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Water Quality Determination Using Soil and Vegetation Communities in the Wetlands of the Andes of Ecuador

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Abstract: The bofedales are high Andean ecosystems of great socioeconomic and ecological importance. The Chimborazo Fauna Production Reserve has 15 bofedales in its jurisdiction, located in the provinces of Chimborazo, Bolívar, and Tungurahua. The objective of this study was to establish the relationship between plant species composition and the physicochemical characteristics of water and soil. To determine the floristic composition, destructive sampling of species was applied, and three sampling points of 1 m^2 were established every 100 m per wetland. At each sampling point, physical-chemical variables were recorded in situ and in the laboratory for water and soil. The floristic analysis identified 78 riparian species of riparian plants (63 vascular, 12 bryophytes, 4 pteridophytes) and 1 lichen. In the aquatic environment, seven vascular plants, recognized as macrophytes, were recorded. The results show great heterogeneity in the soil, water, and vegetation characters because they respond to a mineralization gradient (as indicated by the high values of electrical conductivity and dissolved ions). Additionally, it was observed that the total amount of soluble solids that characterizes the Los Hieleros wetland (W11) is independent of hardness and chemical oxygen demand, which correlate with each other and, in turn, better describe the Pachancho wetland (W12). The highest degree of turbidity corresponds to the Cóndor Samana (W9) and Portal Andino (W10) wetlands. The Culebrillas (W6), Puente Ayora ANI (W14), and Pampas Salasacas (W1) wetlands are characterized by the presence of dissolved oxygen, so it is assumed that these are the wetlands with the best water quality. Consequently, it is imperative to double efforts to describe the ecology and status of these high Andean wetlands in order to promote their conservation.

Keywords: floristic inventory; HJ-Biplot; soil sampling; vegetation communities; water quality

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1. Introduction

There is an urgent need to identify strategies for the preservation, restoration, and management of ecosystems [1]. Population growth, expansion of the agricultural and livestock frontiers, and industrial development worldwide are exerting strong pressures on natural ecosystems, especially aquatic ecosystems [2,3].

Wetlands are highly productive ecosystems [4,5] and comprise 8.5% of the Earth's land surface [6]. They cover a total area of 12.1 million km^2 and account for 40.6% of the total value of ecosystem services (ES) [7,8].

The 1999 wetland classification of the Ramsar Convention identifies wetlands as non-forested peatlands [9]. Their main functions include water pollution treatment, biogeochemical cycling adjustment, drought control, climate change mitigation [10], and contribution to the Earth's sustainability [11,12]. The ecological characteristics of these ecosystems are grouped into components. Functions and properties [13]; the components being biotic and abiotic conditions such as soil, water, and animals [14–16], so they tend to be very dynamic with constantly changing energy reserves [17].

The wetlands of the Andean tropics are in the high Andes Mountain range, at an altitude of more than 3.000 m.a.s.l. [18]. In Ecuador, there are 13 Ramsar wetlands [19] and 59 peatland-type ecosystems (known as bofedales in the Ecuadorian Andes) covering an area of 286.659 hectares and distributed throughout the continent [20]. These ecosystems include those wetlands and wetland complexes that are part of the páramo, jalca, and puna ecosystems, as well as other high Andean and related ecosystems [21], most of which are in protected areas that seek to conserve biodiversity [22]. The coverage of terrestrially protected areas is increasing every year and currently covers just over 15% of the land area [23,24]. In Ecuador, protected areas represent approximately 20% of the national territory [25].

The Chimborazo Fauna Production Reserve (RPFCH) is part of the National System of Protected Areas of Ecuador and is located in the provinces of Chimborazo, Bolivar, and Tungurahua. Altitudes in the reserve range from 3.800 to 6.310 m.a.s.l. [25]. The RPFCH covers 58.560 hectares [20,26], of which 39% are wetland-type ecosystems: 24% of the wetland ecosystem is in the intervened category, 12% is moderately conserved, and the remaining 3% is conserved [20].

Abiotic conditions, such as soil. Plant hydrology and water chemistry are the decisive factors in the pattern of wetland ecology [14–16,27–29]. Plants are the main primary producers, playing an important role in the maintenance and stability of these ecosystems [30,31]. Submerged wetland plants (macrophytes) provide a variety of ecological functions and services, such as providing substrate for algae and invertebrates [32] and influencing biogeochemical cycles and productivity [33]. However, plants, similar to other components of aquatic ecosystems, currently face increasing anthropogenic threats [34].

Several studies have shown that soil nutrients are one of the main factors affecting plant productivity [35]. Changes in the types and variations of plant functional traits [36,37] are decisive factors in the regulation of soil functions [38], because coexisting species with contrasting trait values increase overall resource acquisition and use through complementary niche effects [39,40]. The loss of plant species diversity caused by changes in land-use intensity leads to a reduction in individual soil functions, such as soil nitrogen and water retention [41,42].

For some time, researchers have been trying to determine the influence of vegetation cover on soil and water conditions [43]. This study evaluates the relationship between biotic (plants) and abiotic (soil-water) components of the wetlands located in the Chimborazo Wildlife Production Reserve (RPFCH), thus understanding the correspondence between vegetation and the environment and allowing the development of programs focused on the protection and conservation of these high Andean ecosystems.

2. Materials and Methods

2.1. Study Area

The study was conducted in 15 bofedales of the RPFCH in the interior of the Andes, with a temperature ranging from −3 to 14 °C and an average annual precipitation of 1000 mm and a humidity percentage of 70–85% [25].

The vegetation cover is formed by mixed natural communities of peatlands, sporadic water quinielas, and buffer vegetation, resulting in a deep and peaty organic soil.

The bofedales are located between 3840 and 4314 m.a.s.l. in the provinces of Bolivar (6 bofedales), Chimborazo (3 bofedales), and Tungurahua (6 bofedales), where they cover areas ranging from 2 to 155 ha (Figure 1).

