REVISTA ÁGUAS SUBTERRÂNEAS

Evaluation of microbiological and physicochemical contamination of groundwater in the coastal wet-land of Pantanos de Villa (Lima-Peru)

Avaliação da contaminação microbiológica e físico-química das águas subterrâneas na área úmida costeira de Pantanos de Villa (Lima–Peru)

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ABSTRACT

Background: Groundwater quality in tropical wetlands remains poorly studied. Los Pantanos de Villa, a key wetland located on Peru's desert coast, is recognized as a Protected Natural Area and a Ramsar site yet faces ongoing threats. This study aims to assess groundwater contamination in the wetland using microbi-ological (Escherichia coli, total and fecal coliforms) and physicochemical parameters, as well as water quality indices; (2) Methods: Annual sampling in 2023 was conducted at 12 locations (4 test pits and 8 piezometers), during the high recharge season (March) and low recharge season (September). Parameters were compared to national (Peru) and international (U.S.) standards. Two water quality indices—CCME and NSF—were applied; (3) Results: Microbiological contamination levels were dangerously high at all sampling sites. Physicochemical parameters exceeded permissible limits in at least one season. The CCME index classified 100% of samples as poor quality, and the NSF index classified 75% as poor and 25% as medium quality; (4) Conclusions: Groundwater in the Pantanos de Villa wetland exceeds national and international contamination thresholds. Microbiological pollution is particularly concerning. Water quality indices confirm a degraded state.

RESUMO

Introdução: A qualidade das águas subterrâneas em áreas úmidas tropicais permanece pouco estudada. Los Pantanos de Villa, uma importante área úmida localizada na costa desértica do Peru, é reconhecida como Área Natural Protegida e sítio Ramsar, porém enfrenta ameaças contínuas. Este estudo tem como objetivo avaliar a contaminação das águas subterrâneas da área úmida utilizando parâmetros microbiológicos (Escherichia coli, coliformes totais e fecais) e físico-químicos, bem como índices de qualidade da água; (2) Métodos: Em 2023, foi realizada amostragem anual em 12 locais (4 poços de teste e 8 piezômetros), durante o período de alta recarga (março) e baixa recarga (setembro). Os parâmetros foram comparados com padrões nacionais (Peru) e internacionais (EUA). Foram aplicados dois índices de qualidade da água — CCME e NSF; (3) Resultados: Os níveis de contaminação microbiológica foram perigosamente elevados em todos os pontos de amostragem. Os parâmetros físico-químicos excederam os limites permitidos em pelo menos uma das estações. O índice CCME classificou 100% das amostras como de baixa qualidade, e o índice NSF classificou 75% como de baixa qualidade e 25% como de qualidade média; (4) Conclusões: As águas subterrâneas da área úmida Pantanos de Villa excedem os limites nacionais e internacionais de contaminação. A poluição microbiológica é particularmente preocupante. Os índices de qualidade da água confirmam um estado degradado.

1. INTRODUCTION

Wetlands are the most productive ecosystems in the world and host an important diversity of species (López-Saut; Rodríguez-Estrella; Chávez-Ramírez,2014). They provide important ecosystem services, and carbon sinks, which are relevant for mitigating the effects of climate change, improving water quality, and conserving biodiversity (Mitsch; Gosselink, 2015). Despite this, wetlands are often subject to anthropogenic impacts such as urbanization, agriculture and drainage (Davis, 2003), which directly affect the quality of water resources and cause their degradation.

In Latin America, research usually focuses on surface water sources (rivers and lakes), while groundwater receives less attention (Aponte, 2017). Likewise, due to geographical diversity, these studies are complicated to carry out in certain areas (Rodríguez Vásquez, 2017). In Peru, coastal wetlands represent a reservoir of freshwater and a constant recharge of aquifers (Aponte, 2017), these environments form a biological corridor and host a very important biodiversity (Quiñonez; Hernández, 2017).

A notable wetland within the study area is the Pantanos de Villa Natural Protected Area (NPA), which was incorporated into the National System of Protected Areas by the Peruvian state in 2006 as a wildlife refuge (Servicio Nacional de Áreas Naturales Protegidas, 2016). In a similar manner, the urban ecosystem in question is overseen by PROHVILLA. The wetland's international importance has been underscored by its designation as a RAMSAR site since 1997 (Ramsar, 2023). However, the wetland is located within the metropolitan area of Lima and is surrounded by urban areas. Consequently, it is subject to persistent anthropogenic pressure, which can have detrimental effects on water resources and the ecosystem. The present study evaluated the groundwater quality of the wetland, considering both microbiological and physicochemical indicators.

2. MATERIALS AND METHODS

2.1. Location and general characteristics

This research was conducted in the coastal wetland Los Pantanos de Villa (12°12 'S, 076°59'W) and its buffer zone (Figure 1) located in the southern part of Lima, Peru. This wetland was classified as a Natural Protected Area (NPA) by Resolution No. 358-2001-INRENA. The buffer zone is characterized by being adjacent to the NPA and being under special protection (RP N°169-2016-SERNANP). The wetland has an area of 263.27 ha (Lima, 2022). It is designated as a Refugio de Vida Silvestre and a Ramsar Site of International Importance due to its ecological value and biodiversity, especially for resident and migratory bird species (Ramsar, 2023).

2.2. Geology

The geological framework of Pantanos de Villa reflects its position within the southwest termination of the Rímac River alluvial fan on the Lima coastal plain. Sediments in the area consist mainly of Quaternary alluvial and marine deposits such as sand and gravel, deposited through both fluvial and coastal mechanisms (INGEMMET, 2019). Structural features including local faulting influence groundwater pathways that feed the wetland, linking it to deeper aquifer systems of the Rimac basin. These connections affect both the quantity and timing of groundwater inflow into the marsh system (Chacón; Pajuelo, 2013).

2.3. Climatology

The climate is typical of the Peruvian coastal desert, with average annual temperatures between 17.2 and 23.0 °C, relative humidity between 84.4 and 99%, and low rainfall. The area surrounding the wetland is used for urban, industrial and service activities (Arana, 2022).

2.4. Geomorphology and Hydrology

In terms of geomorphology, the wetland has a minimum altitude of 1 m.a.s.l. and a maximum altitude of 5 m.a.s.l., since it is in the lower part of the hydrogeographic basin of the Rimac River valley. Pantanos de Villa occupies a shallow depression within the coastal plain, formed by fluvial and marine influences shaping the Rímac alluvial fan and surrounding coastal sediments. Its hydrology is largely controlled by groundwater

upwelling,
which maintains persistent shallow lagoons and marshes with brackish water conditions. These surface waters reflect a combination of subsurface discharge from the local aquifer and groundwater pathways derived from the broader Rímac basin system. (SERNANP, 2023; RAMSAR, 2023).

