

Assessment of Aquifer Contamination in the Northeast of the Montevideo Department, Uruguay

Karina Pamoukaghlián¹, Elena Alvareda², Virginia Martinato¹, Valery Bühl³, Paulina Pizzorno⁴, Valeria Rodríguez¹, Elyana Muñoz¹

¹Instituto de Ciencias Geológicas, Facultad de Ciencias, Montevideo, Uruguay

²Departamento del Agua, Centro Universitario Regional Litoral Norte, Universidad de la República, Montevideo, Uruguay

³Área Química Analítica, DEC, Facultad de Química, Universidad de la República, Montevideo, Uruguay

⁴Centro Especializado en Química Toxicológica (CEQUIMTOX), Área Toxicología, DEC, Facultad de Química, Universidad de la República, Montevideo, Uruguay

Email: kpamoukaghlian@gmail.com, alvareda@fq.edu.uy

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Abstract

Increasingly frequent water scarcity conditions necessitate the implementation of alternative water sources to supply the Department of Montevideo. In order to identify a potential alternative source, a water quality assessment and potential contamination evaluation of the fractured aquifers in the northeast of the Department were conducted. These aquifers are composed of Paleoproterozoic rocks from the Montevideo Belt. Based on a previously conducted hydrogeological and hydrogeochemical study, 10 wells in a pilot area northeast of Montevideo were sampled for microbiological and nitrite analyses. Additionally, 10 samples from the same wells were analyzed at the Faculty of Chemistry to detect total arsenic concentrations in groundwater. The elevated nitrate concentrations, along with the absence of nitrites, indicate an oxidizing environment and persistent contamination, likely associated with diffuse sources such as septic systems and possibly also linked to the use of organic fertilizers. This situation, coupled with the detection of microbiological contamination (fecal coliforms and *Pseudomonas*), highlights the high vulnerability of the fractured aquifer to human activities in an urban and peri-urban context. Regarding total arsenic (tAs) concentrations in groundwater, they do not exceed the WHO's recommended limit of 10 µg/L, except for one value that slightly exceeds this limit. Although there are indications of contamination in the fractured aquifer studied, these studies should be continued to develop an appropriate remediation plan that would allow these aquifers to be used as an alternative source of drinking water.

Keywords

Water Quality, Aquifer, Total Arsenic, Uruguay

1. Introduction

Considering the increasingly frequent water scarcity, it is necessary to implement alternative water sources to supply the Department of Montevideo. In order to find a possible alternative source, an assessment of water quality and potential contamination of the fractured aquifers in the northeast of the Department was carried out. The study area (**Figure 1** and **Figure 2**) is geologically located within the Tandilia Terrane, where the Pando Belt is expressed with metamorphic rocks (schists, amphibolites, gneiss) of the Montevideo Formation and granitic intrusions. The following units are particularly found in the study area: La Paz Granite, Punta Espinillo Granite, and Punta Carretas Orthogneiss. These Paleoproterozoic rocks are overlain by thin Cenozoic sedimentary rocks and sediments. Based on a previously conducted hydrogeological study (Pamoukaghlián et al., 2024), 10 wells in a pilot area northeast of Montevideo were sampled for microbiological analysis (2 samples) and nitrite analysis (1 sample) at the Altix Laboratory. Additionally, 10 samples from the same wells were analyzed to detect total arsenic (tAs) concentrations in groundwater; these analyses were carried out at the Faculty of Chemistry.

The elevated nitrate concentrations, along with the absence of nitrites, indicate an oxidizing environment and persistent contamination, likely associated with diffuse sources such as septic systems and possibly also linked to the use of organic fertilizers such as chicken manure. This situation, coupled with the detection of fecal coliforms and *Pseudomonas aeruginosa* in some of the analyzed water samples, demonstrates the high vulnerability of the fractured aquifer to human activities in an urban and peri-urban context.

