute and Chronic Aquatic Life Values: Strontium*

[23] IDEM (1924). Indiana Department of Environmental Management Office of Water Quality - Water Quality Standards Section. *Tier II Acute and Chronic Aquatic Life Values: Barium*

[24] Johnson, J H., Crookshank, H.R., and Smalley, H E. (1980). Lithium toxicity in cattle. *Veterinary and Human Toxicology*, 22(4), pp. 248–251.

[25] Kadjangaba, E. (2007). *Etude hydrochimique et isotopique du système zone non saturée – nappe dans la zone urbaine de N'Djaména : impact de la pollution*. Thèse, Université d'Avignon et des Pays de Vaucluse, France, 185 p.

[26] Kszos, L.A., Beauchamp, J.J., and Stewart, A.J. (2003). Toxicity of lithium to three freshwater organisms and the antagonistic effect of sodium. *Ecotoxicology, 12*(5), pp. 427–437. https://doi.org/10.1023/A:1026160323594

[27] Langmuir, D. (1997). *Aqueous environmental geochemistry*. Prentice Hall.

[28] Mahamat Nour, A., Vallet-Coulomb, C., Bouchez, C., Ginot P., Doumnang J.C., Sylvestre F., and Deschamps P. (2020). Geochemistry of the Lake Chad Tributaries Under Strongly Varying Hydro-climatic Conditions. *Aquat Geochem* 26, pp. 3–29. https://doi.org/10.1007/s10498-019-09363-w

[29] MDH (2019). *Strontium and groundwater – Health advisory levels*. Minnesota Department of Health. https://www.health.state.mn.us/communities/environment/risk/docs/guidance/gw/strontiuminfo.pdf

[30] Nambatingar, N. (2011). *Contribution à l'étude analytique des polluants (en particulier de type métaux lourds) dans les eaux du fleuve Chari lors de sa traversée de la ville de N'Djamena.* Thèse, Université Claude Bernard - Lyon I, France. 164 p.

[31] Nambatingar, N., Clement, Y., Merle, A., New Mahamat, T., and Lanteri P. (2017). Heavy Metal Pollution of Chari RiverWater during the Crossing of N'Djamena (Chad). *Toxics*, 5, 26. https://doi.org/10.3390/toxics5040026

[32] NHMRC (2011). *Australian Drinking Water Guidelines Paper 6: National Water Quality Management Strategy*. National Health and Medical Research Council, Australian Government.

https://www.nhmrc.gov.au/about-us/publications/australian-drinking-water-guidelines

[33] NNEPA (2020). *Navajo Nation Water Quality Standards for Metals and Protection of Crops, Livestock, and Humans*. Navajo Nation Environmental Protection Agency, Window Rock, AZ. https://www.epa.gov/system/files/documents/2024-03/final-navajo-nation-metals-wqs-protection-of-crops-livestock-and-humans-april-2020.pdf

[34] OEHHA (2021). *Proposed notification level for vanadium*. California Office of Environmental Health Hazard Assessment. https://oehha.ca.gov/water/proposed-notification-level-vanadium

[35] Pawlisz, A.V., R.A. Kent, U.A. Schneider, and C. Jefferson. (1997). Canadian water quality guidelines for chromium. *Environ. Toxicol. Water Qual.*, 12, pp. 185–193.

[36] Roche M.A. (1967). *Première estimation des apports en sels au lac Tchad par le Chari*. Rapport, Centre ORSTOM de Fort Lamy (Tchad), 50 p.

[37] Sigg, L., Behra, P. and Stumm, W. (2014). *Chimie des milieux aquatiques* (5th ed.). Dunod.

[38] Sorlini, S., Palazzini, D., Sieliechi, J. M., and Ngassoum, M. B. (2013). Assessment of Physical-Chemical Drinking Water Quality in the Logone Valley (Chad-Cameroon). *Sustainability*, 5(7), pp. 3060-3076. https://doi.org/10.3390/su5073060

[39] Stumm, W. and Morgan, J.J. (1996). *Aquatic chemistry: Chemical equilibria and rates in natural waters* (3rd ed.), Wiley.

[40] Tchoroun, M., Noumi, G.B., Tchadanaye, N.M., and Dikdim Dangwang, J.M. (2022). Heavy Metals Pollution Level in Water, Fish and Sediments from the Logone River Within Moundou City (Chad). *International Journal of Environmental Monitoring and Analysis*. 3(5), pp. 275-281. https://doi.org/10.11648/j.ijema.20150305.15

[41] Vicat J.P., Doumnang Mbaigane, J.C., and Nadjilem, D.N. (2023). Physicochemical Characterization of Pond Waters in the Kanem Region, Republic of Chad. *International Journal of Multidisciplinary Research and Publications,* 6(4), pp. 68- 75.

[42] WHO (2022). *Guidelines for drinking-water quality: Fourth edition incorporating the first and second addenda*. World Health Organization. Geneva. https://www.who.int/publications/i/item/9789240045064

[43] Wolff, J.P. (1964). *Carte géologique de la République du Tchad* (échelle 1 : 1 500 000) [Carte en 2 feuilles]. Bureau de recherches géologiques et minières, Paris.