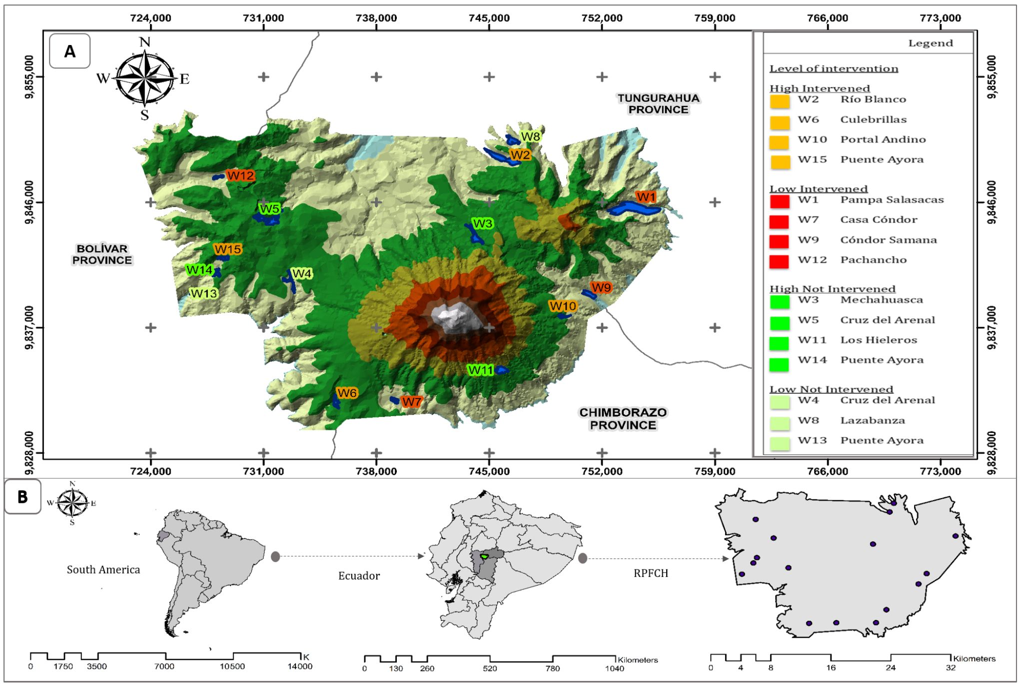

Figure 1. Map of the study area. (**A**) Geographic location of the wetlands of the RPFCH (BNI: Low Intervened Level. BI: Low Intervention. AI: High Intervention. ANI: High Intervened Level (**B**) Location in relation to South America and Ecuador.

2.2. Floristic Sampling and Inventory

Field work was carried out in September 2018 and February 2019. Sampling units were distributed for each bofedal: point one (P1) in the upper zone of the bofedal, point two (P2) in the intermediate zone, and point three (P3) in the lower zone of the bofedal. They were then georeferenced (Appendix A) using a GARMIN OREGON 650 GPS (Garmin Iberia S.A.U., Barcelona, Spain).

Plots of 1 m^2 [44] were established along the slope of the bofedales between 3825 and 4240 m.a.s.l. A total sweep was made within the plot, considering the edge error and keeping the conditions within the unit intact to carry out subsequent measurements.

Species identification was carried out in two authorized herbariums in Ecuador: the herbarium of the Department of Biological Sciences of the Pontificia Universidad Católica del Ecuador in Quito (QCA Herbarium) and the herbarium of the Escuela Superior Politécnica de Chimborazo (CHEP).

2.3. Measurement of Selected Physicochemical Variables: Collection and Analysis of Water Samples

All measurements and water sample collection were performed randomly in duplicate; in each wetland, two liters of water were taken. Values of pH, temperature (°C), dissolved oxygen DO (mg/L) and electrical conductivity EC (µS/cm), were measured in situ, using a pH meter (PCE-PH22—Apera Instruments, Wuppertal, Germany), a portable oximeter (HI9146-04—HANNA Instruments, Limena, Italy), and a portable multiparameter probe (MM40—Crison Instruments, Barcelona, Spain).

Water samples (2 L each) were collected using glass bottles (1000 mL) and placed in portable coolers at −10 °C without preservatives. They were then sent to the Water-Industrial Effluents Environmental Analysis Laboratory (LASA-Quito) to be analyzed according to the standard method APHA (Table 1) [45]. The parameters analyzed were pH; Temperature (Temp. °C); Ammonium (NH_4. mg/L); Calcium (Ca. mg/L); Electrical conductivity (Cond. uS/cm); Biological oxygen demand (BDO. mg/L); Chemical oxygen demand (C.O.D. mg/L); Hardness (mg $CaCO_3$/l); Phosphorus (P. mg/L); Magnesium (Mg. mg/L); Nitrates (mg/L); Nitrites (mg/L); Dissolved oxygen (Diss. O. mg/L and %); Totally suspended solids (TSS, mg/L); and Sulfates (mg/L).

Table 1. Methods and parameters used for the analysis of physicochemical samples from the bofedales of the RPFCH.

Parameters	Units	Method
Fecal Coliforms	NMP/100 mL	SM 9221 E
Ammonium (NH_4)	mg/L	SM 4500-NH3 EPA 350.2/350.3
Calcium (Ca)	mg/L	SM 3111 B
Electrical conductivity	uS/cm	HACH 8160
Biological oxygen demand (B.O.D.)	(mg/L)	SM 5210 B
Chemical oxygen demand (C.O.D.)	mg/L	SM 5220 D
Hardness	mg/L	SM 2340 C
Phosphorus (P)	mg/L	SM 4500-P
Magnesium (Mg)	mg/L	SM 3111 B
Nitrates (NO_{3-})	mg/L	SM 4500 NO_3-E
Nitrites (NO_{2-})	mg/L	HACH 8507
Sulfates ($SO_4{}^{2-}$)	mg/L	SM 4500 $SO_4{}^{2-}$
Dissolved oxygen	%	SM 4500–O G
Turbidity	NTU	SM 2130 B
Totally suspended solids	mg/L	Gravimetric 2540-D

2.4. Soil Sampling and Analysis

A two-dimensional sampling was performed since peatlands have an irregular shape of less than 1000 m^2. Six samples were taken/peatland; the distribution per sample was 1 every 15 linear meters (4) and at the bottom of the peatland (2) at a depth of 30 cm. A total of 96 samples were collected for analysis of granulometry and organic matter. The samples were collected in wide-mouthed glass jars with lids and Teflon seals and transported to the Soil Laboratory of the Faculty of Natural Resources of the Escuela Superior Politécnica de Chimborazo, where they were analyzed following the methodology of the Soil Analysis Manual of the Soil Laboratory Network of Ecuador [46].

2.5. Data Analysis

Statistical analyses on the floristic and physical composition of wetland soil and water chemistry data were performed using R statistical software version 3.3.1 [47].

To detail the key variables explaining the high variability in the dataset. Principal Component Analysis (PCA) [48] with the packages FactoMineR version 2.8 [49] and ggbiplot version 3.4.2 [50] was applied to standardized soil and water variables. This allowed for the selection of physicochemical variables (e.g., Nitrites, Calcium, Magnesium, Conductivity, Hardness, pH, Electrical Conductivity, Phosphorus, and Potassium) and physical habitat attributes, while reducing the dimensionality of the data set. Biplots were made for the first two components based on the resulting scores and loadings that provided an overview of the relationships between multiple variables and sites with the highest level of intervention within the protected area [51,52].

With an integrating approach and with the desire to obtain greater discrimination of the data, the HJ-Biplot [53] multivariate analysis was carried out in MultBiplot Software.