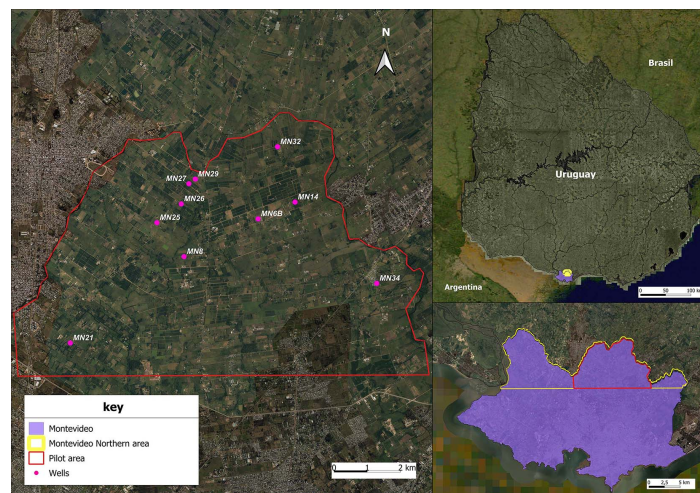


Figure 1. Study area.

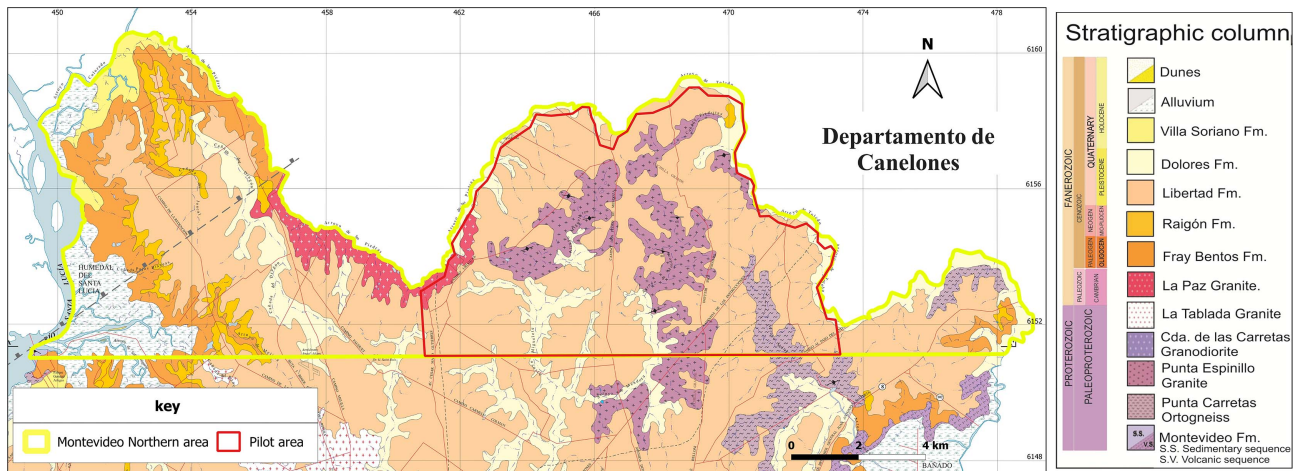


Figure 2. Geological map of the study area.

2. Geological and Hydrogeological Framework

The regional geological context is framed within the Piedra Alta Terrane (sensu Bossi et al., 1998) or the Tandilia Terrane (sensu Bossi et al., 2005) if the Colonia shear zone is considered a terrane boundary (Ribot et al., 2005). Within this context, the geological units corresponding to the Pando Belt are presented: the Paleoproterozoic Montevideo Formation (Abre et al., 2014) and the granites that intrude it. The Montevideo Formation is composed of mica schists, para-amphibolites, and para-gneiss, sometimes graphitic. The Paleoproterozoic granites that intrude this unit are: the Soca Granite, the Coronilla Granite, and the La Tuna Granite. The Neoproterozoic La Paz Granite also intrudes the Montevideo Formation. Cenozoic sediments (Fray Bentos, Raigón, Libertad, and Dolores Formations) overlie Paleoproterozoic and Neoproterozoic rocks.

According to the geological map by Spoturno et al. (2004), the following Paleoproterozoic geological units are found in the study area: deformed granites of Punta Espinillo, and Punta Carretas Orthogneiss, and a Neoproterozoic unit: the La Paz Granite. These units form the fractured aquifers in northern Montevideo (see Figure 2). In the preliminary study area, granitic rocks (Punta Espinillo Granite) are found with sedimentary cover from the Libertad and Dolores Formations.

