

Optimizing Soil Fertility in the Chari-Logone Basin (Chad Republic): The Role of Nitrates, Phosphates, Sulfates, and Major Cations

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Abstract

Alluvial deposits from the Chari-Logone basin play a fundamental role in the natural fertilization of soils and agricultural productivity in the region. Indeed, annual floods deposit sediments rich in essential nutrients such as nitrates, phosphates, and sulfates, as well as major cations such as calcium (Ca^{2+}), magnesium (Mg^{2+}), and aluminum (Al^{3+}). These deposits directly contribute to improving the chemical fertility of farmland and market gardens located along the river and its tributaries. As part of this study, 48 sediment samples were collected from various sites in the Chari-Logone Basin and analyzed in the LABEN (Laboratory of Water and Natural Substances at the University of N'Djamena) using a HACH DR2400 spectrometer. The results show significant spatial variability in nutrient concentrations. Nitrate concentrations ranged from 0 to 295 mg/L, phosphate concentrations from 0.35 to 5.8 mg/L, and sulfate concentrations from 6.6 to 270 mg/L. For cations, the values recorded range from 0.01 to 9.56 mg/L for calcium, 0.20 to 4.96 mg/L for magnesium, and 0.10 to 4.61 mg/L for aluminum. Analysis of average Fe/Al ratios reveals the presence of young, ferralitic, and ferruginous soils that are particularly well-developed in areas downstream of N'Djamena. In light of these results, it appears essential to promote integrated and sustainable management of the basin's water and soil resources. This management must balance the needs of agriculture and market gardening with environmental conservation. This involves optimizing nutrient use, applying targeted soil amendments, implementing crop rotation, improving water management, and taking measures to combat erosion. This agroecological approach aims to enhance the sustainability and resilience of produc-

tion systems in the Chari-Logone basin.

Keywords

Optimization, Environment, Soils, Chari-Logone Basin

1. Introduction

Rural landscapes are indeed facing increasing levels of damage and pollution, which must be managed in a rational manner. Soil has always been regarded as a source of nutrients, and for nearly two centuries, one of the main objectives of agronomists and soil chemists has been to identify and quantify, in various soils, the reserves of elements presumed to be assimilable and capable of nourishing crops. With the global population projected to reach 9.5 billion by 2050, agricultural production will need to increase by 70% to ensure food security [1]. However, approximately 33% of the world's soils are already degraded by erosion, salinization, and loss of organic matter [2]. In this context, optimizing soil fertility through the management of major nutrients—namely nitrogen in the form of nitrates (NO_3^-), phosphorus in the form of phosphates (PO_4^{3-}), and major cations (Ca^{2+} , Mg^{2+} , Na^+ , K^+)—has become essential [3].

Globally, nitrogen and phosphorus are the main drivers of agricultural intensification. The use of nitrogen fertilizers has increased ninefold since 1960 and accounts for nearly 50% of the increase in crop yields [4]. However, nitrogen use efficiency remains low, with 50% to 70% of applied nitrogen lost through leaching and volatilization, which contributes to water pollution and eutrophication [5]. Phosphorus is a non-renewable mineral resource. Cordeil *et al.* [6] estimate that exploitable reserves could be depleted within 50 to 100 years, making recycling and improving utilization efficiency urgent priorities. Sulfur, which was long supplied by industrial atmospheric emissions, has become a limiting factor in many regions of the world following the reduction in SO_2 emissions [7]. Finally, the major cations— Ca^{2+} , Mg^{2+} , and K^+ —control soil structure, pH, and cation exchange capacity, while excess Na^+ is responsible for the salinization of 10% of the world's irrigated land [8].

In sub-Saharan Africa, the situation is even more critical. The continent possesses 60% of the world's reserves of uncultivated arable land but has the lowest cereal yields: 1.2 metric tons per hectare compared to a global average of 4 metric tons per hectare [9].

This low productivity is primarily due to a lack of nutrients. According to Sanchez [10], African soils lose an average of 30 to 60 kg of NPK per hectare per year without sufficient replenishment, and 75% of them contain less than 1% organic matter. Deficiencies in nitrogen, phosphorus, and potassium are widespread [11]. Phosphorus is particularly problematic because 80% of the applied P is rapidly bound by iron and aluminum oxides in tropical soils and becomes unavailable to plants

[12].