Biplot analysis is a procedure for the simultaneous graphic representation of the rows and columns of a matrix, which allows summarizing the information of a matrix of rank r in a space of dimension q less than r. The Biplot that absorbs the greatest possible information, in terms of variability, of a matrix X of rank r is the one corresponding to the matrix of rank q, which constitutes the low-rank approximation of X, which is obtained from the decomposition in singular values of X [54] as:

$$X_{(q)} = U_{(q)}\, D_{(q)\lambda}\, V^{T}{}_{(q)} \tag{1}$$

where $U_{(q)}$ is the matrix, whose columns contain the first q eigenvectors of XX^T. $D_{(q)\lambda}$ is the diagonal matrix with the first q singular values of X, and $V_{(q)}$ is the matrix containing the q first eigenvectors of X^TX. This expression also corresponds to the singular value decomposition of $X_{(q)}$. There are two classic options to achieve better quality representation of either the columns (GH) or the rows (JK).

Galindo [53–55] proposes taking $A = U_{(q)}\ D_{(q)\lambda}$ y $B = D_{(q)\lambda}\ V^{T}_{(q).}$ The Biplot thus constructed was called HJ-Biplot by its author, respecting the logic of the names proposed by Gabriel 1971. Its main characteristic is that both the rows and the columns reach the highest quality of representation. In this case, it is obvious that the internal product of the vector markers will not reproduce the data of the starting matrix, even retaining the q dimensions. However, this is not a problem since the objective is generally not to reproduce the original data but to obtain a simultaneous approximation of the rows and columns of X in which both are well represented.

3. Results

3.1. Floristic Inventory

The floristic inventory (Table 2) identified 85 plant species, of which 72 species (85%) are vascular and 13 species (15%) are non-vascular. Only seven of the species (7.5%) have aquatic characteristics. The most abundant family was Asteraceae, with 15 species. Poaceae with 7 species and Apiaceae with 5 species are among the most representative. The greatest percentage of the species identified (85%) are native, with a distribution area restricted to the moorlands of the center and south of the country; the place of origin of 7% of the species could not be identified; 4% of the species have been introduced in the areas; while the remaining 4% are endemic species of the country: *Halenia pulchella, Gnaphalium chimboracense,* and *Nototriche hartwegii*, the same ones that, according to the Red Book of Endemic Plants of Ecuador [56], are in states of least concern (with a population number of 30), vulnerable (with a population number of 2), and the last one in endangered status (with a population number of 2), respectively.

Table 2. Floristic diversity of the wetlands of the Chimborazo Fauna Production Reserve (* = aquatic species. N/N = No name. N/D = No data).

Order	Family	Cientific Name	Origen	Number of Individuals
Apiales	Apiaceae	*Azorella pedunculata* (Spreng.) Mathias & Constance. 1995	Native	11,988
		Eryngium humile Cav. (1800)	Native	1085
		Oreomyrrhis andicola (Kunth) Endl. ex Hook. f. (1846)	Native	156
		Azorella biloba (Schltdl.) Wedd. (1860)	Native	351
		Azorella aretioides (Spreng.) Willd. ex DC. (1830)	Native	88
Alismatales	Hydrocharitaceae	*Elodea canadensis* Michx. (1803) *	Native	1405
	Potamogetonaceae	*Potamogeton filiformis* Pers. (1805) *	Native	148
Asterales	Asteraceae	*Baccharis caespitosa* (Ruiz & Pav.) Pers. (1807)	Native	1421
		Bidens andicola Kunth. 1820	Native	115
		Achyrocline alata (Kunth) DC. (1837)	Native	64
		Gamochaeta americana (Mill.) Wedd. (1855)	Native	8
		Gnaphalium spicatum (Forssk.) Vahl. 1788	Native	19
		Hypochaeris sessiliflora Kunth. 1820	Native	2022
		Monticalia arbutifolia (Kunth) C. Jeffrey. 1992	Native	79
		Oritrophium peruvianum (Lam.) Cuatrec. (1961)	Native	5
		Werneria nubigena Kunth. 1820	Native	71
		Xenophyllum humile (Kunth) V.A. Funk. 1997	Native	131
		Erigeron ecuadoriensis Hieron. (1896)	Native	18
		Erigeron L. (1753)	N/D	10,360
		Culcitium Bonpl. (1808)	N/D	5
		Gnaphalium purpureum L.(1753)	Native	84
		Gnaphalium chimboracense Hieron. ex Sodiro. (1900)	Native	4
Brassicales	Brassicaceae	*Rorippa pinnata* (Sessé y Moc.) Rollins. 1960 *	Native	5609
Bartramiales	Bartramiaceae	*Breutelia chrysea* (Müll. Hal.) A. Jaeger	Native	4307
		Bartramia potosica Mont. (1838)	Native	40,579
Bryales	Bryaceae	*Rhodobryum* (Schimp.) Limpr. (1892)	N/DI	255
	Mniaceae	*Plagiomnium rhynchophorum* (Harv.) T.J. Kop. (1971)	Native	491
Cyatheales	Cyateaceae	*Alsophila* R. Br. (1810)	N/D	39
Dipsacales	Valerianaceae	*Valeriana microphylla* Kunth. 1818	Native	178
		Valeriana rigida Ruiz & Pav. (1798)	Native	23