Taking into account the hydrological characterization of the Piedra Alta Terrane presented by Montaña et al. (2014), the lithotypes within it are distinguished in relation to their hydraulic conductivity. Coarse-grained granites tend to generate open fracture systems, which favor water accumulation and circulation. Gneisses exhibit open and interconnected fractures, which also favor water accumulation and circulation. Gneisses have fractures with little or no infilling, also resulting in good productivity (Montaña Xavier, 1998).

Pamoukaghlián et al. (2024) identified a main fracture direction in the study area as NNE and NE. In the northwest sector, a clearly NE main direction was observed, and in the northeast sector, a NE main direction and a NW subsidiary direction were observed (Figure 2). These authors identified the following frac-

ture directions: a) NE-trending fractures up to 2000 m long are associated with maximum flow rates of 32 m³/h and minimum flow rates of 1.3 m³/h, with an average of 6.4 m³/h. b) NW-trending fractures up to 1500 m long are associated with maximum flow rates of 22 m³/h and minimum flow rates of 2.5 m³/h, with an average of 9 m³/h. c) N-S-trending fractures with few associated wells have flow rates of up to 6 m³/h.

It is important to note that there are no prior water quality assessments in the area studied.

The overall objective of this work is to make an assessment evaluating certain water quality parameters of the fractured aquifers in northeastern Montevideo, using as a reference the preliminary hydrogeological model of Pamoukaghlián et al. (2024).

The specific objectives are: a) to assess microbiological contamination and compare it with the analysis of nitrate, nitrite, and ammonium ions; b) to analyze total arsenic in groundwater as a potentially toxic parameter.

3. Materials and Methods

Based on the hydrogeological characterization (Pamoukaghlián et al., 2024), a pollution study was conducted in the northeastern area of Montevideo.

The following activities were carried out: a) a literature review and review of historical background; b) a survey of boreholes in a selected pilot area in Toledo Chico; c) sampling of 10 wells in winter and spring; d) microbiological and nitrite analyses at the Altix Laboratory, Montevideo; e) nitrate and ammonium analyses by ion chromatography at the Water and Soil Laboratory (CENUR Litoral Norte); f) determinations of tAs by spectrometry at the Faculty of Chemistry (UDELAR); and i) processing and integration of the results.

Two samples for each well were collected for microbiological analysis (fecal coliforms and *Pseudomona*); one sample for each well was collected for nitrite analysis and one sample per well was collected for tAs analysis. The samples were conserved at 18°C temperature and holded in 24 hours before sending to the laboratory for all cases.

In order to determine nitrate and ammonium, the samples were filtered with 0.45 µm membrane filters. The samples were injected into an Aquion DIONEX Thermo® ion chromatograph. The method applied corresponds to the reference of the standard methods for waters and effluents APHA-4110B (APHA 23rd ed.) (Baird et al., 2007), in the same way as reported by Alvareda et al. (2025). Detectable limits for ammonium is 0.071 mg/L and for nitrate 0.047 mg/L.

At Altix Laboratory detectable limits for nitrites are between 0.02 and 0.05 mg/L and detectable limits for *Pseudomona* and fecal coliforms are both 0 - 300 UFC/placa.

Total arsenic (tAs) in water samples was determined using hydride generation coupled to microwave-induced plasma optical emission spectrometry (HG-MP-AES), a methodology previously developed and validated for groundwater (Pizzorno

& Bühl, 2026). The method includes a pre-reduction step with NaI in an acidic medium, followed by arsine generation using NaBH₄, which is then transported to the plasma where the arsenic is detected at 193.7 nm. Validation, performed according to the Eurachem guide, showed a linear range of 2.5 - 250 µg·L⁻¹, with a LOD of 0.8 µg·L⁻¹ and a LOQ of 2.5 µg·L⁻¹. The precision (RSD < 5%) and accuracy (95% - 110%) demonstrate adequate analytical performance (Pizzorno & Bühl, 2026). Detection limit for tAs analysis is 0.8 µg/L.

A brief description of the sample wells, including depth, flow rate, construction details and water use is stated in **Table 1**.

Table 1. Sampled well information, including water use.