In Chad, agriculture employs more than 80% of the working population and relies on soils that are mostly poor. The country comprises four major agroecological zones: the Saharan, Sahelian, Sudanese, and Lake Chad zones. The Sahelian and Sudanese soils are tropical ferruginous soils characterized by nitrogen, phosphorus, and organic matter content of less than 1% [13]. Sorghum yields do not exceed 0.6 to 0.8 metric tons per hectare, which is four times less than the potential [14].

In southern Sudan, soil acidity ($\text{pH} < 5.5$) leads to aluminum toxicity and phosphorus immobilization, requiring liming [15]. In the Lake Chad basin and the Chari Delta, intensive irrigation promotes the accumulation of Na^+ and soil salinization [8]. Furthermore, studies on the water quality of the Chari River show high levels of COD and trace metals, raising questions about the impact of these pollutants on the fertility of floodplain soils.

Given these constraints, the central question is: How can we optimize the management of nitrates, phosphates, sulfates, and major cations to improve the fertility of Chadian soils and agricultural productivity, while minimizing the risks of soil degradation and water pollution?

The overall objective is to assess the contribution of nitrates, phosphates, sulfates, and major cations in the alluvial sediments of the Chari-Logone basin in order to propose strategies for optimizing soil fertility for sustainable agriculture and vegetable farming.

To this end, our work will consist of analyzing sediments along the Chari watershed to assess the concentrations of certain elements that agricultural and other inputs could increase, given that this is an area of agricultural and market gardening practices.

Geographical Location

The Chadian part of the Chari-Logone basin is situated between 9° and 13° north latitude and 14° and 20° east longitude [16]. It covers an area of approximately 270,000 km^2 , representing 45 per cent of the total basin, which spans 600,000 km^2 [17]. The river system is dominated by two main watercourses: the Chari River, which is 1200 km long in Chad, rises in the Central African Republic and flows through N'Djamena; and the Logone River, which is 1000 km long, rises in Cameroon and joins the Chari at N'Djamena before flowing into Lake Chad [18]. The province of Hadjer-Lamis, the area covered by this study, is situated north of N'Djamena, between $12^\circ 30'$ and $14^\circ 30' \text{N}$ and $14^\circ 30'$ and 18°E [19]. The Chadian part of the basin is home to around 12 million people, representing over 60 per cent of the national population [17]. According to the RGPH2 [20], the Hadjer-Lamis province has a population of 1,150,000. The local population relies on agriculture: food crops and market gardening along the Chari and Logone rivers, and rice cultivation in the floodplains; on livestock farming - the second-largest herd in Africa, comprising cattle, sheep and camels; and on fishing, which accounts for more than 70 per cent of national fish production [16]. These activities, combined

with urban and industrial effluents concentrated around N'Djamena, place significant pressure on the quality of the basin's sediments [17].

2. Materials and Methods

2.1. Material

- Samples: 48 soil samples collected along the Chari watershed as showing in **Figure 1**.
- Equipment: A digital camera, a GARMIN GPS device, an ISO-SCAN pH meter, a HACH DR 2400 spectrometer, and an electrical conductivity meter (WTW-315i/SET).