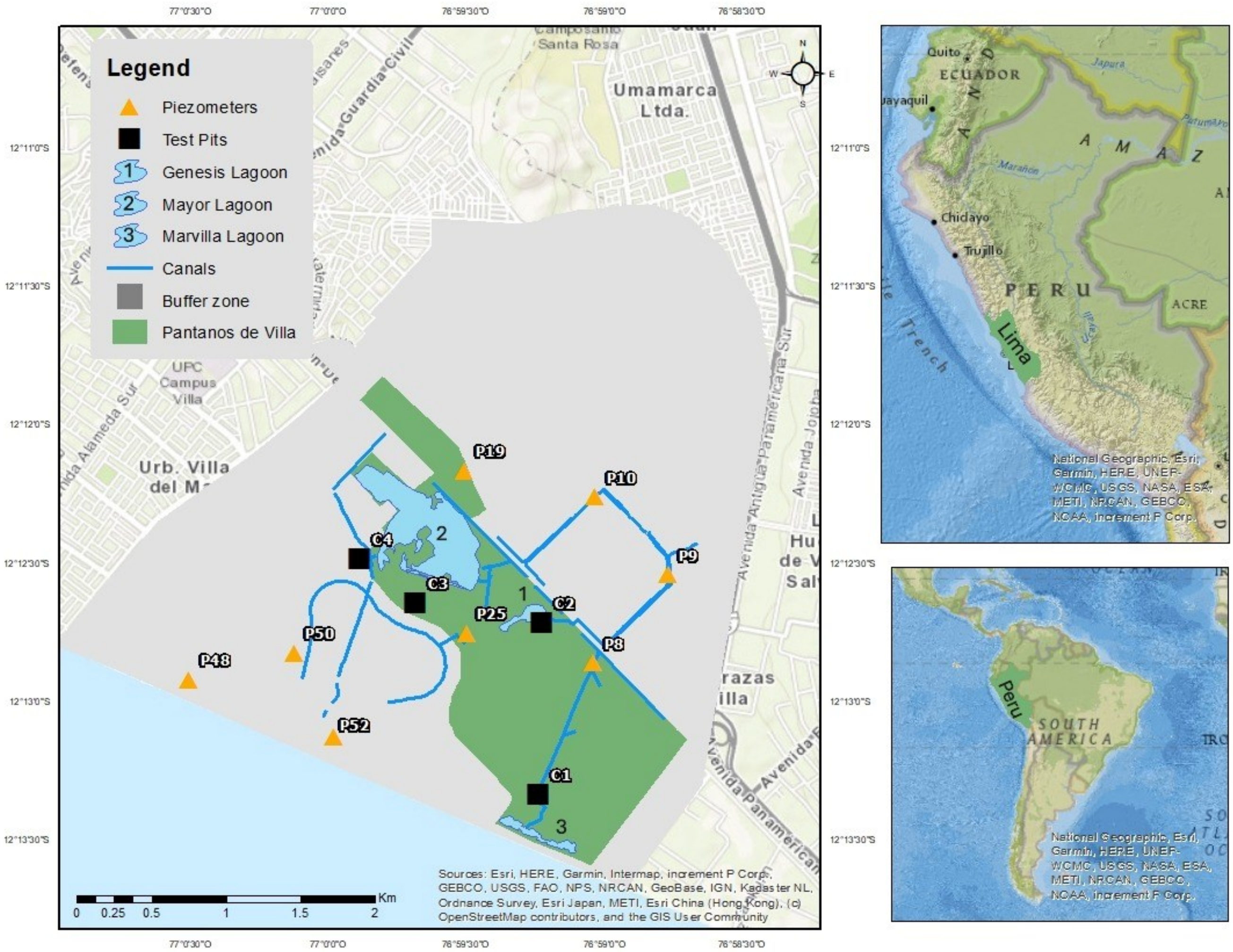

Figure 1. Map of groundwater quality sampling points inside and outside the Pantanos de Villa wetland, Lima, Peru.

2.5. Hydrology

The wetland is characterized as a hydromorphic ecosystem and its importance is due to its biological diversity and water resources, as well as its high scientific and cultural value (INGEMMET, 1991). The hydrogeological dynamics of Pantanos de Villa are primarily grounded in groundwater discharge from the Lima aquifer system, which in turn receives infiltration from the Rímac River basin and related tributaries. At the wetland site, the water table reaches or approaches the surface, producing springs and seepage that feed the lagoons. Hydrogeological assessments indicate hydraulic continuity between the deeper aquifer zones of the Rímac alluvial fan and the wetland's shallow groundwater regime. Urban groundwater abstraction and land-use changes have been shown to influence the local water table, affecting the wetland's water balance and long-term sustainability (INGEMMET, 2019; Ramsar, 2023).

2.6. Sample Method

The sample set included 12 sampling points, 6 of which were situated within the wetland environment and 6 in the surrounding area. The sampling points comprised 4 pits and 8 piezometers, as illustrated in Figure 1. The coding was based on the hydrographic network formed by the piezometers owned by the Municipal Authority of Los Pantanos de Villa (PROHVILLA). Sampling was conducted in two stations in the year 2022, considering that a higher water recharge occurs in the month of March (summer) and a lower water recharge in September (winter)

(INGEMMET, 2019). The U.S. Geological Survey (USGS) methodology was employed in the NFM for the purpose of groundwater quality sampling (United States Geological Survey, 2006).

The collection of groundwater samples was executed through the implementation of two distinct meth-odologies. The initial approach entailed the utilization of PROHVILLA's operational piezometers. The samples were extracted using a bailer (Figure 2). This method involves extracting the sample three times to minimize the disturbance of the water column (Gomo; Vermeulen; Lourens, 2018). The second phase of the experiment involved the construction of 4 pits, with dimensions of approximately 1 x 1 x 1 meters. Two of these pits were positioned within the confines of the wetland, while the remaining two were situated in the external environment. Subsequent to the creation of the test pits, with the prescribed depth, a bailer was uti-lized to extract the groundwater sample. After the extraction of the sample, the extracted soil was deposited at the place of origin (United States Geological Survey, 2006).

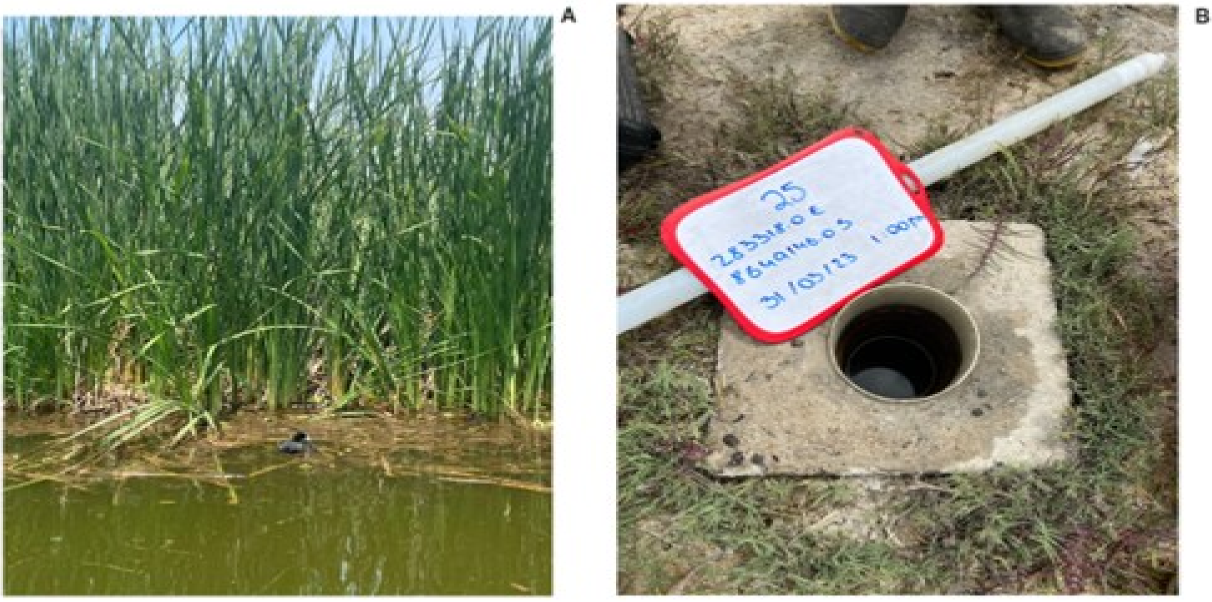

Figure 2. Surface water of the Pantanos de Villa wetland (A) and groundwater (B).

The evaluation of groundwater quality necessitated an in-situ assessment of physicochemical parame-ters, including pH, TSS, EC, and temperature. This assessment was conducted using a Hanna Model HI 98311 Multiparameter, a tool designed for comprehensive analysis of water quality parameters. Subse-quently, an ex-situ evaluation was conducted to assess the microbiological characteristics, namely the presence of Escherichia coli, total coliforms, and fecal coliforms, as well as the physicochemical parameters, including total phosphorus, nitrates (NO3-), COD, BOD, oils and fats. The samples were dispatched to the R-LAB S.A.C. laboratory, which is certified by INACAL in Lima, Peru.

The parameters were analyzed by comparison with the Environmental Water Quality Standards of the Peruvian Regulations, hereinafter EQS - Water, of category 4: Conservation of the Aquatic Environment, subcategory E1: Lagoons and lakes, which includes natural surface water bodies that are part of fragile ecosystems, protected natural areas and/or buffer zones, and that have characteristics that require an addi-tional level of protection (Ministerio del Ambiente, 2017). This national regulation was used as a reference, as Peru does not have a specific regulation for groundwater. Likewise, it was decided to use a complementary international standard from the United States, which is the Groundwater Quality Standards 15A NCAC 2L.0202. (North Carolina Environmental Quality, 2022).

2.7. Water quality index

In order to assess the groundwater quality in a comprehensive way, the calculation of the Water Quality Index (ICA - PE) was carried out by the National Water Authority (Autoridad Nacional del Agua, 2018). This index follows the methodology of the Water Quality Index of the Canadian Council of the Ministry of the Environment (CCME_WQI).