Well	Depth (m)	Flow rate (m ³ /h)	Construction	Water use
MN6B	43	18	Semi-emergent	Agriculture
MN08	45	8	Semi-emergent	Vineyards
MN14	30	14.2	Semi-emergent	Agriculture
MN21	30	0.3	Curb well	Not using
MN25	50	3.8	Semi-emergent	Agriculture
MN26	44	1.5	Semi-emergent	Agriculture
MN27	60	20	Semi-emergent	Agriculture
MN29	40	15	Semi-emergent	Agriculture
MN32	28	5	Semi-emergent	Chicken briden
MN34	40	10	Semi-emergent	Vineyards

4. Results

The chemical results of the analyzed waters are presented in **Table 1**.

Two sampling campaigns were conducted for microbiological analysis (August and November 2025), resulting in the absence of fecal coliforms and *Pseudomonas aeruginosa* in 30% of cases. However, low levels of both were detected in some samples.

The detection of fecal coliforms serves as the primary microbiological indicator of recent fecal contamination in aqueous systems. UNIT 833 mandates a strict zero-tolerance threshold (0 CFU/100 mL), as their presence directly correlates with the co-occurrence of enteric pathogens, posing immediate gastrointestinal health risks and signaling critical breaches in sanitation barriers.

Pseudomonas aeruginosa is an opportunistic pathogen regulated under stringent zero-tolerance criteria in bottled waters due to its high resilience, capacity for biofilm formation within distribution networks, and intrinsic resistance to multiple antimicrobials. Its monitoring is essential to prevent nosocomial and systemic infections in immunocompromised populations and to verify the efficacy of secondary disinfection protocols. UNIT 833 mandates a strict tolerance threshold (0 CFU/100 mL).

Nitrites, nitrates, and ammonium were also analyzed, detecting very low levels for nitrites, always below the maximum permissible levels according to UNIT: 2008 standards; however, nitrate levels occasionally exceeded the maximum permissible levels. Ammonium was not detected in any sample.

Nitrites represent a transient, highly toxic intermediate state within the nitrogen cycle, with regulatory limits capped at stringent thresholds (0.2 mg/L) due to their acute biochemical toxicity. Ingested nitrites induce methemoglobinemia by oxidizing hemoglobin to methemoglobin, which severely impairs systemic oxygen transport and indicates proximate organic or agricultural pollution.

Nitrates constitute the most stable, oxidized form of nitrogen in water bodies, primarily originating from anthropogenic activities such as intensive synthetic fertilization and livestock runoff. Regulated at a maximum permissible value of 50 mg/L. Elevated nitrate concentrations undergo *in vivo* reduction to nitrites, thereby contributing to infantile methemoglobinemia and serving as a key biomarker for chronic environmental eutrophication.

While dissolved ammonium exhibits low direct mammalian toxicity at ambient levels, its regulatory benchmark (0.5 mg/L) functions as a critical indicator of recent sewage or agricultural discharge. From an operational standpoint, ammonium readily reacts with free chlorine during water treatment to form chloramines, drastically depressing disinfection kinetics, reducing residual efficacy, and compromising organoleptic properties. Ammonium was not detected in the analyzed samples.

Chemical results of the analyzed waters are presented in **Table 2**.

Considering that possible microbiological contamination could possibly come from septic tanks, these septic tanks were georeferenced (**Figure 3, Table 3**) to visualize the proximity to water wells, verifying that in most cases they do not respect the recommended protection limits (Navarrete & García, 2002). Wells which are placed at a distance minor than 60 m (MN21, MN25, MN27, MN32) are affected by microbiologic contamination, suggesting that this is a plausible cause of contamination.

Another cause of microbiological contamination could be the use of organic fertilizers. In the nearby of wells MN6B, MN13, MN21, MN25 and MN26 these kind of fertilizers are used and the well samples evidence in all cases the presence of fecal coliforms.

Table 2. Nitrate, Nitrite and microbiological analysis.