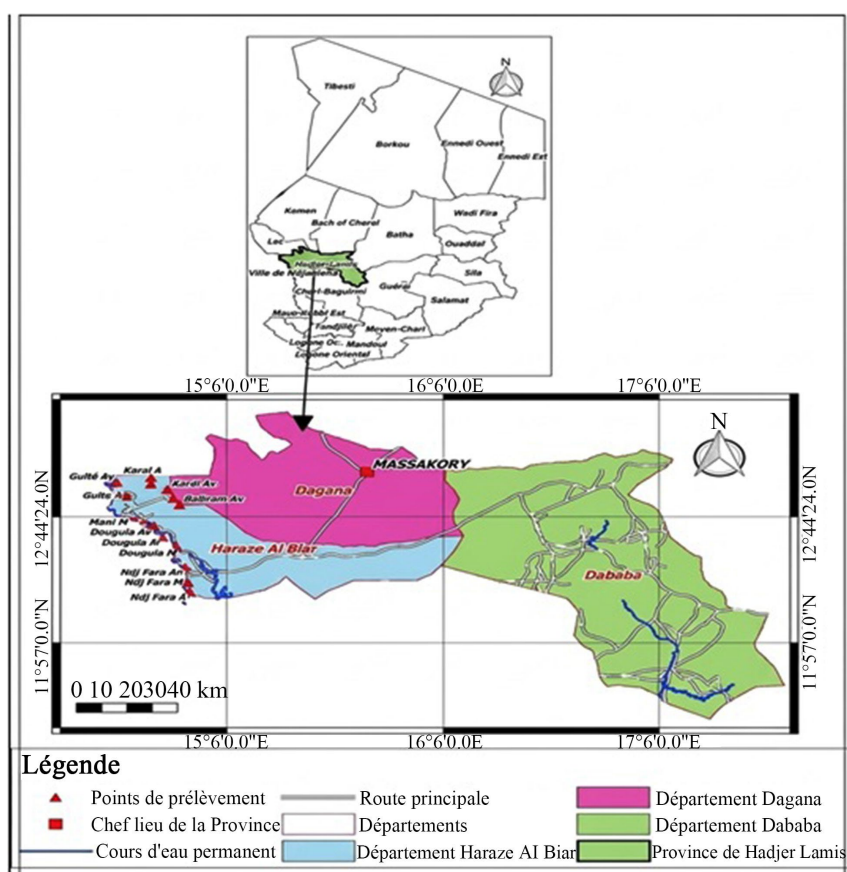


Figure 1. Map of the study area and sampling sites in the Chari-Logone Basin, N'Djamena, Chad.

2.2. Methods

- Grinding and sieving: A total of six areas were selected for sampling. Samples were collected from a 40-cm-thick layer, with three samples taken from each area to account for the horizontal heterogeneity of the substrate as showing in **Figure 1**.

The bottles used were made of polypropylene and thoroughly cleaned at LABEN. Grinding was performed in an agate mortar and pestle after drying in the

laboratory. Next, the sediments were sieved to separate the grain size fractions: less than 2 mm, between 2 mm and 63 μm , and less than 63 μm . Sieving allowed the sediments to be separated into four fractions. After each handling step, the sieves are cleaned with water and alcohol.

Finally, the fractions ranging from 2 mm to 63 μm were placed in bags for analysis at LABEN (Laboratory of Water and Natural Substances) of the Faculty of Exact and Applied Sciences in N'Djamena.

Procedure.

- 10 ± 0.05 g of soil is suspended in 50 ± 0.1 mL of distilled water and shaken for one hour on a shaking plate. Then allow to stand for 2 hours.
- 10 ± 0.05 g of soil is suspended in 50 ± 0.05 mL of 0.01 mol/L calcium chloride solution and stirred for 1 hour on a shaking plate. Then allow to stand for 2 hours.

The pH is then measured using an ISO-SCAN pH meter.

Temperature measurements were taken in the field using a thermometer.

This measurement was performed using a Consort C933 multiparameter meter equipped with a measurement cell featuring automatic temperature compensation.

Ion Analysis.

Nitrates

Nitrates DR/2400 UV Spectrophotometer for water, wastewater, and seawater; Cadmium Reduction Method. Metallic cadmium reduces nitrate to nitrite. In an acidic medium, the nitrite ion reacts with sulfanilic acid to form an intermediate diazonium salt. This salt reacts with gentisic acid to form an amber-colored solution.

Phosphate

Phosphorus, Hydrolyzable UV Spectrophotometer DR/2400 (0.00 to 5.00 mg/L PO_4^{3-} for water and wastewater), PhosVer 3 method with acid hydrolysis, Test 'N Tube technique for water, wastewater, and seawater. Phosphorus present in condensed inorganic forms (meta-, pyro-, and other polyphosphates) must be converted to reactive orthophosphate prior to analysis. Pretreating the sample in a hot acidic medium provides the conditions for the hydrolysis of these condensed inorganic forms.

Turn on the COD reactor. Preheat to 150°C. Place the safety screen in front of the DCO reactor. Ensure that safety equipment is in place to protect the operator from splashes in the event of a reagent leak. See the DCO reactor user manual for temperature setting Instructions. Enter the program number stored for orthophosphate, Test 'N Tube (PO_4^{3-}).

Sulfates

Extraction with distilled water.

Add the Sulf Ver 4 reagent (supplied with the DR 2400); read the absorbance at the appropriate wavelength of 450 nm.

Result: SO_4^{2-} concentration in mg/L.

Calcium

Ca extraction is performed using ammonium acetate (1 M, pH 7).

Analysis using the HACH DR 2400

EDTA methods by titration within the following ranges:

- Sandy soils: 0.05 - 5 cmol/kg;
- Clay soils: 5 - 20 cmol/kg;
- Calcareous soils: >20 cmol/kg.

Magnesium

Extraction is performed using ammonium acetate (1 M, pH 7).