Table 2. *Cont.*

Order	Family	Cientific Name	Origen	Number of Individuals
Ephedrales	Ephedraceae	*Ephedra rupestris* Benth. (1846)	Native	129
Equisetales	Equisetaceae	*Equisetum bogotense* Kunth. 1815	Native	177
Ericales	Ericaceae	*Disterigma empetrifolium* (Kunth) Drude. 1889	Native	483
		Pernettya prostrata (Cav.) Sleumer. 1935	Native	122
		Vaccinium floribundum Kunth. 1819	Native	89
Caryophyllales	Caryophyllaceae	*Drymaria ovata* Humb. & Bonpl. ex Schult. (1819)	Native	48
	Polygonaceae	*Rumex acetosella* L. (1753)	Introduced	26
Fabales	Fabaceae	*Lupinus microphyllus* Desr. (1792)	Native	24
		Lupino pubescens Benth. (1845)	Native	18
		Trifolium repens L. (1753)	Introduced	125
Gentianales	Gentianaceae	*Gentiana cerastioides* Kunth. 1819	Native	2716
		Gentiana sedifolia Kunth. 1819	Native	487
		Gentianella corymbosa (Kunth) Weaver & Ruedenberg. 1975	Native	9
		Halenia pulchella Gilg. 1916	Endemic	22
	Rubiaceae	*Galium hypocarpium* (L.) Fosberg. 1966	Native	620
		Galium pumilio Standl. (1929)	Native	783
		Nertera granadensis (Mutis ex L. f.) Druce. 1916	Native	244
Geraniales	Geraniaceae	*Geranium diffusum* Kunth. 1821	Native	2800
Hookeriales	Pilotrichaceae	*Cyclodictyon roridum* (Hampe) Kuntze. 1891	Native	28,598
Malpighiales	Hypericaceae	*Hypericum laricifolium* Juss. (1804)	Native	9
Hypnales	Thuidiacea	*Thuidium peruvianum* Mitt. (1869)	Native	36,412
	Brachytheciaceae	*Brachythecium austroglareosum* (Müll. Hal.) Kindb. (1891)	Native	290
Lamiales	Orobanchaceae	*Bartsia laticrenata* Benth. (1989)	Native	4
		Castilleja fissifolia Sessé & Moc. (1995)	Native	1
	Plantaginaceae	*Sibthorpia repens* (L.) Kuntze. 1898	Native	40
		Plantago australis Lam. (1791)	Native	8
		Plantago rigida Kunth. 1817	Native	7482
Lycopodiales	Lycopodiaceae	*Huperzia crassa* (Humb. & Bonpl. ex Willd.) Rothm. (1944)	Native	36
Marchantiales	Marchantiaceae	*Marchantia* L. (1753)	N/D	10
Malvales	Malvaceae	*Nototriche hartwegii* A.W. Hill. 1909	Endemic	1008
Myrtales	Onagraceae	*Epilobium denticulatum* Ruiz & Pav. (1802)	Native	49
Polypodiales	Dryopteridaceae	*Elaphoglossum engelii* (H. Karst.) Christ. 1899	Native	4185
		Polystichum orbiculatum (Desv.) J. Rémy & Fée. 1853	Native	8
	Polypodiaceae	*Melpomene moniliformis* (Lag. ex Sw.) A.R. Sm. & R.C. Moran. 1992	Native	30
Poales	Juncaceae	*Distichia musczoides* Nees. & Meyen. (1843)	Native	9
	Cyperaceae	*Carex bonplandii* Kunth. 1837	Native	2584
		Eleocharis albibracteata Nees & Meyen ex Kunth. 1837 *	Native	2971
		Eleocharis albibracteata Nees & Meyen ex Kunth. 1837	Native	696
	Poaceae	*Agrostis foliata* Hook. f. (1844)	Native	22
		Agrostis breviculmis Hitchc. (1905)	Native	25,418
		Bromus pitensis Kunth. 1816	Native	5406
		Cortaderia sericantha (Steud.) Hitchc. (1927)	Native	31
		Eragrostis nigricans (Kunth) Steud. (1840)	Native	481
		Muhlenbergia angustata (J. Presl) Kunth. 1833	Native	4
		Phalaris minor Retz. (1783)	Introduced	4545
Pottiales	Pottiaceae	*Leptodontium longicaule* (Müll.Hal.) Hampe ex Lindb. (1869)	Native	1576
		Leptodontium ulocalyx (Müll. Hal.) Mitt.(1869)	Native	30,634
		Leptodontium wallisii (Müll. Hal.) Kindb. (1888)	Native	1900
Porellales	Lejeuneaceae	*Lejeunea* Lib. (1820)	Native	11
Ranunculales	Ranunculaceae	*Ranunculus flagelliformis* Sm. (1815) *	Native	1075
		Ranunculus peruvianus Pers. (1806) *	Native	14
Rosales	Rosaceae	*Lachemilla andina* (L.M. Perry) Rothm. (1937)	Native	531
		Lachemilla galioides (Benth.) Rothm. (1938)	Native	27
		Lachemilla orbiculata (Ruiz & Pav.) Rydb. (1908)	Native	4086
Saxifragales	Haloragaceae	*Myriophyllum quitense* Kunth.1823 *	Native	514

3.2. *Physicochemical Analysis of Water*

Most of the physicochemical variables (Table 3) showed variations between groups and differed by more than one or two orders of magnitude. The Unified Text of Secondary Environmental Legislation (TULSMA) mentions that the established value for this parameter should be between 6.5 and 9.0 pH units; in this study, all the samples analyzed met this value. remaining in the neutral range and demonstrating the absence of substances that could affect it. The water temperature at the sampling sites ranged from 7 to 11 °C (45 to 52 °F). Ammonium concentrations differed greatly in the wetlands in amounts varying between 0.05 and 9.9 (mg/L), while calcium (Ca. mg/L) ranged between 1 and 20 (mg/L). Conductivity remained in the range of 14–289 (µS/cm). being the highest reported in the Casa Condor BI wetland. The concentrations of the chemical parameters, including nitrate, remained in a range of <0.70 (mg/L) during the study period. Nitrite values were less than 0.002 (mg/L), and dissolved oxygen concentrations were between 6 and 7 (mg/L), which corresponded to elevated B.O.D. concentrations.

Concentrations of nutrients that potentially limit primary production, such as phosphorus (P) and nitrates, were very low and, in many cases, below the detection limit (less than 0.01 mg/L in 75% of the cases for total phosphorus and 93% for nitrates (Table 3). According to our physicochemical data, most of the bogs can be considered minerotrophic peatlands [57–59].

3.3. Soil Analysis

The variables analyzed show the values included in Table 4.

3.4. Characterization of Sites with Soil and Water Variables

The multivariate analysis of 31 variables related to physical and physical-chemical aspects of water and soil quality was analyzed with the HJ-Biplot methodology, showing that three axes explained 89.42% of the total variance (Table 5). Axes 1 and 2 explain 70.81% of the variance, so the results will be analyzed with these 2 axes (Figure 2).

