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Colorado River (Argentina) Water Crisis Scenarios and Influence on Irrigation Water Quality Conditions

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Abstract: The characterization and evaluation of water quality in the Valle Bonaerense del Río Colorado (VBRC), Buenos Aires, Argentina, is necessary, given the immense importance of this region for sustaining the population livelihoods and maintaining the ecological balance, especially in the face of drought and climate change scenarios, and loss of crop production yields. This study evaluated the possible reuse of drainage canals from the perspective of their use for irrigation. Surface water samples were collected at four sampling sites during 2015–2021, one over the Colorado river entering the VBRC, and the remaining three drainage canals flow into the Atlantic Ocean. These physicochemical parameters were performed following the protocols proposed using standard methods: total dissolved solids, pH, electrical conductivity (EC), calcium, magnesium, sodium, potassium, carbonates, bicarbonates, chlorides, sulfates and sodium adsorption ratio were analyzed and classified. The irrigation water quality index (IWQI), principal component analysis, hierarchy of classes analysis and statistical analysis were applied to the dataset. The general hydrochemistry of the VBRC river water indicates a slightly alkaline nature, with a mean pH value of 8.03, and the predominance order of the major ions follows the pattern of $Na^+ > Ca^{2+} > Mg^{2+} > K^+$, and $SO_4^{2-} > Cl^- > HCO_3^- + CO_3^{2-}$ for the anions. For the IWQI, 88.06% of the samples analyzed were classified as safe water for irrigation, and a theoretical yield loss was estimated for crops considering the salinity variable, with vegetables showing the highest losses. The surface water from rivers increases the EC due to the decrease in its discharge because of the water crisis affecting Latin America. Water reuse could be useful for one of the three drainage canals. This study concludes that the reuse of drainage water (S2) has great potential as an adaptation strategy to address the water scarcity and climate change challenges in the Colorado river basin. The research highlights the importance of considering this alternative to achieve sustainable water management in the region. Moreover, the data obtained from the study can be used for making policy and resource management decisions. In view of the possible scenarios of low water flow and increases in the EC values, it is recommended to reorient agricultural production toward crops with higher tolerance to salinity as an alternative, to ensure the sustainability and viability of production in the basin.

Keywords: water quality assessment; irrigation; water salinity; water crisis; crops; yield

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Citation: Trillini, M.; Pierini, J.O.; Vallese, F.D.; Dunel Guerra, L.; Pistonesi, M.F. Colorado River (Argentina) Water Crisis Scenarios and Influence on Irrigation Water Quality Conditions. *Sustainability* **2023**, *15*, 8457. https://doi.org/10.3390/su15118457

Academic Editor: Abel Silva Vieira

Received: 23 February 2023
Revised: 12 May 2023
Accepted: 18 May 2023
Published: 23 May 2023

1. Introduction

Throughout history, crop irrigation has played a key role in feeding the world's population, and is expected to play an even greater role in the future. However, good-quality irrigation water supply is likely to decrease in several regions as a result of the increasing municipal, industrial and agricultural competition [1–3]. The development of irrigated agriculture under certain conditions, the constant need to increase crop production and the decreasing availability of water for such purposes urge the focus on practices that lead to a rational and adequate use of water [4]. Quality and quantity optimization of water supply to the soil is of pivotal importance to replenish the water required for crop development and production [5,6]. The adoption of water-saving techniques either to mitigate the effects of climate change or release water that would allow for the expansion of cultivated areas is increasingly encouraged [7].

Agriculture is one of the most important sources of water consumption on the one hand, and water pollution on the other. Water planning and management cost-effective water for irrigation purposes is necessary to ensure sustainable agriculture [8]. In turn, the use of low-quality water in irrigation has been the main cause of the deterioration of soils and the agricultural crops growing on them [9].

In developing countries such as Argentina, agriculture is the major source of the economy because the agricultural sector is the main contributor of foreign exchange to the country, in addition to being an important generator of jobs [10]. Climate impacts on global crop yields could also induce changes in global agricultural trade patterns that increase pressure to produce water-consuming crops in Argentina in a handful of critical basins, including the Colorado basin [11].