Titration is performed using EDTA.

Aluminum

Aluminum UV Spectrophotometer DR/2400 (0 to 0.80 mg/L) for water and wastewater. Aluminon method adapted from *Standard Methods for the Examination of Water and Wastewater*. The Aluminon indicator reacts with the aluminum in the sample to produce a red-orange color. The intensity of the color is proportional to the aluminum concentration. Ascorbic acid is added to eliminate interference from iron.

The AluVer 3 reagent, a powder packaged in capsules, offers exceptional stability and is suitable for use with fresh water.

3. Results

Table 1. Coordinates and chemical properties of the 40 soil samples from the Chari-Logone basin.

Code site	Locality	Soil using	Latitude N° x	Longitude E° y	T° C	pH	NO ₃ ⁻ mg/L	PO ₄ ³⁻ mg/L	SO ₄ ²⁻ mg/L	Ca ²⁺ mg/L	Mg ²⁺ mg/L
NF1	N'Djaména-Fara	vegetable farming	12.3695	14.9086	26	4.56	83	0.35	58.5	9.1	5.4
NF2	N'Djaména-Fara	vegetable farming	12.3823	14.9101	24	5.56	63	1.82	73	4.4	3.1
NF3	N'Djaména-Fara	vegetable farming	12.4018	14.9048	29	7.11	37	0.69	56.5	4.1	1.7
D1	Douguia	vegetable farming + grazing	12.6401	14.8154	28	4.96	15	2.22	70	0.79	0.04
D2	Douguia	vegetable farming + grazing	12.6412	14.8089	27	5.0	147	5.8	220	0.01	1.78
D3	Douguia	vegetable farming + grazing	12.642	14.7981	24	6.18	149	5.6	230	0.66	1.87
M1	Mani	Riz + grazing	12.7264	14.7196	28	6.78	110	2.07	98	1.54	0.09
M2	Mani	Riz + grazing	12.7261	14.6829	28	5.27	197	1.81	140	0.92	0.05
M3	Mani	Riz + grazing	12.7507	14.6602	27	5.35	295	5.8	270	0	0.06
K1	Karal	Corn	12.9226	14.7672	22	5.45	2.7	2.58	6.6	0.04	0.12
K2	Karal	Corn	12.9116	14.7752	26	7.73	2.2	1.11	41	0.02	1.06
B1	Baltram	Corn	12.9517	14.7336	22	9.47	52.5	1.51	38	3.17	0.74
B2	Baltram	Corn	12.9469	14.7461	21	10.18	210	2.44	68	0.2	0.03
B3	Baltram	Corn	12.932	14.7589	21	8.06	65	0.5	29	1.42	0.07
G1	Guité	farming	12.8903	14.6273	22	7.84	3.8	0.81	27	0.45	0.08
G2	Guité	vegetable farming	12.8903	14.6273	20	6.03	122	1.12	42	0.67	0.31

Unity: mg/L only pH; This table shows the pH, nitrates, phosphates, sulfates, and major cations for each site and depth.

The results are presented in **Table 1**.

PH

NF3 > NF2 > NF3M1 > M2 and M3D3 > D1 and D2K2 > K1B2 > B1 > B3G1 > G2.

Overall: Baltram (9.23) > Guité (6.93) > Karal (6.59) > N'Djamena (5.77) > Mani (5.8) > Douguia (5.38) as showing in **Figure 2**.

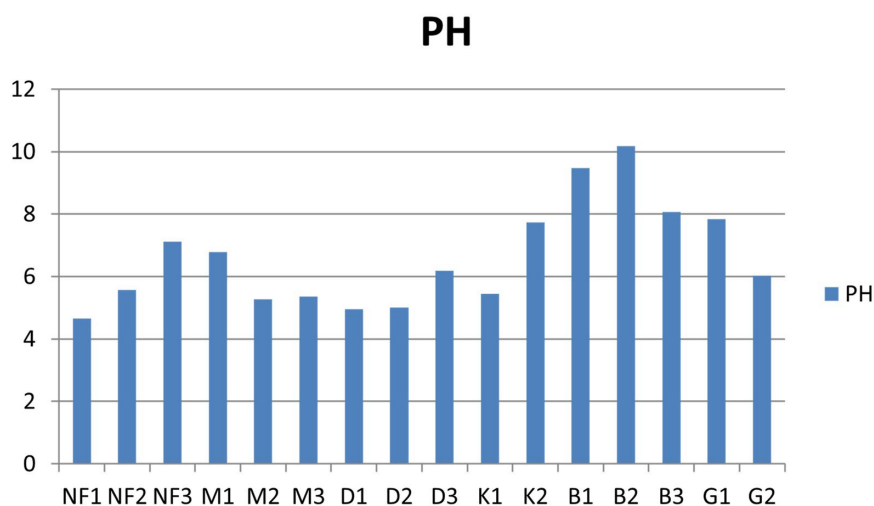


Figure 2. Evolution du PH.