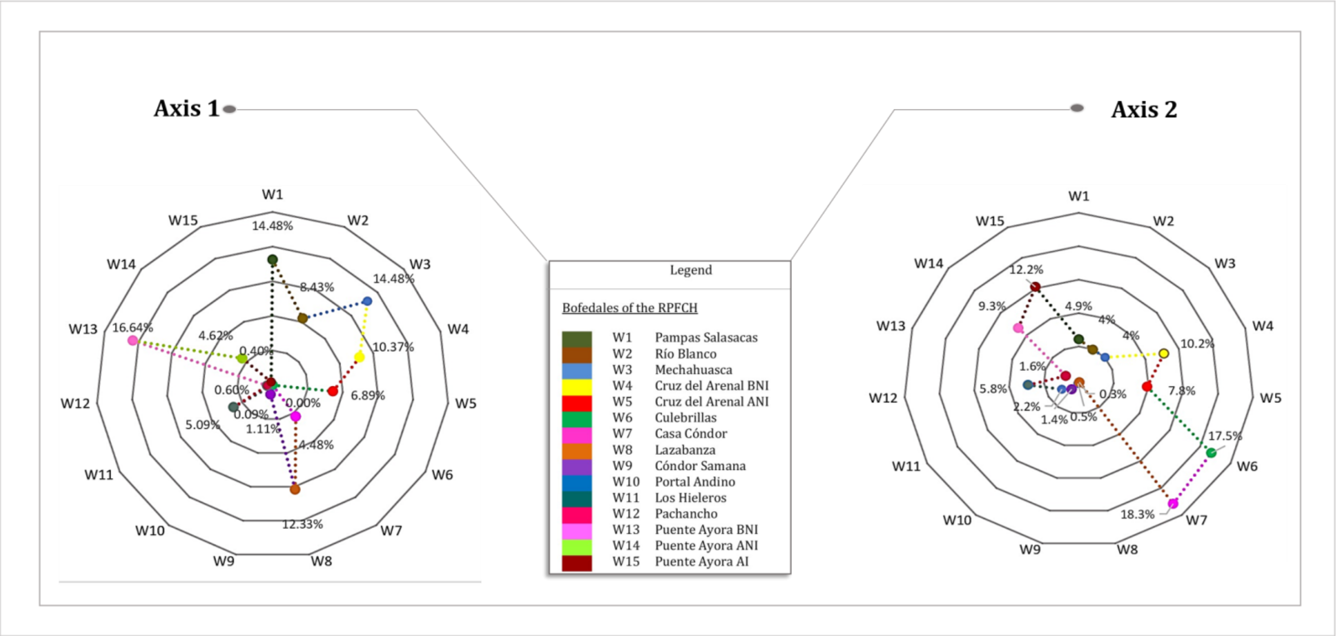

Figure 2. Contributions of wetlands to the multivariate analysis of variables related to physical and physical-chemical aspects of water and soil quality.

Table 3. Physico-chemical analysis of the water of the RPFCH bofedales.

Physicochemical Parameters:	**W1**	**W2**	**W3**	**W4**	**W5**	**W6**	**W7**	**W8**	**W9**	**W10**	**W11**	**W12**	**W13**	**W14**	**W15**	**Water Quality Criteria According to TULSMA for:**		
																Human and Domestic Consumption	**Wildlife Preservation**	**Agricultural Irrigation**
pH	9.70	9.90	7.70	10.20	9.70	11.20	7.90	10.70	11.30	8.90	8.80	9.10	8.70	8.50	8.60	6–9	6.5–9	6.9
Temp (°C)	0.00	3.60	1.80	0.00	0.00	3.70	1.80	0.00	1.90	1.90	1.90	0.00	0.00	0.00	0.00	Natural condition	Natural condition	Natural condition
F. Col. NMP/100 mL	1.99	1.04	0.89	1.00	1.41	0.76	0.93	1.01	1.22	1.22	1.22	2.11	0.92	0.00	1.20	-	-	-
NH_4 (mg/L)	5.30	7.38	8.34	2.25	2.67	2.91	8.37	4.42	10.45	10.45	2.40	7.66	2.79	6.15	3.87	0.05	-	-
Ca (mg/L)	139.20	345.10	224.33	85.63	90.40	115.10	312.33	97.83	270.00	270.00	98.00	287.67	85.73	63.40	107.73	-	-	-
Cond. (uS/cm)	5.37	1.86	6.09	15.90	7.80	0.09	2.64	3.42	3.87	3.87	3.87	25.50	31.50	0.74	11.70	-	-	700
B.O.D. (mg/L)	9.00	12.00	37.00	25.00	15.00	7.00	4.00	19.00	27.00	27.00	27.00	156.00	41.00	3.05	35.00	<2	20	-
C.O.D. (mg/L)	46.00	111.00	86.00	26.00	30.00	43.00	111.00	41.00	96.00	96.00	43.00	110.00	22.00	23.41	28.00	<4	40	-
Hardness (mg $CaCO_3$/l)	0.00	0.00	0.00	0.42	0.49	0.548	0.675	0.00	0.636	0.636	0.636	0.62	0.00	0.07	0.00	400	-	-
P (mg/L)	1.90	2.50	2.30	1.80	1.90	1.60	2.30	1.60	2.00	2.00	0.51	3.20	1.30	1.96	2.20	-	-	-
Mg (mg/L)	0.50	0.40	0.00	0.00	0.30	0.50	0.00	0.60	0.60	0.60	0.30	0.30	0.80	0.30	0.50	-	-	-
NO_{3-} (mg/L)	0.00	0.002	0.000	0.004	0.002	0.019	0.000	0.000	0.010	0.010	0.01	0.00	0.00	0.00	0.00	10	13	-
NO_{2-} (mg/L)	1.00	4.00	2.00	4.00	2.00	1.00	2.00	3.00	2.00	2.00	3.00	29.00	1.00	3.30	41.00	1	0.2	0.5
SO_4^{2-} (mg/L)	77.40	89.60	59.50	90.30	97.00	77.10	76.10	70.10	42.10	42.10	70.00	53.40	74.80	101.20	67.50	>6	>6	>3
Diss. O. (%)	7.55	5.06	0.99	4.44	0.39	9.62	2.75	4.21	106.60	102.60	106.60	59.00	7.51	6.00	2.00	>80%	>80%	-
Tur. (NTU)	60.00	22.00	25.00	29.00	7.00	66.00	19.00	19.00	36.00	66.00	215.00	4.00	36.00	2.00	7.00	-	1000	-
T.S.S. (mg/L)	9.70	9.90	7.70	10.20	9.70	11.20	7.90	10.70	11.30	8.90	8.80	9.10	8.70	8.50	8.60	400	-	250

Physicochemical Parameters: Temperature (Temp. °C); Fecal Coliforms (F. Col. NMP/100 mL); Ammonium (NH_4. mg/L); Calcium (Ca. mg/L); Electrical conductivity (Cond. uS/cm); Biological oxygen demand (B.O.D. mg/L); Chemical oxygen demand (C.O.D. mg/L); Hardness (mg $CaCO_3$/l); Phosphorus (P. mg/L); Magnesium (Mg. mg/L); NO_{3-} (Nitrates. mg/L); NO_{2-} (Nitrites. mg/L); Sulfates (SO_4^{2-} mg/L); Dissolved oxygen (Diss. O. mg/L and %); Turbidity (Tur. NTU); Totally suspended solids (TSS. mg/L). Bofedales: W1 (Pampa Salasacas BI). W2 (Río Blanco AI). W3 (Mechahuasca ANI). W4 (Cruz del Arenal BNI). W5 (Cruz del Arenal ANI). W6 (Culebrillas AI). W7 (Casa Cóndor BI). W8 (Lazabanza BNI). W9 (Cóndor Samana BI). W10 (Portal Andino AI). W11 (Los Hieleros ANI). W12 (Pachancho BI). W13 (Puente Ayora BNI). W14 (Puente Ayora AI). W15 (Puente Ayora ANI).

Table 4. Granulometry and organic matter analysis (indicate the meaning of each abbreviation).