The water quality of a hydrographic basin could be affected by natural and/or anthropogenic factors, which could be either direct, such as pollutant discharges, or indirect, such as rainfall, climate change, etc. It is therefore necessary to store information on water quality conditions and how it changes over time, for the protection and quality control of the water resources [12,13].

The Colorado river in Argentina originates at the confluence of the Grande (34.80 $m^3 s^{-1}$ average) and Barrancas (35.8 $m^3 s^{-1}$ average) rivers, 835 m above sea level. Its waters are shared by the provinces of Mendoza, Neuquén, La Pampa, Río Negro, and Buenos Aires. From its origin in the Cordillera de los Andes to its discharge in the Atlantic Ocean in a northwest–southeast direction, it has an extension of 1200 km, of which 920 km correspond to the Colorado river. Its basin generates an annual discharge of 143.5 $m^3 s^{-1}$, occupying a total area of 47,459 km^2 [14]. Its regime is nival, with floods that begin in October or November and extend until January or February, depending on snow accumulation and weather conditions. Its waters are mainly used for irrigating crops, supplying drinking water to the towns nearby, drinking water for livestock and industrial purposes. The basin has experienced a severe water crisis due to the declining water flows and increased water demand for agriculture and industry. Climate change has exacerbated the water crisis in the region, as it has caused a decrease in precipitation and increased temperatures, leading to increased evaporation and a reduction in water flows. In addition, water management has been inadequate, and the lack of water resource management measures has exacerbated the water crisis in the region [15].

The basin includes the Casa de Piedra Dam located in La Pampa province, 367 km from the source of the river, a vital hydraulic infrastructure for the Colorado river basin in Argentina. Since its construction in 1990, the objectives were: flow regulation to meet the irrigation needs of an area of great agricultural development, provide water to populations, generate hydroelectric power and attenuate floods in the lower course of the Colorado river. It is also the first and only interprovincial basin in Argentina with a program for the qualification of irrigation areas and a flow distribution agreement. It should be noted that the water flow downstream of the dam is directly affected by the reservoir's discharge, underscoring the importance of effective management to ensure a balance between water supply and resource conservation in the region [11,16].

The quality and quantity of water from the river that enters the VBRC has a significant impact on the yields obtained from the crops sown in this area. The importance of this water resource is decisive in terms of the added value obtained from agricultural production. This is finally reflected in the values being marketed, thus generating a fundamental contribution to the regional gross domestic product (GDP). Furthermore, the agricultural production of this region is destined for exportation, thus bringing foreign currency into the country.

It is essential to carry out an exhaustive evaluation of the hydrochemistry of the Colorado river water throughout the irrigation cycle. Its influence on the main crops of the region and drainage canals can contribute to the identification of possible losses in crop yields and the proposal of different management strategies and/or changes in long-term agricultural production. In parallel, it is also important to collect information regarding the chemical characterization of discharges into the sea and the contribution of pollutants discharged into the riverbed.

In the VBRC, the irrigation water concession system is administered through the Corporación de Fomento del Valle Bonaerense del Río Colorado (CORFO Río Colorado). The irrigation water quality, crop yields and hazards associated with soil characteristics are complex phenomena that involve the analysis of several variables. As such, the use of a water quality index provides a single number that expresses the overall water quality at a given place and time as a function of the intervening parameters [17]. The aim of the water quality index is to turn complex data into information that is easily understood and used by the public [18,19]. It should be noted that no studies have been carried out to date on the irrigation water quality index (IWQI) relating crops to irrigation water quality in the VBRC [20–22].

Sampling at irrigation sites and drainage canals, also called water collectors, seems to be an excellent source of information for the local and temporal insight into the water status of the rivers in order to monitor their water quality [23]. Multivariate statistics, of which the use has been increasing over time, are the most common methods for the processing and analysis of this information [24–26]. As they operate with a large volume of spatial and temporal data, they are used to carry out studies on water quality and ecological status. Further different statistical techniques, such as a class hierarchy analysis (HCA), principal component analysis (PCA), factor analysis (FA) and discriminant analysis (DA), have been used to perform this type of study because they have the capacity to assess temporal and spatial variations in river water quality, identify the possible sources of water pollution and cluster monitoring stations into groups with similar characteristics [27–31].