Nitrates

Nitrate concentrations fluctuate significantly, with a maximum of 295 mg/L and a minimum upstream of N'Djamena-Fara.

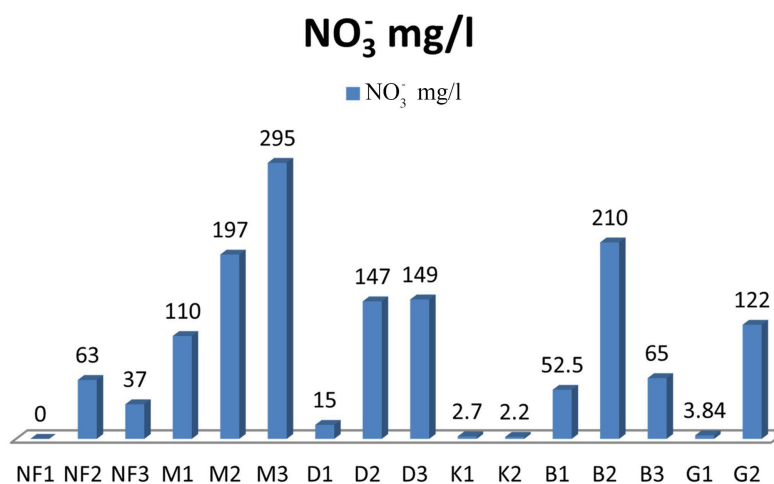


Figure 3. Trend of Nitrate concentrations.

Two locations show concentrations that vary little between two different sampling points. These are Douguia, midstream and downstream, with concentrations of 147 mg/L and 149 mg/L, respectively and Karal midstream and downstream, with concentrations of 2.7 g/L and 2.2 mg/L. Another notable case

is Baltram, which shows a peak concentration of 210 mg/L between 52.5 mg/L upstream and 65 mg/L downstream. This may indicate an influx linked to agricultural inputs, as this is an area of intense agricultural activity. Average concentrations from upstream to downstream: Mani (200.66 mg/L), Baltram (109 mg/L) > Douguia (103.66 mg/L) > Guité (62.92 mg/L) > N'Djamena-Fara (50 mg/L) as showing in **Figure 3**.

Phosphates

Phosphate concentrations are low at N'Djamena-Fara (0.35 mg/L) and Baltram (0.5 mg/L). In most cases, they range between 1 mg/L and 3 mg/L, with two peaks (5.8 mg/L) at Mani and Douguia.

Overall: Douguia (4.54 mg/L) > Mani (3.22 mg/L) > Karal (1.845 mg/L) > Baltram (1.48 mg/L) > N'Djamena-Fara (0.95 mg/L) as showing in **Figure 4**.

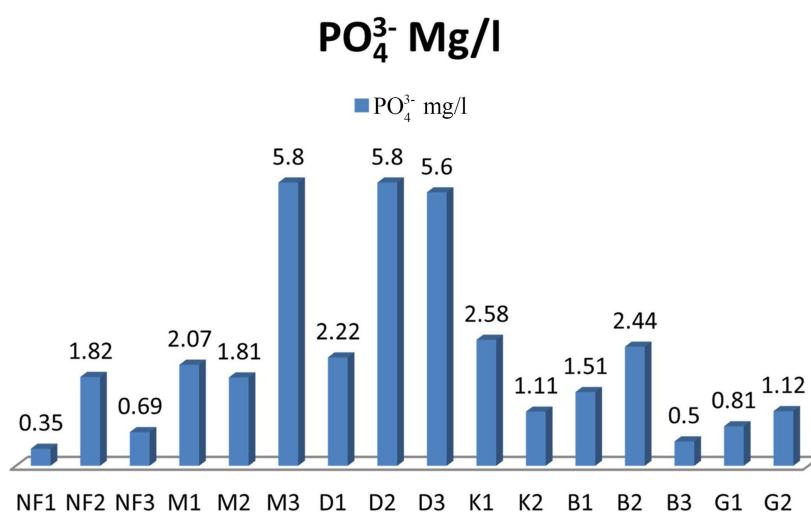


Figure 4. Trend of Phosphate concentration.