Bofe	pH	Elec. Cond (uS)	Organic Matter (%)	NH_4 (mg/kg)	P (mg/kg)	K (mg/kg)	Texture	Organic Carbon (%)	Gran > 2.0 (mm)	Gran > 1 (mm)	Gran > 0.5 (mm)	Gran > 0.25 (mm)	Gran > 0.1 (mm)	Gran < 0.1 (mm)
W1	5.10 L.Ac.	177.5 Non-saline	1.4%	23.78 B	35.24 A	0.47 B	Loamy sand	0.81%	0.36 gr	13.64 gr	22.73 gr	29.03 gr	25.66 gr	18.58 gr
W2	5.32 L.Ac.	285.0 Non saline	2.9%	9.11 B	29.68 M	1.12 A	Sandy loam	1.68%	1.10 gr	21.52 gr	23.84 gr	17.83 gr	20.33 gr	15.38 gr
W3	5.37 L.Ac.	292.0 Non saline	2.6%	27.95 B	25.96 M	0.57 M	Loamy sand	1.50%	0.13 gr	4.40 gr	14.62 gr	25.89 gr	36.88 gr	18.08 gr
W4	5.97 L.Ac.	136.7 Non saline	1.1%	7.26 B	38.02 A	0.36 B	Loamy sand	0.63%	0.73 gr	12.44 gr	14.14 gr	17.17 gr	37.75 gr	17.77 gr
W5	5.65 L.Ac.	324.0 Non saline	5.0%	15.60 B	27.12 M	0.65 A	Loamy sand	2.90%	0.76 gr	9.54 gr	8.79 gr	7.05 gr	8.01 gr	9.90 gr
W6	5.76 L.Ac.	217.0 Non saline	1.3%	8.92 B	30.37 A	0.67 A	Loamy sand	0.75%	0.10 gr	1.82 gr	1.91 gr	9.13 gr	67.25 gr	19.79 gr
W7	5.32 L.Ac.	603.0 Non saline	3.4%	15.68 B	41.04 A	1.25 A	Loamy sand	1.97%	0.95 gr	15.12 gr	14.82 gr	17.94 gr	33.27 gr	17.90 gr
W8	5.07 L.Ac.	214.0 Non saline	4.5%	24.21 B	26.43 M	0.86 A	Loamy sand	2.61%	0.45 gr	2.44 gr	8.6 gr	14.65 gr	42.72 gr	31.14 gr
W9	5.36 L.Ac.	149.1 Non saline	3.4%	21.89 B	37.09 A	0.61 M	Loamy sand	1.97%	0.35 gr	8.25 gr	29.59 gr	8.67 gr	18.29 gr	34.85 gr
W10	5.32 L.Ac.	140.6 Non saline	1.3%	12.70 B	25.73 M	0.58 M	Loamy sand	0.75%	1.72 gr	16.68 gr	19.40 gr	15.35 gr	23.76 gr	23.09 gr
W11	5.20 L.Ac.	231.0 Non saline	1.3%	10.85 B	32.00 A	0.78 A	Loamy sand	0.75%	1.04 gr	8.19 gr	8.88 gr	17.92 gr	40.75 gr	23.22 gr
W12	5.66 L.Ac.	252.0 Non saline	2.5%	11.47 B	49.62 A	1.21 A	Loamy sand	1.45%	1.02 gr	0.7 gr	3.79 gr	11.49 gr	47.69 gr	35.31 gr
W13	5.44 L.Ac.	164.0 Non saline	3.7%	21.78 B	30.84 A	0.78 A	Sandy loam	2.14%	0.30 gr	9.95 gr	11.75 gr	13.76 gr	35.37 gr	28.87 gr
W14	5.46 L.Ac.	197.7 Non saline	3.1%	12.26 B	32.92 A	0.95 A	Sandy loam	1.79%	2.61 gr	19.60 gr	16.92 gr	7.97 gr	22.08 gr	30.82 gr
W15	5.47 L.Ac.	223.0 Non saline	3.4%	15.50 B	33.16 A	0.81 A	Sandy loam	1.97%	0.21 gr	2.80 gr	5.61 gr	8.51 gr	33.56 gr	49.31 gr

Parameters: Elec. Cond: Electrical conductivity; % OM: Percentage of Organic Matter; NH_4: Ammonium; P: Phosphorus: K: Potassium; Soil pH: slightly acidic (L.Ac.) Presence level: A: High; M: Medium; B: Low; Gran: Granulometry.

Table 5. Eigenvalues and percentages of explained and cumulative variances.

Axes	Eigenvalues (Inertia)	Explained Variance (%)	Cumulative Variance (%)
1	302,578.13	43.43	43.43
2	190,750.44	27.38	70.81
3	129,685.88	18.61	89.42
4	38,703.43	5.57	94.99
5	17,163.43	2.46	97.45

The variables that best contribute to axis 1 are those corresponding to Altitude, Surface, and Nitrates, which make up the physical component. The other variables are located on axis 2, which we identify as the bio-physical component. The most outstanding water and soil quality indicators are: nitrites, calcium, magnesium, conductivity, hardness, pH, electrical conductivity, phosphorus, potassium content, and granulometries >1, >0.5, and >0.25 (Table 6).

Table 6. Contributions of variables to the multivariate analysis of variables related to physical and physical-chemical aspects of water and soil quality.

Variables	Axis 1	Percentage Contribution Axis 1 (%)	Axis 2	Percentage Contribution Axis 2 (%)
Altitude	667	19.2%	332	9.5%
Ha	376	10.8%	139	4.0%
Tc	101	2.9%	44	1.3%
B.O.D	160	4.6%	9	0.3%
C.O.D	0	0.0%	8	0.2%
NH_4	4	0.1%	68	1.9%
P	149	4.3%	12	0.3%
NO_{3-}	251	7.2%	10	0.3%
NO_{2-}	8	0.2%	113	3.2%
Sulfates	1	0.0%	2	0.1%
Ca	79	2.3%	158	4.5%
Mg	55	1.6%	103	2.9%
Electrical conductivity	339	9.8%	259	7.4%
Hard	271	7.8%	311	8.9%
Diss.O	2	0.1%	20	0.6%
Turbidity	11	0.3%	3	0.1%
T.S.S	9	0.3%	19	0.5%
pH	1	0.0%	133	3.8%
EC	435	12.5%	347	9.9%
Organic Matter	14	0.4%	6	0.2%
NH_4	41	1.2%	23	0.7%
P	5	0.1%	263	7.5%
K	134	3.9%	319	9.1%
OC_s	14	0.4%	6	0.2%
Organic Carbon	24	0.7%	13	0.4%
Gran > 2	62	1.8%	78	2.2%
Gran > 1	57	1.6%	356	10.1%
Gran > 0.5	90	2.6%	178	5.1%
Gran > 0.25	3	0.1%	121	3.4%
Gran > 0.1	14	0.4%	21	0.6%
Gran < 0.1	94	2.7%	39	1.1%
Total	3471	100.0%	3513	100.0%

According to the Biplot analysis of the Chimborazo Fauna Production Reserve wetlands, the variables hardness, conductivity, and electrical conductivity, which are highly correlated, are independent of altitude above sea level. The Mechahuasca (W3), Cruz del Arenal ANI (W5), Culebrillas (W6), and Puente Ayora ANI (W14) wetlands are effectively those located at an altitude above 4100 m.a.s.l. Pampas Salasacas (W1), Puente Ayora BNI (W13), Lazabanza (W8), and Cruz del Arenal BNI (W4) are the lowest and do not have representative variables that group them together except for altitude (Figure 3).