Due to the water crisis of the Colorado river in 2015, an interdisciplinary framework agreement was created between the Universidad Nacional del Sur (UNS), Instituto Nacional de Tecnología Agropecuaria (INTA), Comisión de Investigaciones de la Provincia de Buenos Aires (CIC) and CORFO, to promote the development of research and carry out studies aimed at improving the efficiency of water use and preservation of water resources in the VBRC. This work is part of the agreement.

The purpose of this study is to improve the understanding of hydrologic dynamics and analyze irrigation water quality in the lower Colorado river basin during a 7-year period (2015–2021). To this end, the IWQI, HCA and hydrosaline analysis of the waters were carried out to estimate their influence on crop productivity in the VBRC. Water quality from the drainage canals flowing into the sea was also analyzed to evaluate their possible reuse as irrigation water, as well as identify their dispersion on the coast due to the potential discharges produced upstream.

2. Materials and Methods

2.1. Study Area

The VBRC, which is located in the south of Buenos Aires province, Argentina, has developed as an important irrigation area for agricultural production. It extends from Meridian V, the western limit of Buenos Aires province, to the maritime coast of the Atlantic Ocean toward the east. It includes the cities of Pedro Luro, Hilario Ascasubi, Villalonga and Mayor Buratovich, some of them on the left and the other on right banks, respectively, of the Colorado river, covering an area of 535,000 ha, of which 137,145 ha are used for irrigation (Figure 1) [32,33].