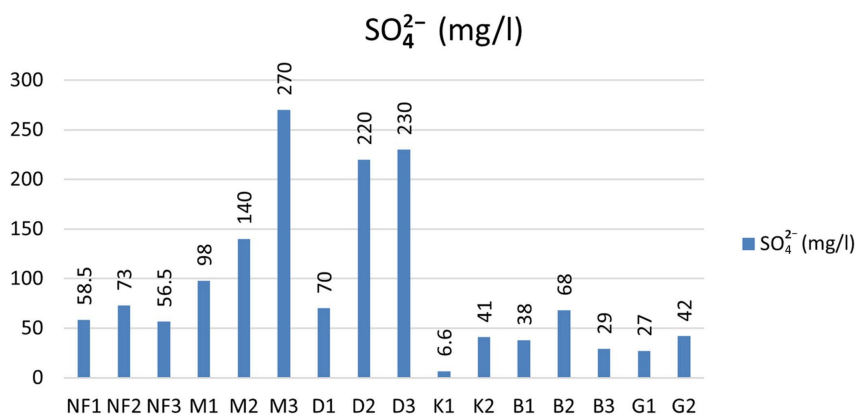


Figure 5. Trends of sulfate concentrations.

Overall: Douguia (173.33 mg/L) > Mani (169.33 mg/L) > N'Djamena-Fara (62.66 mg/L) > Baltram (45 mg/L) > Guité (34.5 mg/L) > Karal (23.8 mg/L) as showing in **Figure 5**.

Evolution des éléments majeurs le long du bassin versant du Chari en mg/l.

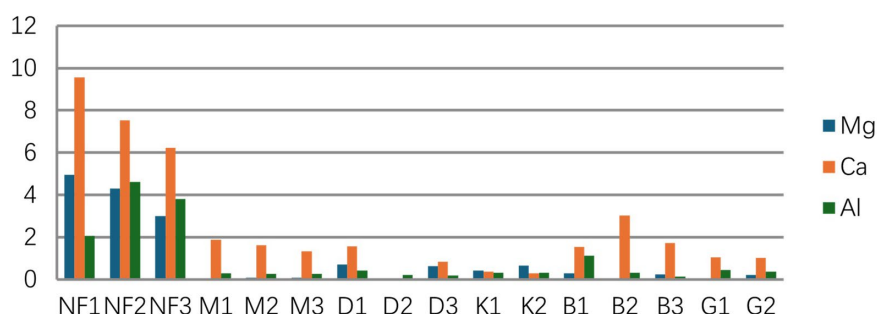


Figure 6. Changes in the major elements along the Chari Delta.

- **Magnesium**

N'Djamena-fara (4.09 mg/L) > Karal (0.54 mg/L) > Douguia (0.45 mg/L) > Baltram (193 mg/L) > Guité (0.13 mg/L) > Mani (0.07 mg/L) in **Figure 6**.

- **Calcium:**

N'Djamena-fara (7.77 mg/L) > Baltram (2.09 mg/L) > Mani (1.61 mg/L) > Guité (1.034 mg/L) > Douguia (0.80 mg/L) > Karal (0.32 mg/L) in **Figure 6**.

- **Aluminium:**

N'Djamena-Fara (3.49 mg/L) > Baltram (0.52 mg/L) > Guité (0.40 mg/L) > Karal (0.315 mg/L) > Mani (0.27 mg/L) > Douguia (0.26 mg/L) in **Figure 6**.

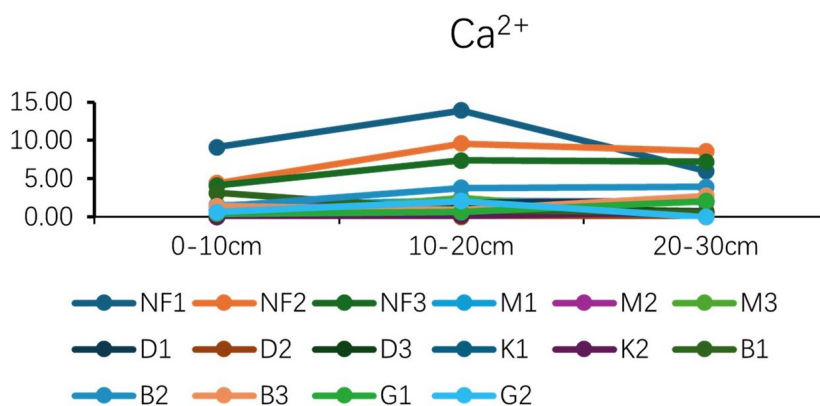


Figure 7. Changes in calcium concentration with depth.