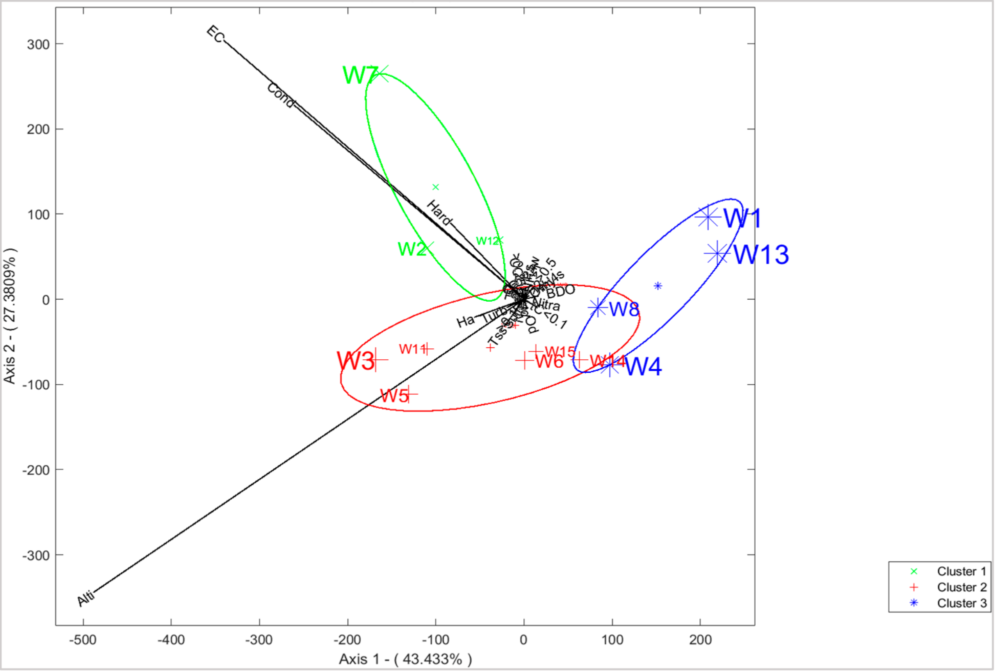

Figure 3. Biplot outcome of bofedals and physiochemical variables displayed in the 1 and 2 axes.

To find an additional configuration, we excluded the variables altitude, conductivity, and electrical conductivity, which were the most representative in the global analysis, and observed that the total amount of soluble solids that characterizes the Hieleros wetland (W11) is independent of hardness and chemical oxygen demand, which are correlated with each other and better describe the Pachancho wetland (W12). The highest degree of turbidity corresponds to the Cóndor Samana (W9) and Portal Andino (W10) wetlands. The Culebrillas (W6), Puente Ayora ANI (W14), and Pampas Salasacas (W1) wetlands are characterized by the presence of dissolved oxygen, so it is assumed that these are the wetlands with the best water quality. The other wetlands do not have outstanding variables that allow their discrimination since they share similar values (Figure 4).

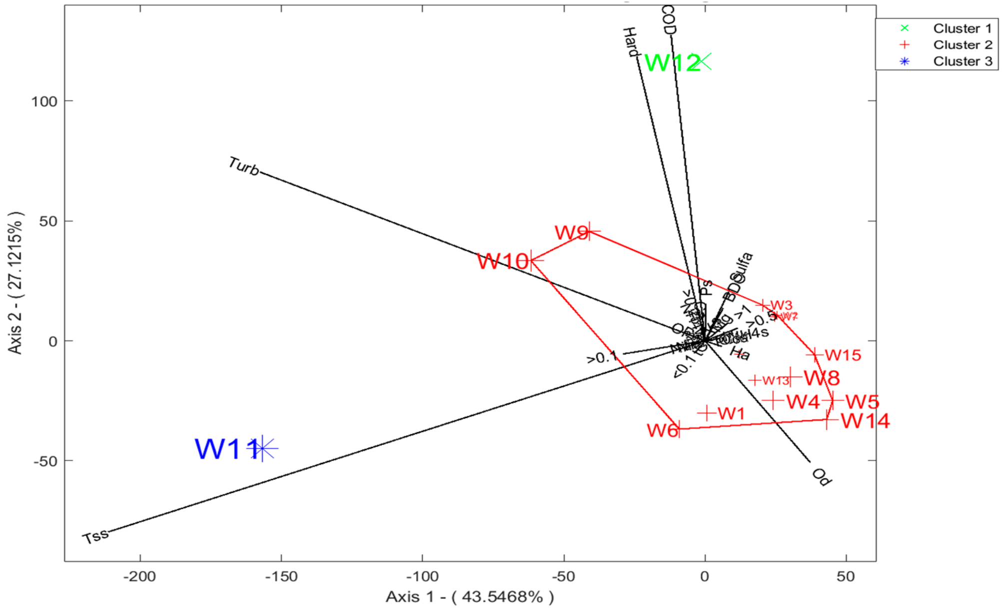

Figure 4. Biplot result of wetlands and physicochemical variables shown in axes 1 and 2, excluding the most representative variables.

4. Discussion

In general, the 16 bofedales of the Chimborazo Fauna Production Reserve present a similar number of species. with a total of (63 vascular, 12 bryophytes, and 4 pteridophytes) and 1 lichen, belonging to 64 genera and 35 families; a pattern typical of Andean paramos that are characterized by a floristic diversity richer in species than that of any other tropical-alpine ecosystem [60–62].

Bofedales are usually complexes of different plant communities whose composition and abundance are related to the amount and availability of water [63]. Vegetation is directly related to macroinvertebrate microenvironments [64]. Several authors have suggested that compositional changes in vegetation are mainly determined by the elevation gradient [65,66].

In this study, we determine the relative contribution of variables driven by natural impact [67] and the effect of environmental filters (water and soil), considered decisive factors in shaping plant diversity patterns and the ecology of these bofedales in general [14–16,27–29]. As shown by studies by Scheffer [68], macrophyte cover and diversity contribute to the structural heterogeneity of the aquatic environment and thus may be guiding factors for system functioning [69,70] and the abundance and diversity of higher trophic levels [71].