The purpose of establishing the methodology for calculating the WQI is to express the condition or state of water quality based on established ranges.

The index establishes a rating by comparing the monitoring results that do not meet the Environmental Quality Standards (EQS), the number of parameters that exceed ECA-Water and the magnitude of the exceedance (Canadian Council of Ministers of the Environment, 2001). The established rating ranges from poor to excellent (Table 1).

Table 1 – Interpretation of the ICA-PE rating

CCME_WQI	Rating	Interpretation
95-100	Excellent	Water quality is protected with no threats or damage. Conditions are very close to natural or desired levels
80-94	Good	Water quality deviates somewhat from natural water quality. However, desirable conditions may be with some minor threats or damage.
65-79	Favorable	Natural water quality is occasionally threatened or impaired. Water quality often deviates from desirable values. Many uses need treatment.
45-64	Regular	Water quality does not meet quality objectives; desirable conditions are often threatened. Many of the uses need treatment.
0-44	Poor	Water quality does not meet quality objectives, almost always threatened or impaired. All uses need prior treatment.

The other water quality index used for the evaluation is the one established by the National Sanitation Foundation (NSF) of the United States. This index was calculated using the ICATEST software, where the parameter data are entered, and the index is calculated based on the weighting factor generated by the software. It also has its own interpretation with established colors and values (Table 2).

Table 2 – Interpretation of the National Sanitation Foundation Index (NSF, USA)

NSF-WQI	Qualification
91-100	Excellent
71-90	Good
51-70	Average
26-50	Poor
0-25	Very Poor

2.8. Data analysis

A statistical analysis was performed considering two groups, the buffer zone (outside the wetland) versus the interior of the Pantanos de Villa wetland, as well as the winter versus the summer season. The variable analyzed was the quality of the groundwater, considering microbiological and physicochemical parameters. To verify the normal distribution of the data, the Shapiro-Wilk test was performed, which was not fulfilled for the physicochemical and microbiological data, so the non-parametric Mann-Whitney U test was applied. IBM SPSS Statistics v.26 software was used for all data analysis.

3. RESULTS

3.1. Physicochemical parameters

The pH obtained an average of 7.29 (summer - winter) with values within the ranges of the EQS - Water and the international standards for groundwater in the United States (North Carolina Environmental Quality, 2022). As for temperature, values were also obtained according to Peruvian standards, with an average of 21.49°C and with ranges of (19.80 - 24.20°C). Regarding oils and fats, an average (summer - winter) of 16.88 mg/L was obtained, with a range of <1.6 to 30.6 mg/L. Three sampling points outside the wetland (P52, P48 and C4) and two points inside the wetland (C2 and P25) exceeded the limits of the national regulations.

Another parameter evaluated was total phosphorus, where 75% of the points evaluated inside and outside the wetland exceed the EQS - Water. Of the 25% that do not exceed the regulations, one point is located inside the NPA (C3V) and two outside (C4V and P52I) (Figure 3. a and b). For the nitrate parameter, inside the NPA, 50% of the sampling points exceed the national standard of 13 mg/L (Peru) and the international standard of 10 mg/L

(USA), and outside the wetland, 66.6% of the total exceed the standard (Figure 3. c and d). Regarding the electrical conductivity, it was found that 100% of the points exceeded the national regulations, both inside and outside the NPA. This is due to the characteristics of the location of the wetland, which is a coastal ecosystem adjacent to the sea.

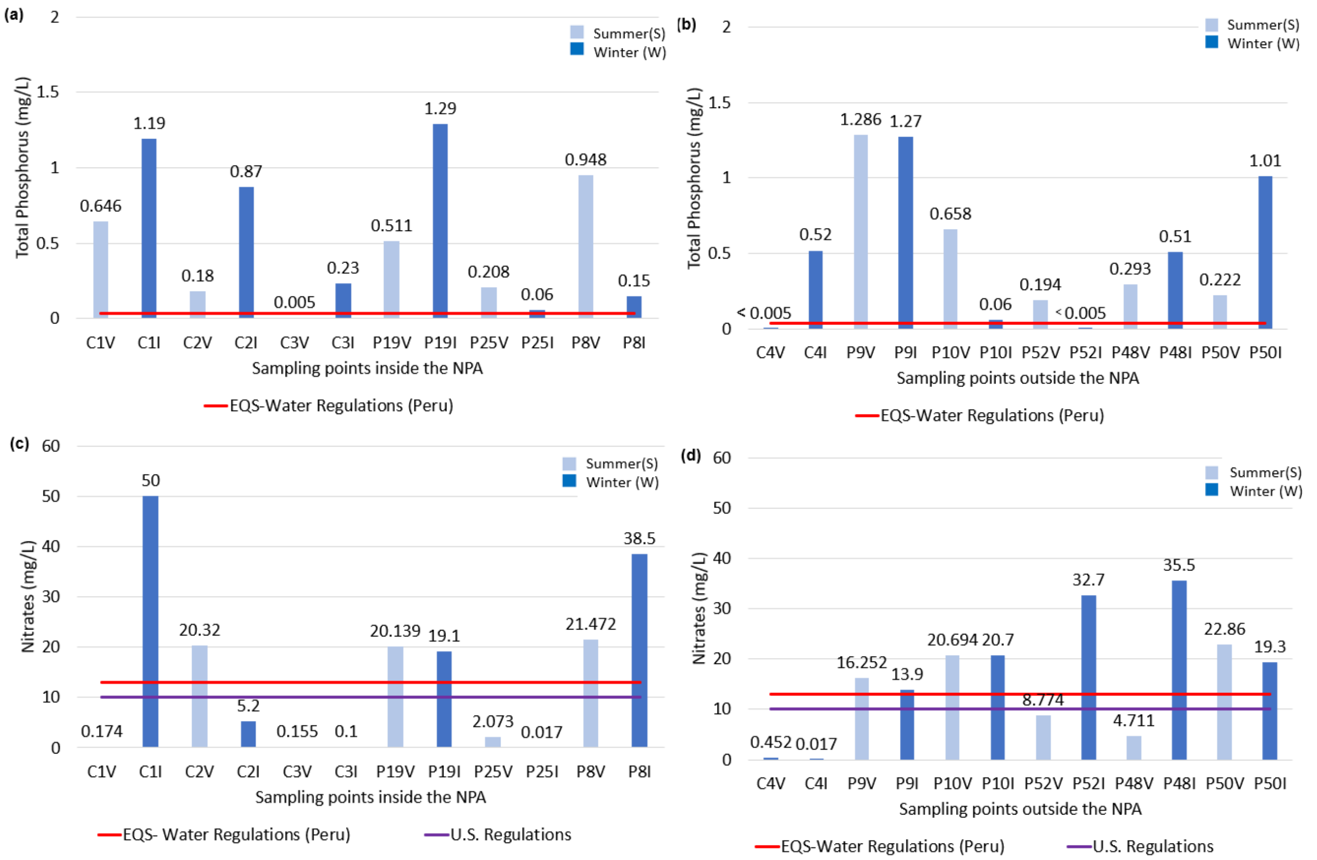

Figure 3. Comparison of Physicochemical Parameters inside and outside the wetland (a) Total Phosphorus (mg/L) inside the and (b) Outside the NPA. (c) Nitrates (mg/L) inside the NPA and (d) Outside the NPA.

When analyzing the COD parameter, all values exceeded the EQS - water. The sampling point with the highest value (C2) was 1853.3 mg/L located inside the wetland and near the Genesis Lagoon (Figure 4 a and b). For TSS, all points exceeded national and international (U.S.) regulations. The sampling point with the highest concentration was C1, located within the wetland adjacent to the Marvilla Lagoon (Figure 4 c and d). The BOD results show that all sampling points, inside and outside the NPA in the summer and winter seasons, exceed the ECA water value, and the highest value is found inside the NPA, being the point (C2V) in the summer season with a value of 966 mg/L, this point is located adjacent to the Genesis Lagoon (Figure 4 e and f).

3.2. Microbiological parameters

For total coliforms, a value of 50 MPN/100 mL is established for EQS-water (Peru) and 100 MPN/100 mL for U.S. standards. The analysis showed that the groundwater points evaluated in the wetland, except for one (P25V), exceed the national and international environmental quality standards. A particular case was the summer sampling point (C2V), located within the NPA, where the highest value of 13 000 000 MPN/100 mL is presented (Figure 5). Similarly, the behavior of the two outlier points with a higher concentration is observed.