At N'Djaména-Fara, calcium concentration increases, peaking at 10 and 20 cm, and then decreases thereafter.

At Douguia, calcium concentration remains stable at the surface down to 20 cm and then decreases thereafter.

In Mani, calcium levels increase, peaking at 10 and 20 cm before decreasing; the same pattern is observed in Karal and Guité in **Figure 7**.

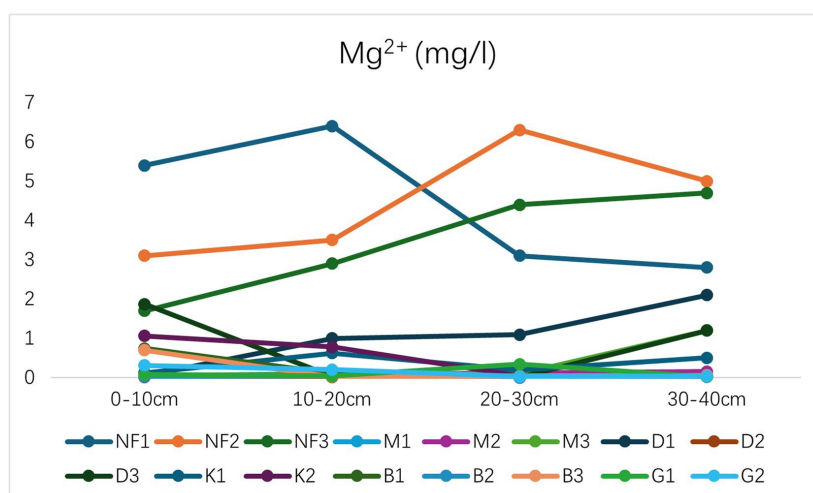


Figure 8. Changes in magnesium concentration with depth in soils of the Chari-Logone Basin, N'Djamena, Chad.

In N'Djaména, magnesium concentrations increase with depth. In Douguia and Mani, however, magnesium concentrations first increase and then decrease, suggesting leaching at depth and indicating a magnesium-deficient soil. An accumulation is observed at a depth of about 10 to 20 cm, followed by leaching at a depth of 30 cm.

In Karal and Baltram, magnesium decreases with depth. In Guité, however, it first decreases and then increases, indicating leaching at the surface followed by accumulation at depth in **Figure 8**.

Aluminum concentrations increase with depth at N'Djaména-Fara and Douguia. At Mani, concentrations first decrease and then stabilize. At Karal, aluminum concentrations first decrease and then increase slightly. Guité shows a trend opposite to that of Karal in **Figure 9**.

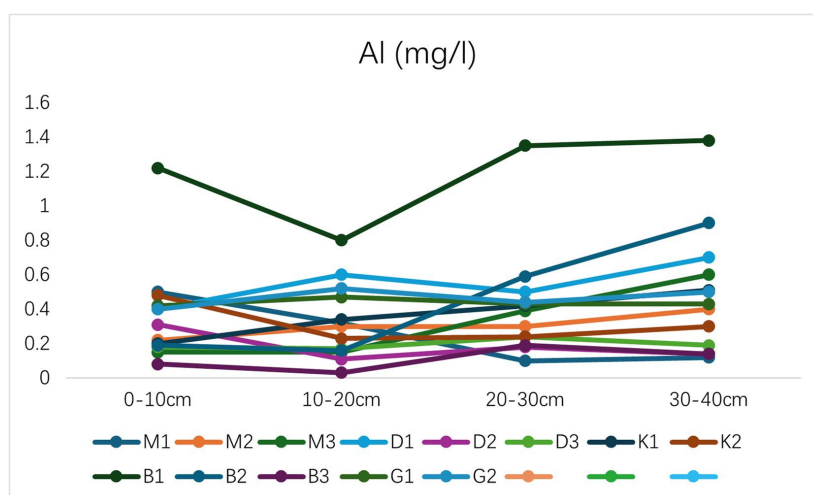


Figure 9. Aluminium concentration as a function of depth.