In this study, soil properties between habitats were markedly different. To find a possible structure in the variability of the database, a principal component analysis (PCA) was performed. This analysis showed that the first three dimensions explained 89.42% of the total variation in the data. Thus, it was shown that in the relative contribution of soil Sulfates and Biochemical Oxygen Demand had the lowest loadings in PC1, while Altitude, Electrical Conductivity, Potassium, and Phosphorus had the highest loadings in PC2.

The latter improves the efficiency of soil microbial decomposition [34]. Such a trend could be the result of higher plant biomass and high nutrient content [72]. In their study, Scheffer [68] determined that soil cover was a more useful indicator than diversity indices or plant community composition in terms of water requirements.

However, this result contrasts with the findings of research conducted in cultivated soils and with the presence of afforestation. For example. Yang et al. [73] showed that in cultivated land, OC. TP. C/N, and OP levels predominate, unlike the studies of Yu et al. [74] and Fang et al. [75].

A fundamental aspect of aquatic systems are the abiotic characteristics of the water, which are generally influenced by the nature of the substrate; however, some may have variations related to the increase of organic matter. In this study, in terms of water circulation, temperature did not vary significantly between wetlands. However, this parameter is closely related to dissolved oxygen and BOD; bacteria and microorganisms develop rapidly in warm water; at cold temperatures, the concentration of dissolved oxygen is higher and the probability of survival of aquatic species is greater [76].

Conductivity remained in the range 143.50–209 µS/cm being the highest reported in the Casa Condor BI wetland; it corresponds to the hardness of water with high calcium content [77]. The concentrations of n-nitrates in the samples analyzed were less than 0.70 mg/L suggesting that the contribution of discharges of this compound is minimal. Research carried out in Uruguay for surface waters reports concentrations of less than 2 mg/L of n-nitrate, thus reporting that levels of less than 3 mg/L could be considered characteristic of natural waters [78,79]. Nitrate showed a tendency to be negatively correlated with aquatic plant cover and aquatic plant species richness. For example, a study by Coronel [80] indicated that concentrations of this nutrient appeared to be determined by aquatic plants rather than the nutrient limiting vegetation growth.

Dissolved oxygen is an indicator of organic matter contamination; low concentrations of this parameter can be located where organic matter is decomposing, meaning that bacteria that use oxygen to break down waste are also low in warm, slow-moving waters [81]. Waters with dissolved oxygen concentrations above 4.1 mg/L are considered good quality; in the RPFCH wetlands, DO concentrations remained above 6.11 mg/L [75].

Practically, for the PCA with water parameters in the wetlands, Ca presented the highest loads, while pH showed the lowest loads, perhaps because the main sources of hydrogen ions supplied to the wetlands are the result of rainfall runoff input, nitrogen immobilization, carbonic acid dissolution, organic acid dissociation, and sulfur oxidation in low water conditions [28,82], as demonstrated in a study by Yabe et al. [83], where pH values gradually decreased due to the above factors.

Both the chemical characteristics of the water and the aquatic plant communities present in the bofedales of the Chimborazo Fauna Production Reserve seem to respond to a mineralization gradient (as indicated by high values of electrical conductivity and dissolved ions). From a conservation point of view, the wetlands studied harbor an important percentage of the country's native plants. In addition, due to the geographic location of the wetlands of the RPFCH, these areas offer an ideal system for the study of meta-communities (dispersal-linked communities) [84].

5. Conclusions

This research focused on establishing the relationship between plant species composition and the physicochemical characteristics of water and soil. Seventy-nine plant species were identified (62 vascular, 12 bryophytes, 4 pteridophytes, and 1 lichen). In the aquatic environment, seven vascular plants, recognized as macrophytes, were recorded. The results show a great heterogeneity in the soil, water, and vegetation characters, as they respond to a mineralization gradient (as indicated by the high values of electrical conductivity and dissolved ions). Additionally, it was observed that the total amount of soluble solids that characterizes the Los Hieleros wetland (W11) is independent of hardness and chemical oxygen demand, which correlate with each other and better describe the Pachancho wetland (W12). The highest degree of turbidity corresponds to the Cóndor Samana (W9) and Portal Andino (W10) wetlands. The Culebrillas (W6), Puente Ayora ANI (W14), and Pampas Salasacas (W1) wetlands are characterized by the presence of dissolved oxygen, so it is assumed that these are the wetlands with the best water quality. Consequently, it is imperative to redouble efforts to describe the ecology and status of these high Andean wetlands in order to promote their conservation.

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Appendix A

Table A1. Characterization of wetlands.

Bofedal	Province	Latitude	Longitude	Altitude (m.a.s.l.)	Total Area (ha)	Ecological Classification
Los Hieleros ANI	Chimborazo	745,741	9,833,916	4442	25.67	Subnival evergreen moorland grassland and shrubland
Culebrillas IA	Chimborazo	735,446	9,831,848	4160	13.31	Páramo flooded grassland
Casa Cóndor BI	Chimborazo	739,244	9,831,672	4008	9.40	Páramo flooded grassland
Lazabanza BNI	Tungurahua	746,734	9,850,338	4039	26.46	Subnival moorland humid grassland
Cóndor Samana BI	Tungurahua	751,109	9,839,489	3825	21.36	Páramo upper montane moist upper montane grassland
Pampas Salasacas BI	Tungurahua	754,972	9,845,283	3854	154.40	Páramo upper montane moist upper montane grassland
Río Blanco AI	Tungurahua	746,179	9,849,003	4016	65.44	Evergreen shrubland and moorland grassland
Mechahuasca ANI	Tungurahua	743,954	9,844,037	4240	35.48	Páramo Grassland
Portal Andino AI	Chimborazo	750,019	9,837,891	4120	7.62	Subnival evergreen grassland and shrubland of the moorland
Cruz del Arenal ANI	Bolívar	731,162	9,844,778	4240	57.75	Subnival evergreen grassland and shrubland of the moorland
Puente Ayora ANI	Bolívar	728,478	9,841,941	4105	12.19	Subnival evergreen grassland and shrubland of the moorland
Puente Ayora BNI	Bolívar	726,486	9,839,401	3842	0.29	Evergreen shrubland and moorland grassland
Puente Ayora AI	Bolívar	728,013	9,841,127	4120	12.84	Subnival evergreen grassland and shrubland of the moorland
Pachancho BI	Bolívar	728,315	9,847,854	4040	8.78	Subnival evergreen grassland and shrubland of the moorland
Cruz del Arenal BNI	Bolívar	732,671	9,840,421	4120	18.78	Páramo upper montane moist upper montane grassland

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