According to the results obtained for fecal coliforms, within the NPA, 42% of the points evaluated exceed the EQS - Water and 75% exceed the international standards (USA). Outside the NPA, 50% of the points evaluated exceed the national standard and 83% exceed the international standard (USA). In the case of Escherichia coli, 67% of the total points evaluated within the NPA exceed the EQS - Water. One of the non-exceeding points (P25) was found in both seasons with values of 1.8 MPN/100 ml (Figure 6). Outside the NPA, 100% of the points evaluated exceed the national standard.

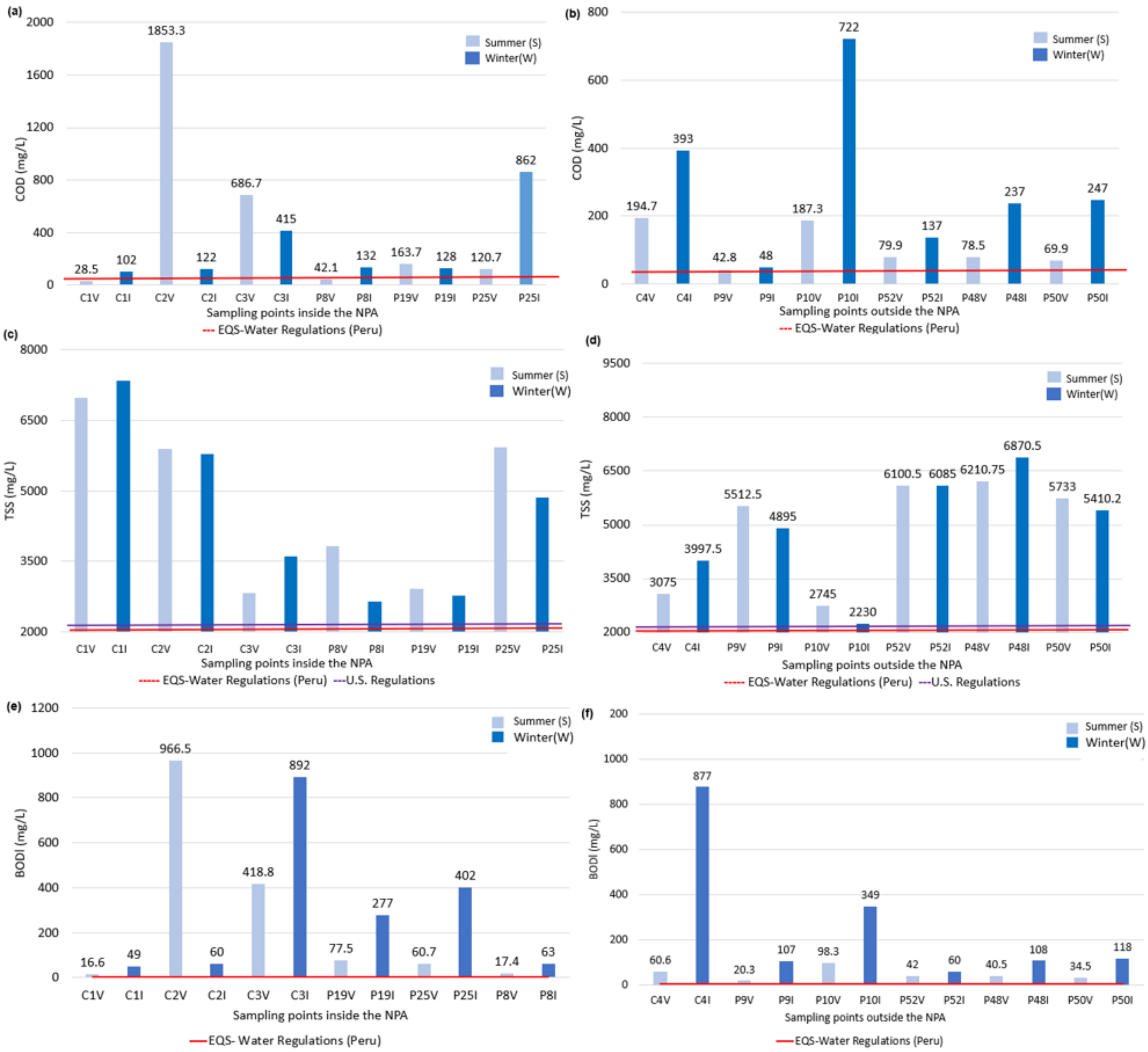

Figure 4. Comparison of physicochemical parameters inside and outside the wetland (a) COD (mg/L) inside the NPA and (b) COD outside the NPA. (c) TSS (mg/L) inside the NPA and (d) TSS outside the NPA. (e) BOD (mg/L) inside the NPA and (f) BOD5 outside the NPA.

Likewise, an analysis was made according to the direction of the water flow, from the starting zone, outside the wetland, when the water enters the wetland, and when the watercourse reaches the Pacific Ocean. Total coliforms showed their highest values inside the NPA (Figure 7), but their concentration decreased at points P25 and P50. Similarly, fecal coliforms reached their highest concentrations within the NPA at points C1 and C2. Finally, the highest and lowest concentrations of *Escherichia coli* were recorded within the NPA. This shows the absence of a defined pattern in the microbiological contamination of the watercourse, although sampling points with critical values were identified at C1 and C2, within the NPA, where the microbiological parameters analyzed exceed national and international water quality standards.

Statistical analysis of the data, performed using the non-parametric Mann-Whitney U test, showed that none of the physicochemical and microbiological parameters showed significant differences ($p < 0.05$) between the areas inside and outside the wetland. Both total and fecal coliforms and *E. coli* concentrations were elevated in both sites. Similarly, COD and BOD parameters showed high mean values in both areas. EC and TSS, which are expected to be elevated due to the nature of the wetland and its direct relationship with the ocean, also showed elevated levels inside and outside. The lack of significant differences suggests that the contamination is similar inside and outside the NPA.