Well	Nitrites ^a (mg/L)	Nitrate ^a (mg/L)	Fecal coliforms ^a (cfu/mL)		Pseudomonas ^a (cfu/mL)	
	08/08/2025	08/08/2025	08/08/2025	19/11/2025	08/08/2025	19/11/2025
MN6B	0.03	67.847	25	Absence	Absence	Absence
MN08	0.11	70.718	Absence	Absence	Absence	Absence
MN14	0.06	46.011	46	Absence	Absence	Absence
MN21	0.07	19.583	31	3	Absence	3

Continued

MN25	0.04	15.945	102	2	3	1
MN26	0.09	17.965	52	Absence	26	20
MN27	<0.02	35.89	Absence	1	1	1
MN29	0.03	0.047	Absence	Absence	Absence	Absence
MN32	0.04	17.727	83	1	Absence	Absence
MN34	0.04	39.421	3	Absence	Absence	Absence

^aAll samples were analyzed by duplicate.

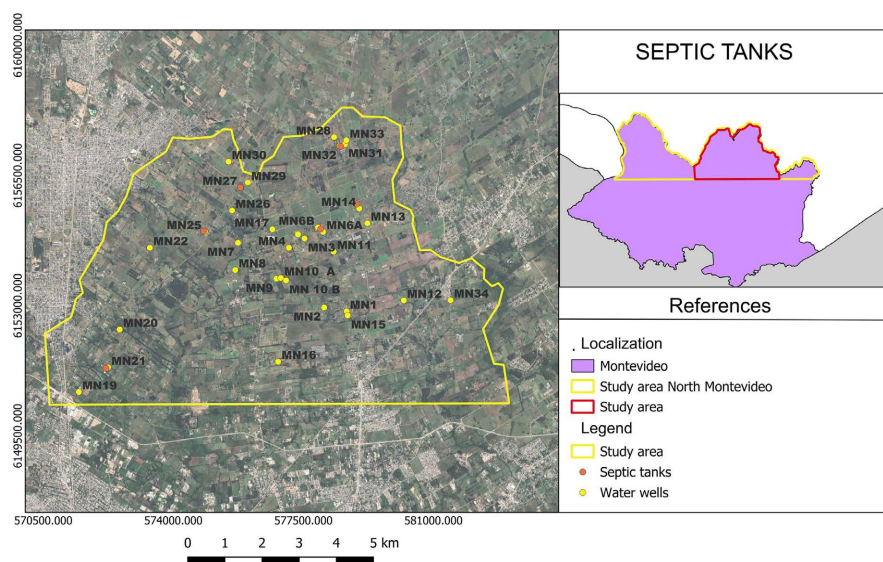


Figure 3. Georeferenciation of septic systems and well.

Table 3. Well information including distance to septic tank.

Well	Distance to septic tank (m)
MN6A	101.09
MN6B	83.66
MN14	134.96
MN27	9.56
MN25	34.42
MN21	58.50
MN31	127.99
MN32	29.17

Regarding total arsenic (tAs) concentrations in groundwater, values generally do not exceed the WHO guideline of 10 µg/L, except for one value that slightly exceeds this limit (**Table 4, Figure 4**). However, the detected values, although low, suggest the presence of a nearby As source. This could be attributed to possible slow recharge from the aquitard formed by the sediments of the Libertad For-

mation, since the higher values in the southeast of the area correspond to areas with greater coverage of these sediments and there are references about the high As levels originated from this unit (Collazo et al., 2020; Pamoukaghlián et al., 2023).