4. Discussion

In fact, inorganic (mineral) phosphorus can constitute a significant portion of soil

phosphorus reserves [18]. It is present primarily in an oxidized state, mainly as a complex with Ca, Fe, Al, and silicate minerals.

In organic soils, it is primarily bound to Al and Fe [19]; consequently, the phosphorus saturation level of these soils could be defined by the molar ratio (P/Al+Fe) [20]. The forms of the ion vary with pH. At a pH of 5 to 8, the H_3PO_4 and PO_4^{3-} forms are negligible, leaving the chemical equilibrium between H_2PO_4^- and HPO_4^{2-} to determine the form of phosphate present. At pH 6, approximately 90% of the phosphate is in the H_2PO_4^- form, while at pH 7, this figure drops to 60% [21]. Only a portion of the easily mineralizable organic phosphorus and the inorganic phosphorus weakly adsorbed onto clay colloids is available [22].

The amount of phosphorus available for plant nutrition in the soil solution is low due to the very low solubility of this element: between 0.5 and 1 mg/L on average, which represents between 0.04 and 1.6 kg P/ha [23]. In the short term, the main factors responsible for the adsorption of phosphate ions are aluminium and iron oxides and free binding, as well as calcium and magnesium in exchangeable form [24].

Most of the phosphate ions introduced into the soil are bound and do not undergo desorption, nor do they exhibit the same mobility.

Ammonium in the soil can be converted into nitrates by a group of bacteria known as nitrite- and nitrate-forming bacteria.

This process, called nitrification, is controlled by the partial pressure of oxygen in the root zone, pH, temperature, and organic carbon concentration [25].

Nitrate is the dominant form of nitrogen in the soil solution. This highly mobile form is therefore susceptible to leaching in large quantities in most soils.

Factors that can influence nitrate retention include pH and metal sesquioxides [26]. [27] showed that nitrates are adsorbed onto soil at acidic pH levels in a nonspecific manner at the surface through electrostatic attraction.

Sulfates play a key role in plant growth, particularly in the synthesis of proteins and enzymes [28].

In sub-Saharan Africa, a systematic study showed that the application of sulfates can increase crop yields by 20% to 60%, depending on the crop type and the applied rate.

Cereals such as maize and rice respond particularly well to sulfate application [29].

A deficiency (<10 ppm) or excess (>20 ppm) of sulfates can impact agricultural productivity. The optimal rate is between 10 and 20 ppm.

Limestone in the soil affects its pH, which in turn influences phosphorus uptake; in limestone-rich soils high in Ca^{2+} , the dominant form of phosphorus is P-Ca (calcium-bound phosphate) [30].

Several authors state that phosphorus adsorption in calcareous soils is generally proportional to the amount of CaCO_3 , which provides a significant adsorbent surface for phosphorus [31]. CaCO_3 surfaces tend to promote the nucleation and growth of calcium phosphate [32].

5. Environmental Impacts

However, the presence of these elements has consequences for the soil.

Nitrates can pollute water (eutrophication, human health).

Phosphates cause eutrophication of water bodies, leading to a loss of biodiversity.

Sulfates acidify soil and water when present in excess;

Calcium generally has little impact but is beneficial for acidic soils;

Magnesium is essential for plants, but in excess, it disrupts soil balance;

Aluminum, on the other hand, is toxic to plants when the pH is low; as such, it affects acidic soils.

To address this, targeted applications and appropriate fertilizer doses are needed, along with improving nutrient use, reducing leaching, and limiting erosion through plant cover (which limits erosion and absorbs excess nutrients).

6. Conclusions

It is important to manage nitrates, phosphates, sulfates, calcium, magnesium, and aluminum in the soil of the Chari Delta in order to maximize agricultural production and protect the environment. There is, in fact, a synergy among these various elements studied, as we observe better nitrogen uptake when sulfur is sufficient, just as phosphorus availability is linked to pH and the Ca/Mg ratio.

Indeed, a balanced application of NPK-S-CaMg helps optimize crop yield and resilience.

From this perspective, soil analysis is important for adjusting nutrient applications and using organic amendments (manure, compost) to provide complementary benefits.

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Author Contributions

M.G.: conceived the study, conducted the fieldwork, wrote the manuscript, and contributed to funding; N.D.C.: Supervised the project, managed project administration, and contributed to funding; T.L.: Performed data analysis, reviewed and edited the manuscript. All authors read and approved the published version of the manuscript; M.G.: Mallet II Guedna; N.D.C.: Nekoulngang Djetounanko Clarisse; T.L.: Tekoum Léontine.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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