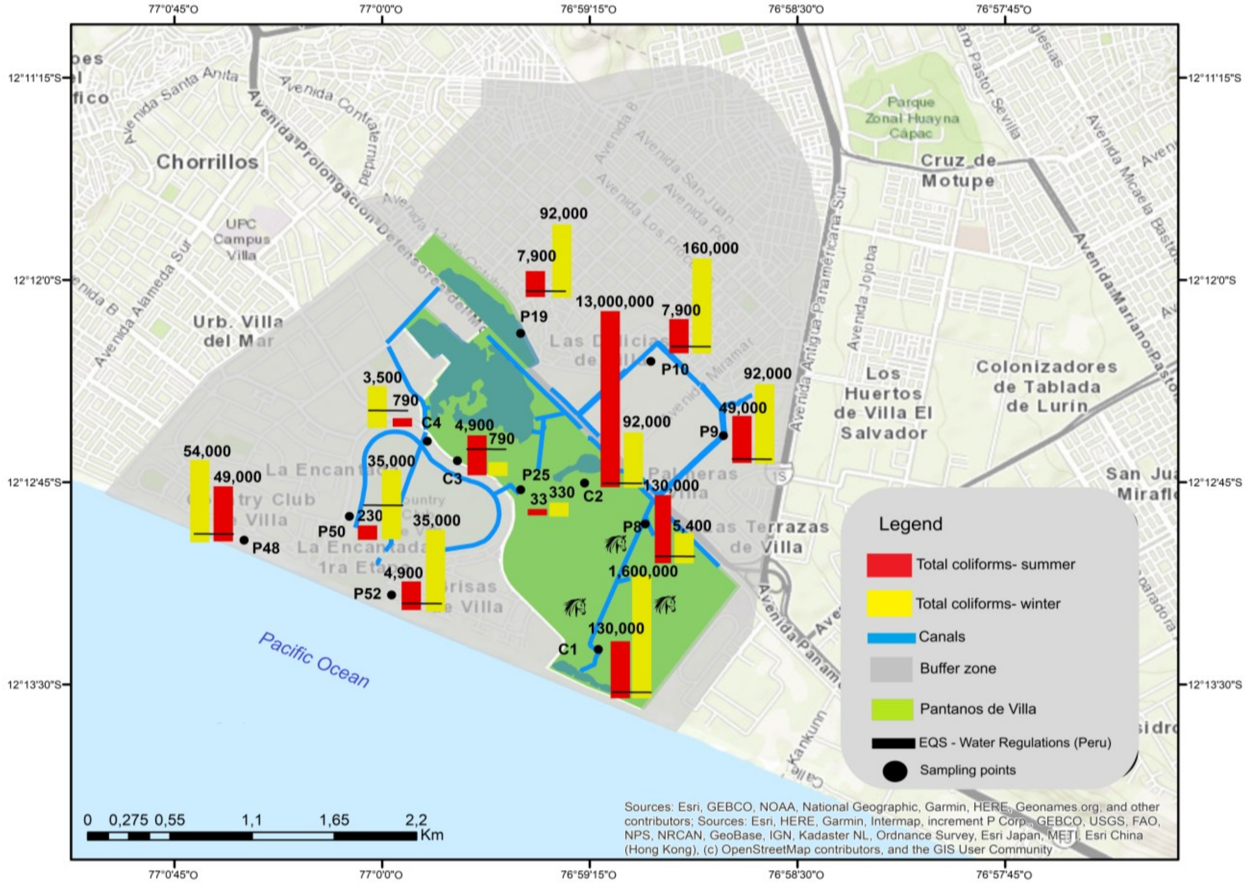

Figure 5. Total Coliforms evaluated in groundwater during summer and winter of 2023, inside and outside the Pantanos de Villa Wetland.

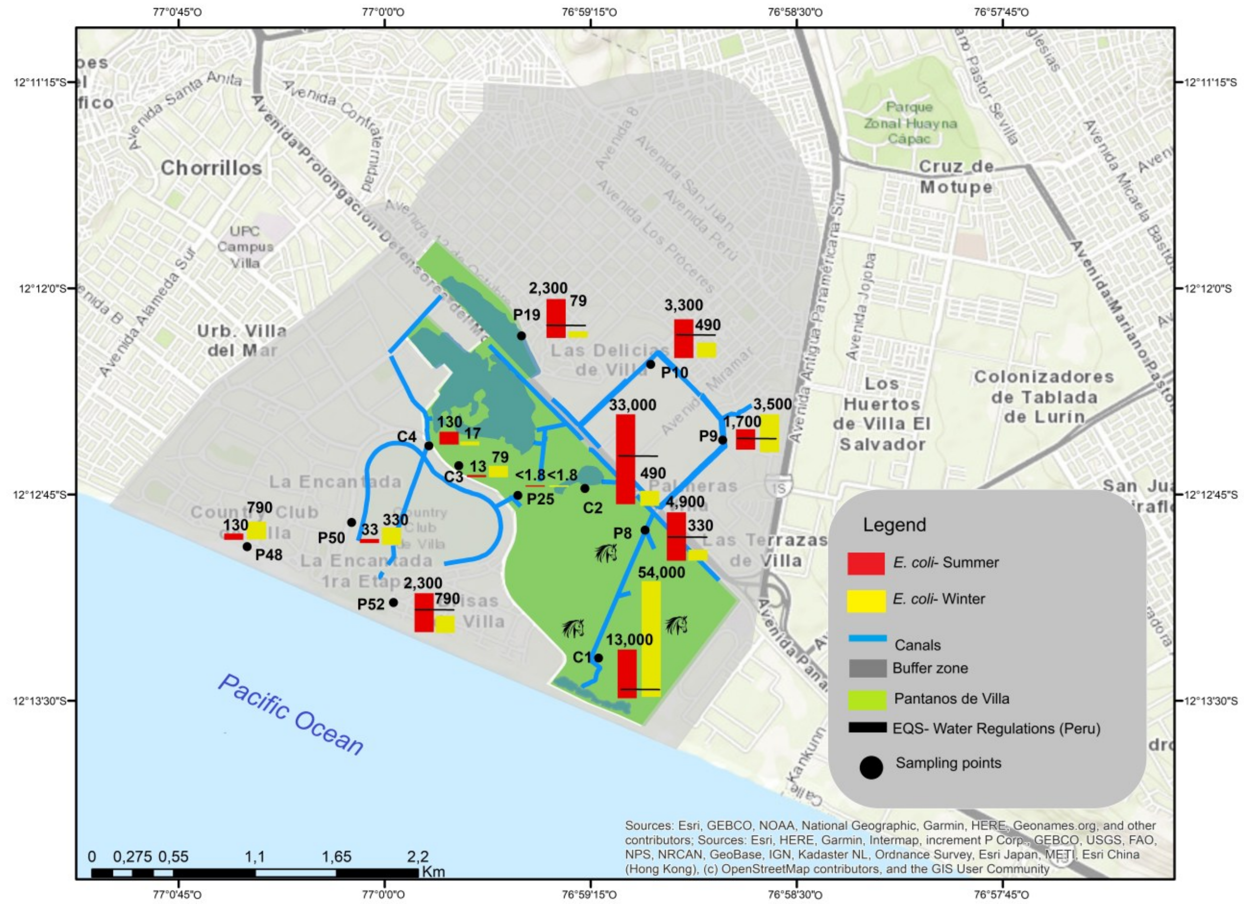

Figure 6. *Escherichia coli* evaluated groundwater during summer and winter of 2023, inside and outside Los Pantanos de Villa.

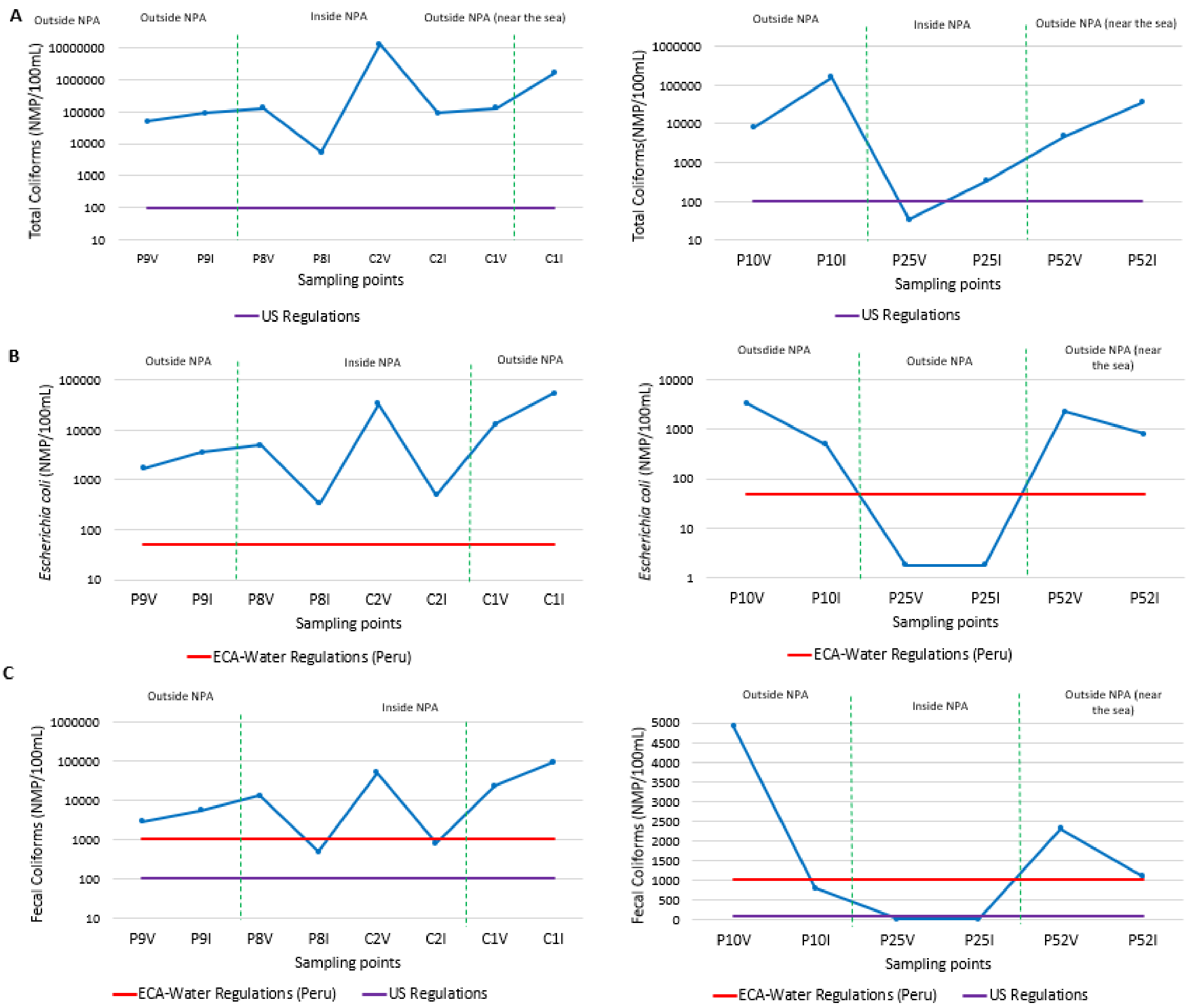

Figure 7. Comparison of microbiological parameters according to the water flow of the Pantanos de Villa wetland and national and international regulations. (a) Total coliforms (MPN/100ml) (b) Escherichia coli (MPN/100ml) (c) Fecal Coliforms (MPN/100ml).