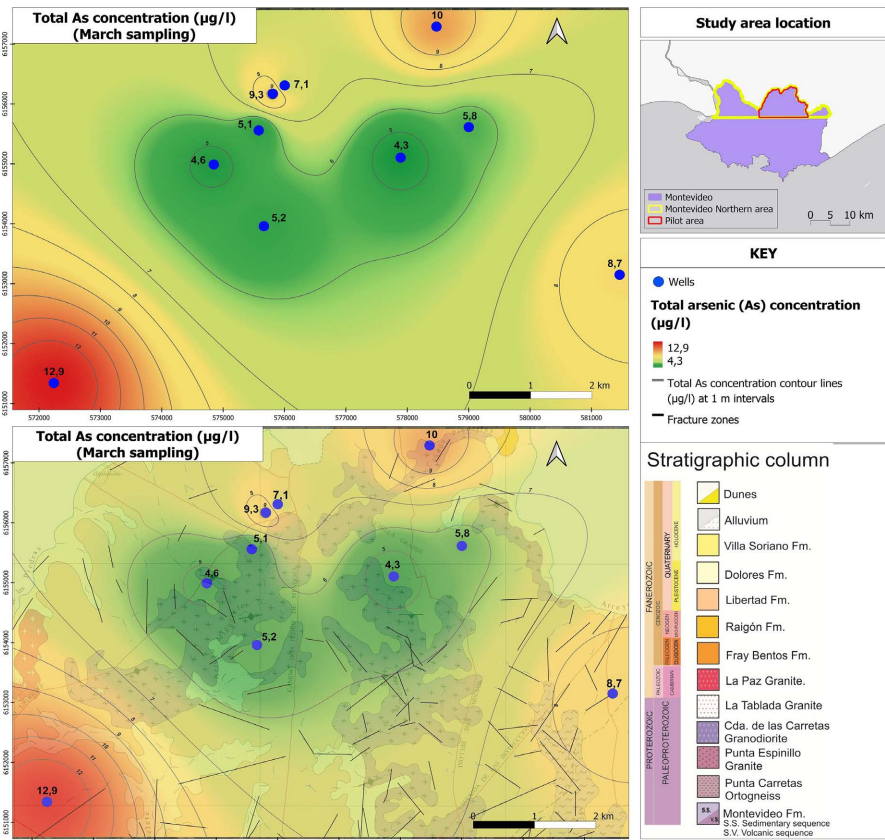


Figure 4. Iso-Concentrations of total arsenic (tAs).

Table 4. Total arsenic (tAs) concentration in groundwater.

Well	Total As (µg/L)	Error
MN6B	4.3	0.2
MN08	5.2	0.3
MN14	5.8	0.3
MN21	12.9	0.6
MN25	4.6	0.2
MN26	5.1	0.3
MN27	9.3	0.5
MN29	7.1	0.4
MN32	10.0	0.5
MN34	8.7	0.4

5. Discussion

The assessment of water quality in the fractured aquifers of northeastern Monte-

video reveals a hydrogeochemical and microbiological pattern consistent with a well-established, chronic contamination process, in accordance with the specific objectives of this study. The simultaneous presence of high concentrations of nitrate (NO_3^-) and the absence of nitrite (NO_2^-) and ammonium (NH_4^+) constitutes a biogeochemical signature characteristic of a system that has reached a state of equilibrium after a prolonged residence time.

This profile is explained by the nitrification process, a two-stage aerobic microbial oxidation in which NH_4^+ is first transformed into NO_2^- and then into NO_3^- (Pankow, 2019). In aquifers with long-standing contamination, the bacterial communities responsible for the second stage are highly developed, ensuring rapid and efficient nitrite conversion. As a result, NO_2^- does not accumulate to detectable levels. Furthermore, the generally oxygenated conditions of the environment inhibit denitrification, allowing nitrate to persist and accumulate as a stable end product (Appelo & Postma, 2004; Fetter, 2001). The absence of NH_4^+ confirms that the source is not injecting recently reduced nitrogen, or that the hydraulic transit time has been sufficient to complete the oxidation.

The simultaneous detection of fecal coliforms and *Pseudomonas* spp., along with the described nitrogen profile, indicates a continuous or recurring input of organic matter of human or animal origin. These microorganisms act as tracers of persistent fecal contamination, while the chemical pattern demonstrates that the nitrogen cycle has had sufficient time to complete. This scenario rules out a one-off or acute event and supports the hypothesis of a chronic impact, where the aquifer operates as a nitrate reservoir derived from a sustained source.

In the context of the study area, agricultural activity and the use of fertilizers (both synthetic and organic, such as poultry manure) represent plausible sources of nitrogen and microbiological contamination. After application to the soil, nitrogen in the form of ammonium or urea undergoes efficient nitrification, generating highly soluble and mobile NO_3^- . Unlike NH_4^+ , which adsorbs to soil colloids, NO_3^- is not retained by the negative charges of the soil matrix, which favors its leaching into the water table during precipitation or irrigation events (Brady & Weil, 2016). The absence of ammonium in the groundwater samples corroborates that the transformation occurred predominantly in the unsaturated zone, before recharge to the fractured aquifer. The widespread use of organic fertilizers among local producers would further explain the persistence of microbiological indicators in the water.