The same test was carried out to evaluate the physicochemical and microbiological parameters by season (summer-winter). As a result, only the biochemical oxygen demand BOD showed a significant difference ($p < 0.05$) according to the sampling season. The average value was lower in summer than in winter. It should be noted that the other parameters had high averages in both sampling seasons, such as microbiological parameters, but they were not significantly different (Figure 8).

3.3. Water Quality Index (Peru)

The ICA - Peru, based on the CCME, resulted in "poor quality" groundwater at all 12 sampling points, inside and outside the wetland, and in both summer and winter seasons (Table 3). The water quality would not meet the conservation objectives of Peruvian regulations and is threatened.

3.4. NSF Water Quality Index (USA)

The ICA-NSF water quality index had a similar result to the ICA-Peru, where nine sampling points had a "poor quality", while three sampling points (C3, C4 and P25) had a "medium quality". These three sampling points are very close to each other, have similar physical characteristics and show a better quality according to ICA-NSF compared to the other points evaluated (Table 3).

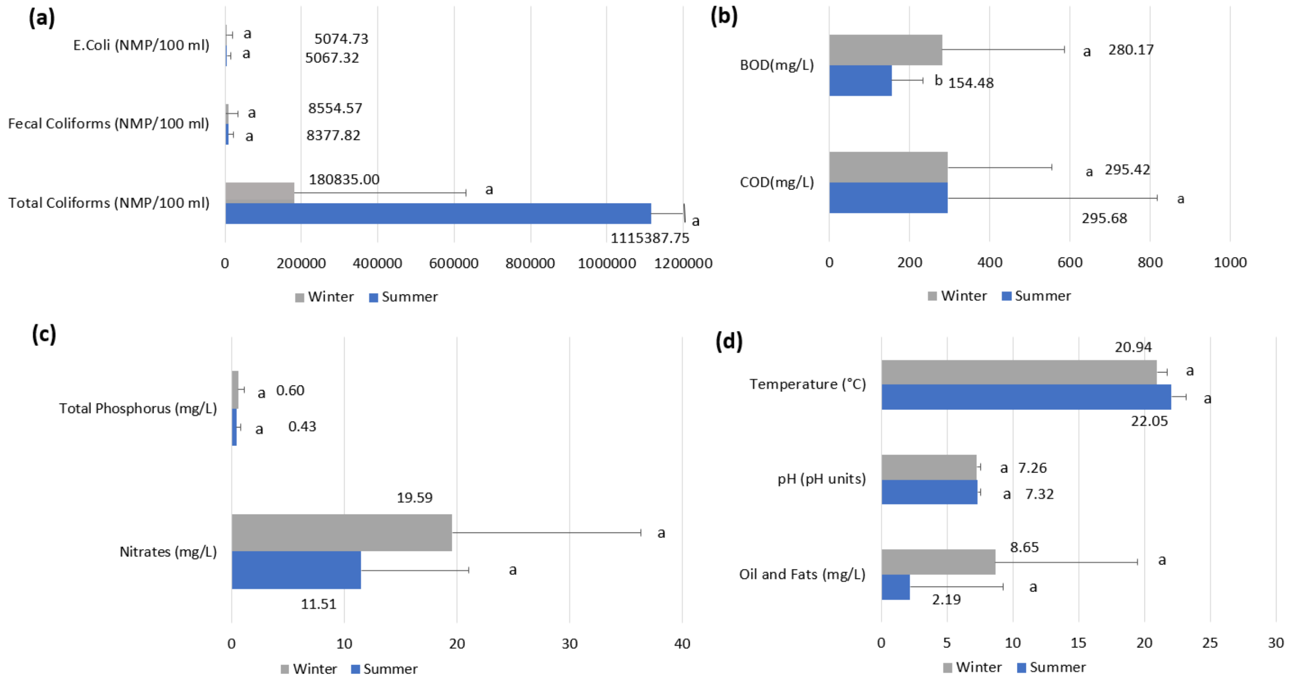

Figure 8. Comparison of physicochemical and microbiological parameters in winter and summer for the Pantanos de Villa wetland. (a) Microbiological parameters (MPN/100ml) (b) COD and BOD (c) Nitrates and total phosphorus. (d) Temperature, pH, and oils and fats. Each graph shows the average values and standard errors. Similar letters (a) indicate no significant difference between groups according to the Mann-Whitney U test.

Table 3 – Water quality indices assessed for groundwater in the Pantanos de Villa wetland

Code	Location	Season	ICA-CCME_WQI (Peru)		ICA-NSF (EE. UU.)	
C1	Inside NPA	Summer	26.26	Poor	43.78	Poor
		Winter	15.85	Poor	26.33	Poor
C2	Inside NPA	Summer	10.80	Poor	38.71	Poor
		Winter	21.30	Poor	37.62	Poor
C3	Inside NPA	Summer	35.53	Poor	58,94	Average
		Winter	34.66	Poor	53.94	Average
C4	Outside NPA	Summer	40.15	Poor	53.29	Average
		Winter	26.55	Poor	52.98	Average
P8	Inside NPA	Summer	16.08	Poor	34.01	Poor
		Winter	25.33	Poor	41.21	Poor
P9	Outside NPA	Summer	15.85	Poor	34.35	Poor
		Winter	15.85	Poor	33.25	Poor
P10	Outside NPA	Summer	16.11	Poor	34.67	Poor
		Winter	25.43	Poor	43.01	Poor
P19	Inside NPA	Summer	16.11	Poor	35.61	Poor
		Winter	25.17	Poor	38.13	Poor
P25	Inside NPA	Summer	30.59	Poor	63.2	Average
		Winter	31.07	Poor	64.46	Average
P52	Outside NPA	Summer	16.33	Poor	43.56	Poor
		Winter	20.83	Poor	41.7	Poor
P48	Outside NPA	Summer	25.92	Poor	47.47	Poor
		Winter	15.99	Poor	35.34	Poor
P50	Outside NPA	Summer	29.57	Poor	47.25	Poor
		Winter	25.17	Poor	36.21	Poor

4. DISCUSSION

4.1. Evaluation of physicochemical parameters

Regarding the parameters that were evaluated, pH and temperature levels were found to be in accordance with both national and international standards. These findings were consistent with the results reported in the study conducted by Puma-Quispe *et al.* (2022). However, oils and fats were found to exceed the national regulations (EQS-water) in three sampling points that were located outside the NPA. During the winter months, as low temperatures prevail, solubility in water is diminished. This phenomenon leads to the accumulation of substances at the water's surface, forming layers that can exceed regulatory limits. Excessive accumulation of these substances poses a threat to aquatic ecosystems, potentially causing harm to aquatic life (Vallejo, 2010).

The total phosphorus levels measured at all sampling points exceed the limits established by Peruvian regulations during at least one of the evaluated periods. A particularly notable increase in total phosphorus was observed during the winter months, which may be attributed to the contribution of water recharge, a factor that has been shown to favor increased concentrations of this element. Conversely, the application of detergents as a source of phosphorus outside the wetland has been demonstrated to elevate the trophic status of the water resource. This occurs because these compounds are ultimately deposited in the ecosystem's lagoons (Sánchez, 2020). Similarly, nitrates in groundwater typically occur in low concentrations; however, their levels can be increased by anthropogenic activities such as agriculture, domestic and industrial effluents, and the use of detergents in washing activities in the channels external to the wetland (Álvarez, 2016).

The electrical conductivity of the water samples collected from the Pantanos de Villa site exceeded the national standard at all sampling points. This is attributable to the geographical location of Pantanos de Villa, which is a coastal wetland adjacent to the sea. The higher salinity content of the soil and water at this location is reflected in the results (Cabrejos Bermejo, 2018). This has been documented in a comparable manner in the coastal wetland of Ventanilla, where values that surpass the EQS - Water benchmark have been observed (Canales Cuadros *et al.*, 2022).

Regarding BOD, the data demonstrate that all sampling points exceed the Peruvian standard at both stations. The available organic matter is a factor that generates an increase in BOD concentration. The reason for this is that high concentrations require more oxygen for its decomposition, thereby increasing BOD (Mitsch; Gosselink, 2015). With respect to COD, point C2, situated in proximity to the Genesis lagoon, exhibits the most elevated value (1,853.3 mg/L). The values exhibited a substantial increase in comparison with the study conducted by Puma-Quispe *et al.* in 2022 in the wetland (Puma-Quispe *et al.*, 2022).

The TSS concentration at all sampling points exceeded the established standards, exhibiting a direct correlation with electrical conductivity. The relationship between conductivity and TSS concentration is such that an increase in conductivity results in an increase in TSS concentration. This can be attributed to the presence of salts and minerals in the groundwater, which is a common occurrence in arid regions (Escobal Pérez; Chávez Horna; Roncal Rabanal, 2020). In the Poza la Arenilla Wetland (Lima), the maximum surface water value recorded was 171.2 mg/L (Sánchez, 2020), whereas within the NPA, Pantanos de Villa exhibited a maximum value of 7335.3 mg/L. This increase could be attributed to the filtration of waste from homes with silos and horse feces, which would raise the levels of solids in the water (Rivera *et al.*, 2021).

4.2. Evaluation of microbiological parameters

The elevated levels of total coliforms suggest a nutrient-rich source that sustains the bacterial community. This may be associated with the proximity of residences to wetland channels and the absence of septic system utilization, which has a detrimental effect on groundwater quality (Rodríguez *et al.*, 2017). Regarding fecal coliforms, 75% of the sampling points did not comply with the established regulations, with the highest recorded values found in proximity to the Marvilla Lagoon, where avian and mammalian feces may contribute to their proliferation (Fajardo Vidal, 2018).

Concurrently, 58% of the points exhibited levels that exceeded the established limits for Escherichia coli, a bacterium that is characteristic of the intestinal microflora and can be transported from the soil surface to the groundwater (Puma-Quispe *et al.*, 2022). The elevated levels of coliform bacteria observed in the vicinity of lagoons (C1 and C2) can be attributed to the presence of wetland gulls. These birds have been documented to excrete substantial quantities of coliform bacteria in their feces, thereby serving as a significant source of contamination for surface and groundwater bodies (Lu *et al.*, 2008). Furthermore, in certain locations, such as C1, the presence of equines has been observed to potentially impact water quality. This is attributed to the fact that equine feces have been found to contribute to the presence of total and fecal coliforms in the soil and water table (Pauta *et al.*, 2020). As posited by Solarte, Peña and Madera in 2006, these three microbiological parameters are interrelated in nature, as they are derived from human and animal feces, as well as from wastewater and water bodies exposed to fecal contamination (Solarte; Peña; Madera, 2006).

4.3. Water quality indexes (ICA)

The findings of the study indicated a critical situation, with the Peruvian ICA rating groundwater quality as "Poor" at all evaluated points. In contrast, the United States ICA (NSF) classified 75% of the evaluated points as "Poor" and the remaining points as "Medium. The findings, both within and outside the NPA, underscore the deterioration of groundwater quality and its implications for the ecosystem. Conversely, surface water quality in Laguna Marvilla was classified as "Regular," exhibiting fewer impact from horse excreta and the biological activity of the ecosystem (Huamán-Vilca *et al.*, 2020). At the regional level, studies in the Santay wetland (Guayaquil, Ecuador) within a protected area indicated water quality between "good" and "acceptable" (Ramírez; Ortega, 2020), suggesting that concentrations of total coliforms, fecal coliforms, and Escherichia coli have a significant impact on water quality indices. Consequently, the variability in water quality can be influenced by both anthropogenic factors and natural processes, underscoring the necessity of monitoring and management (Perú, 2018).

5. CONCLUSIONS

The groundwater system of Pantanos de Villa exhibits systemic and persistent degradation that is incompatible with the ecological function of a Ramsar-designated protected wetland. Water quality indexes (ICA-PE and NSF) consistently classified the monitored sites as predominantly “poor,” demonstrating that impairment is not isolated but spatially widespread across both the Natural Protected Area (NPA) and its buffer zone. The absence of statistically significant differences between inside and outside NPA sampling points further confirms that administrative protection boundaries do not prevent hydrogeological connectivity or contaminant propagation. This pattern strongly suggests that the wetland operates as an integrated groundwater-dependent ecosystem influenced by basin-scale pressures, particularly urban and anthropogenic inputs affecting the Rímac aquifer system.

Microbiological contamination emerges as the dominant risk factor, with total coliforms and E. coli concentrations exceeding national and international quality standards in nearly all sampling locations and reaching extreme magnitudes at certain points. The magnitude and spatial persistence of fecal indicators indicate chronic sanitary loading rather than sporadic contamination events. Seasonal analysis revealed limited hydrological buffering capacity, as only biochemical oxygen demand (BOD) exhibited significant seasonal variation, while most physicochemical and microbiological parameters remained consistently elevated. This demonstrates that groundwater quality deterioration is driven primarily by continuous inputs rather than short-term seasonal fluctuations, posing sustained ecological and public health risks to the wetland system.

6. RECOMMENDATIONS

Given the demonstrated hydraulic connectivity and chronic microbiological impairment, management strategies must extend beyond the legal boundaries of the protected area and adopt a basin-scale groundwater governance approach. Priority actions should include: (i) systematic identification and control of fecal contamination sources within the buffer zone and upstream recharge areas; (ii) implementation of continuous groundwater monitoring programs with higher temporal resolution to detect persistent loading trends; (iii) strengthening regulation of urban groundwater extraction to prevent further water table decline that may exacerbate contaminant concentration; and (iv) integration of hydrogeological modeling to quantify flow paths and pollutant transport dynamics. Without coordinated, multi-sectoral intervention targeting both water quality and aquifer sustainability, the ecological integrity of Pantanos de Villa will remain at significant long-term risk despite its protected status.

Abbreviations

The following abbreviations are used in this manuscript:

NPA	**Natural Protected Area**
TSS	Total Suspended Solids
EC	Electrical Conductivity
COD	Chemical Oxygen Demand
BOD	Biochemical Oxygen Demand
EQS	Environmental Quality Standards

REFERENCES

ÁLVAREZ, C. C. **Determinación analítica de detergentes en las aguas de los Pantanos de Villa**. 2016. Tesis (Licenciatura en Química) – Pontificia Universidad Católica del Perú, 2016.

APONTE, H. **Humedales de la costa central del Perú***:* un diagnóstico de los humedales de Santa Rosa, Laguna El Paraíso y Albufera de Medio Mundo. [*S. l: s. n.*], 2017.

ARANA TEJALA, L. L. Refugio de vida silvestre Los Pantanos de Villa como socioecosistema desde una metodología socioecológica. **Revista del Instituto de Investigación de la Facultad de Minas, Metalurgia y Ciencias Geográficas**, Lima, v. 25, n. 49, 2022.

AUTORIDAD NACIONAL DEL AGUA. **Metodología para la determinación del índice de calidad de agua ICA-PE, aplicado a los cuerpos de agua continentales superficiales.** Lima: Autoridad Nacional Del Agua, 2018.

CABREJOS BERMEJO, J. R. Evoluciones del nivel estático y conductividad eléctrica del agua subterránea del valle Chancay-Lambayeque, periodo 1996–2014. **Revista Científica Institucional *TZHOECOEN***, Chiclayo , v. 10, n. 1, p. 148–162, 2018. DOI: https://doi.org/10.26495/rtzh1810.125347

CANADIAN COUNCIL OF MINISTERS OF THE ENVIRONMENT. **Canadian Water Quality Guidelines for the Protection of Aquatic Life**: CCME Water Quality; Canadian Council of Ministers of the Environment. Winnipeg: Canadian Council of Ministers of the Environment, 2001.

CANALES CUADROS, H.; CABRERA CARRANZA, C.; ARANA MAESTRE, J. Macroinvertebrados acuáticos y calidad de agua en el Área de Conservación Regional Humedales de Ventanilla, Callao. **Revista del Instituto de Investigación de la Facultad de Minas, Metalurgia y Ciencias Geográficas**, Lima, v. 25, n. 49, 2022.