Regarding tAs, the low concentrations recorded in the fractured aquifers suggest a geogenic origin controlled by water-rock interaction processes on a regional scale. It is likely that the arsenic originates from slow, diffuse recharge from the Libertad Formation, which acts as an aquitard over the fractured system. This mechanism is consistent with the preliminary hydrogeological model presented by Pamoukaghlián et al. (2024), which describes a limited transfer of solutes between the confining unit and the main aquifer. This would explain the presence of trace amounts of arsenic that do not reach levels of acute risk, but require long-

term monitoring.

Overall, the results meet the objectives set by integrating the microbiological assessment with nitrogen parameters (Objective a) and by characterizing the dynamics of arsenic in the system (Objective b). The convergence of chemical, microbiological, and hydrogeological evidence supports a conceptual model of chronic contamination of anthropogenic origin, superimposed on a geogenic background controlled by the regional lithology. These findings align with the preliminary hydrogeological model of Pamoukaghlián et al. (2024) and provide some recommendations for the management and protection of aquifers in northeastern Montevideo, highlighting the need to control fertilization practices and monitor the temporal evolution of critical parameters.

6. Conclusion

This study allowed for the assessment of the hydrochemical and microbiological quality of fractured aquifers in northeastern Montevideo, integrating indicators of nitrogen contamination, microbiological traces, and the presence of total arsenic as a potential risk parameter, in accordance with the stated objectives.

The results show the presence of a diffuse microbiological impact, possibly chronic, although fecal coliform and *Pseudomonas* spp., concentrations remained at low levels. This pattern, associated with the predominance of nitrate and the systematic absence of nitrite and ammonium, reflects a complete and stable nitrification cycle, characteristic of long-term contamination sources and a prolonged hydraulic residence time in the fractured medium. Despite the heterogeneous nature of the environment, no fracture directions with differential vulnerability to contamination were observed. In the case of Arsenic, iso-concentrations of total Arsenic in groundwater have been compared in the map with fracture and geology superimposed, suggesting no fracture control. At the same time, fracture directions associated with different microbiological contamination were analyzed, without observing evidence that the fracture directions control contamination paths.

Regarding arsenic, the total concentration recorded remained mostly below the reference thresholds. Only one sampling point exceeded the WHO guideline (10 µg/L), although it remains within the Maximum Permissible Value established by the UNIT 2008 standard (20 µg/L), currently in force in Uruguay. Given the isolated nature of the detection and the generally low concentrations, chemical speciation (As(III)/As(V)) was not performed. This decision was based on the optimization of analytical resources and the low probability of acute risk, thus prioritizing the evaluation of parameters with the greatest impact on the current water quality.

In line with the principle that prevention is significantly more efficient and economical than remediation, the following management guidelines are recommended:

Control of diffuse sources: Ensure the proper construction, maintenance, and

sanitary distance between effluent disposal systems (septic tanks) and water intakes, in accordance with current regulations.

Preventive monitoring: Establish a network for periodic monitoring in areas of greater hydrogeological vulnerability, prioritizing nitrate, microbiological indicators, and tAs.

Land use management: Regulate and provide training on the application of fertilizers (especially organic ones such as poultry manure), minimizing the recharge of nitrogen and pathogens to the unsaturated zone and the aquifer.

These findings contribute directly to the Assessment of Aquifer Contamination in Northeast Montevideo, offering a scientific basis for the protection of groundwater resources. The integration of hydrogeochemical, microbiological, and local regulatory criteria allows for the design of more efficient monitoring strategies, adapted to the specific dynamics of the fractured aquifer system and the region's productive activities. It is recommended to complement this diagnosis with solute transport studies. The groundwater of the fractured aquifers of northeast Montevideo, although it presents some problems of microbiological contamination, the values of fecal coliforms and *Pseudomonas* detected in the analyzed samples are low.

Although there are indications of contamination in the fractured aquifer studied, these studies should be continued to develop an appropriate remediation plan that would allow these aquifers to be used as an alternative source of drinking water.

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Conflicts of Interest

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

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