CHACÓN, A.; PAJUELO, A. **Factores geológicos en los humedales de Villa**. Lima: INGEMMET, 2013. Available in: https://app.ingemmet.gob.pe/biblioteca/pdf/RFIGMMG-26-3.pdf.

DAVIS, S. Wetland plants: biology and ecology. **Ecological Engineering**, [*s. l.*], v. 19, n. 5, p. 351–352, 2003.

ESCOBAL PÉREZ, L.; CHÁVEZ HORNA, G.; RONCAL RABANAL, M. Efficiency of the Vegetal Tissue of *Armatocereus rauhii* subsp. *balsasensis* (F. Ritter) Ostolaza and *Espostoa mirabilis* F. Ritter (Cactaceae) in the Removal of Total Suspended Solids in the Water for Human Consumption of the District of Balzas – Amazonas. **Arnaldoa**, Trujillo, v. 27, n. 1, p. 157–167, 2020. DOI: https://doi.org/10.22497/1517

FAJARDO VIDAL, N. S. **Evaluación de la calidad microbiológica y fisicoquímica de las aguas en el Área de Conservación Regional Humedales de Ventanilla**, Región Callao, Perú. 2018. Tesis de Magíster (Maestría en Ciencias Ambientales) – Universidad Nacional Mayor de San Marcos, 2018.

GOMO, M.; VERMEULEN, D.; LOURENS, P. Groundwater sampling: flow-through bailer passive method versus conventional purge method. **Natural Resources Research**, [*s. l.*], v. 27, n. 1, 2018.

HUAMÁN-VILCA, S.; ESPINOZA, M.; PAREDES VITE, M.; CHANGANAQUI, D. Evaluación de la calidad del agua de la laguna Marvilla en los Pantanos de Villa (Lima, Perú). **South Sustainability**, [*s. l.*], v. 1, n. 2, 2020.

INSTITUTO GEOLÓGICO, MINERO Y METALÚRGICO. **Evaluación, ordenación y plan de manejo ambiental para el desarrollo integral de los Pantanos de Villa**. Lima, 1991.

INSTITUTO GEOLÓGICO, MINERO Y METALÚRGICO. **Estudio hidrogeológico del refugio de vida silvestre de los Pantanos de Villa (RVSPV), Chorrillos - Lima**. Lima: INGEMMET, 2019.

LIMA. Municipalidad Metropolitana. **Por el que se aprueba el plan de prevención y reducción de riesgos de desastres de los Pantanos de Villa 2022–2024**. Lima, 2022.

LÓPEZ-SAUT, E.; RODRÍGUEZ-ESTRELLA, R.; CHÁVEZ-RAMÍREZ, F. ¿Son las grullas indicadoras de la riqueza de especies de aves acuáticas en humedales en el Altiplano Mexicano? **Acta Zoológica Mexicana**, v. 30, n. 2, 2014.

LU, J. ; SANTO DOMINGO, J. W.; LAMENDELLA, R.; EDGE, T.; HILL, S. Phylogenetic diversity and molecular detection of bacteria in gull feces. **Applied and Environmental Microbiology**, [*s. l.*], v. 74, n. 13, p. 3969–3976, 2008.

MITSCH, W. J.; GOSSELINK, J. G. **Wetlands**. 5th ed. Hoboken: John Wiley & Sons, 2015.

NORTH CAROLINA ENVIRONMENTAL QUALITY. **Groundwater quality standards**. Raleigh: North Carolina Environmental Quality, 2022.

PAUTA, G.; VÁZQUEZ, G.; ABRIL, A.; TORRES, C.; SARI, M. L.; VERA, A. P.. Indicadores bacteriológicos de contaminación fecal en los ríos de Cuenca, Ecuador. **Maskana**, Cuenca, v. 11, n. 2, p. 46–57, 2020.

PERÚ. Ministerio de Desarrollo Agrario y Riego. **Metodología para la determinación del índice de calidad de agua de los recursos hídricos superficiales en el Perú ICA-PE**. Lima: MINAGRI, 2018.

PERÚ. Ministerio del Ambiente. **Decreto Supremo n.º 004-2017-MINAM:** que aprueba los Estándares de Calidad Ambiental (ECA) para Agua. Lima: Ministerio Del Ambiente, 2017.

PUMA-QUISPE, A.; ZAVALETA-MUÑOZ, P. J.; PALMA-VENTURA, T. F.; GARCÍA-MEDINA, V. M. Evaluación de la calidad del agua subterránea en un sector de la zona de reglamentación especial de Los Pantanos de Villa. **South Sustainability**, Lima, v. 3, n. 2, 2022.

QUIÑONEZ, A. S.; HERNÁNDEZ, F. Uso de hábitat y estado de conservación de las aves en el humedal El Paraíso, Lima, Perú. **Revista Peruana de Biología**, Lima, v. 24, n. 2, 2017.

RAMÍREZ, C.; ORTEGA, L. Evaluación de la calidad del agua en el humedal de Santay: un enfoque en áreas protegidas. **Journal of Environmental Studies**, [*s. l.*], v. 15, n. 4, p. 89–102, 2020.

RAMSAR. Los Pantanos de Villa. Gland, 2023. Available in: https://rsis.ramsar.org/ris/884.

RAMSAR. **Perspectiva mundial sobre los humedales**: estado de los humedales del mundo y sus servicios a las personas. Gland: Secretaría de la Convención de Ramsar, 2018. Available in: ramsar_gwo_spanish_web.pdf

RIVERA, M. A. O.; BARAHONA, W. E. C.; COSTALES, J. H. N.; LALVAY, X. A. L.; GUACHICHULLCA, E. J. R. La calidad de las aguas residuales domésticas. **Polo del Conocimiento:** Revista científico-profesional, Manabí , v. 6, n. 3, p. 228–245, 2021.

RODRÍGUEZ VÁSQUEZ, M. I. **Variación de humedales costeros e irrigaciones agrícolas**: el caso de la Albúfera de Medio Mundo y el área agrícola de Huaura. 2017. Tesis (Licenciatura) – Pontificia Universidad Católica del Perú, Lima, 2017.

RODRÍGUEZ, R.; RETAMOZO-CHAVEZ, R.; APONTE, H.; VALDIVIA, E. Evaluación microbiológica de un cuerpo de agua del ACR Humedales de Ventanilla (Callao, Perú) y su importancia para la salud pública local. **Revista de Ecología Aplicada**, Lima, v. 16, n. 1, 2017.

SÁNCHEZ, A. H. S. **Restauración de los canales eutrofizados de abastecimiento de agua a los Pantanos de Villa**. 2020. Tesis (Doctorado) – Pontificia Universidad Católica del Perú, 2020.

SERVICIO NACIONAL DE ÁREAS NATURALES PROTEGIDAS POR EL ESTADO. **Refugio de vida silvestre Los Pantanos de Villa**. Lima, 2019. Available in:https://www.gob.pe/institucion/sernanp/informes-publicaciones/1833908-refugio-de-vida-silvestre-los-pantanos-de-villa.

SERVICIO NACIONAL DE ÁREAS NATURALES PROTEGIDAS POR EL ESTADO. **Prevención, tratamiento y monitoreo de conflictos socioambientales en áreas naturales protegidas de administración nacional**. Lima, 2016. Available in: https://spda.org.pe/wp-content/uploads/2024/02/Prevencion-tratamiento-y-monitoreo-de-conflictos-en-ANP-Baja.pdf.

SOLARTE, Y.; PEÑA, M.; MADERA, C. Transmisión de protozoarios patógenos a través del agua para consumo humano. **Colombia Médica**, Cali, v. 37, n. 1, p. 74–82, 2006.

SOTO, R. Groundwater resources in the Amazon basin: a survey in Colombia, Bolivia, and Peru. **Water**, [*s. l.*], v. 10, n. 7, p. 840, 2018.

UNITED STATES GEOLOGICAL SURVEY. **National field manual for the collection of water-quality data**: collection of water samples. Reston: USGS, 2006.

VALLEJO, A. **Niveles de contaminación en el litoral sur de la bahía de Talara por aceites, grasas y metales pesados.** 2010. Tesis de Máster (Maestría en Gestión y Auditorías Ambientales) – Universidad de Piura, Piura, 2010.