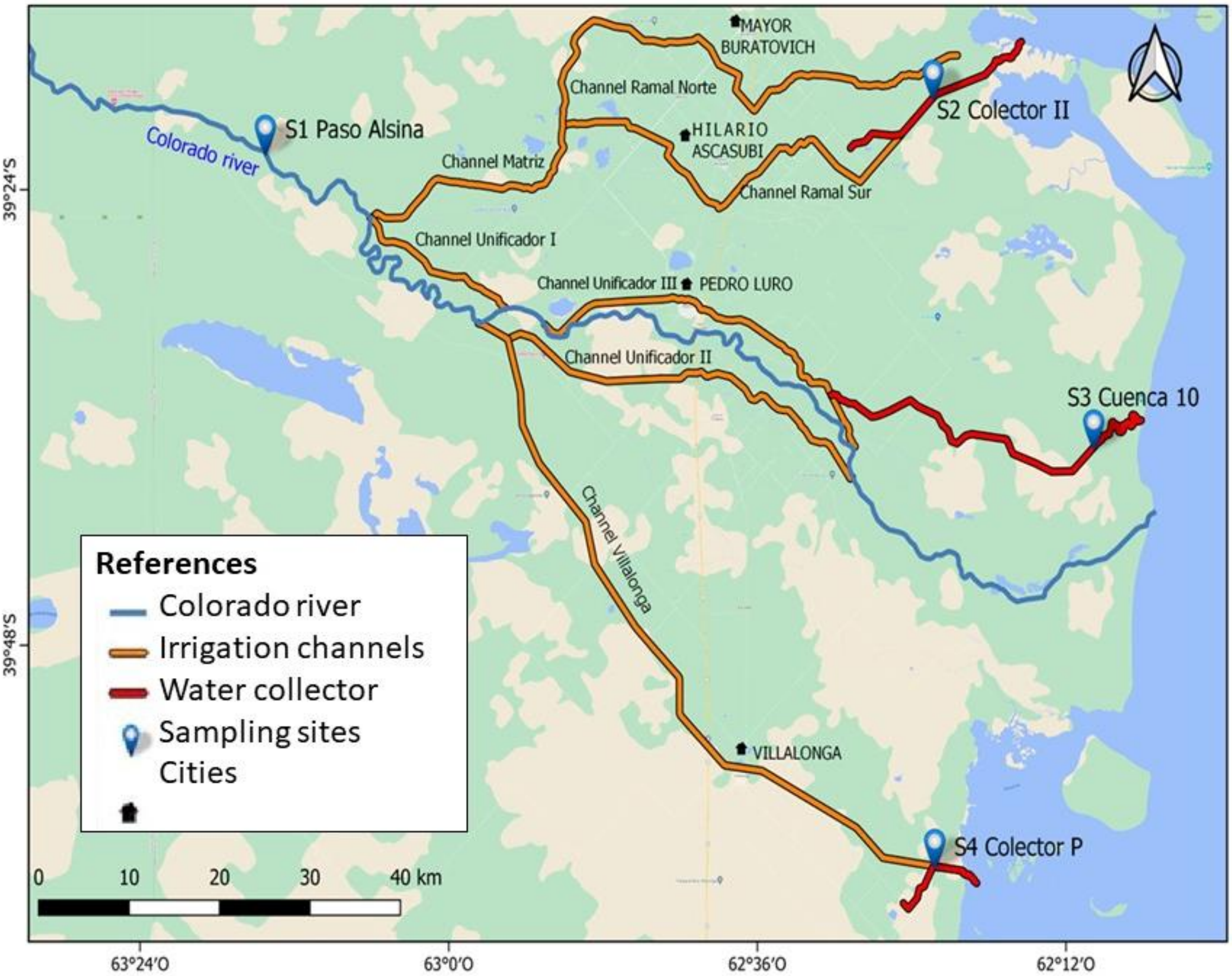

Figure 1. Sampling sites in the VBRC area.

The area has a temperate semi-arid regime, with rainfall that barely exceeds 500 mm per year. Rainfalls are characterized by their irregularity, both in the millimeters accumulated annually and their distribution (data provided by the Instituto Nacional de Tecnología Agropecuaria (INTA) Hilario Ascasubi Meteorological Station). This is the reason why most of the crops grown in the VBRC require irrigation water to complete their cycle. Its soil is predominantly sandy, which allows for the adequate growth of a wide variety of crops, including pastures, cereals and vegetables, with onion being the main crop in the VBRC [16].

The following four sampling sites located in the VBRC were selected, one corresponding to river water and the other three to water collectors or drainage canals flowing into the Atlantic Ocean (Figure 1).

- Station 1 Paso Alsina (S1): 39°22′02.60″ S 63°14′16.26″ W. This area is located in the province of Buenos Aires, about 75 km west of the city of Pedro Luro. S1 was created in 1982, with the objective of regulating the flows of the lower basin, adjusted to the demands of the irrigation system, thus improving the performance of the Casa de Piedra Dam. This site is a strategic place located at the entrance of the VBRC. Its water, which are used for crop irrigation in the area, are distributed through the irrigation canals.

- Station 2 Colector II (S2): 39°19′08.03″ S 62°22′20.39″ W. This area is located 22 km to the southeast of Mayor Buratovich city and 75 km from S1. It collects drainage water from the northern area of the VBRC.
- Station 3 Cuenca 10 (S3): 39°37′35.93″ S 62°09′51.07″ W. This area is located 46 km to the east of the Pedro Luro city and 96 km from S1. It collects drainage water from the southeast area of the VBRC.
- Station 4 Colector P (S4): 39°59′46.63″ S 62°20′33.28″ W. This area is located 25 km to the southeast of the Villalonga city and 104 km from S1. It collects drainage water from the southern area of the VBRC.

The basin has ecoregions [34] classified as Semiarid Pampa Savannas and Grasslands. There is a west–east vegetation gradient in the Colorado river basin due to the tecological changes associated with variations in the altitude, from 4700 amsl in the west to sea level in the east, and variations in precipitation. From a phytogeographical point of view, the study area is divided into the Espinal Province [35], where the predominant landscape is flat or gently undulating plains, occupied by lowland forests, savannas and grasslands. Although there are still areas with stunted forests, agriculture, grazing and logging have fragmented the original ecosystem, modifying the composition of the natural grasslands.

In the study area, there are three edaphic domains called Aridisols, Entisols and Mollisols. The soil characteristics are moderately or poorly developed, with coarse textures, scarcely provided with organic matter, without the presence of clay accumulation layers and mainly with the presence of petrocalcic layers and dune areas. The current land use is for agriculture purposes, and sheep and cattle grazing. In the western zone, it is mainly destined to the latter use, while in the eastern region it is used for both activities [36].

The exposed stratigraphic sequence extends from the Upper Miocene to the present. The oldest units present are constituted by siltstones and sandstones of the Cerro Azul Formation of the Upper Miocene age; sandstones, siltstones, claystones and cinerites of the Upper Miocene-Lower Pliocene of the Río Negro Formation; and fluvial deposits of the Middle Pliocene-Pleistocene. The column is completed with Pleistocene and Holocene units, which are widely distributed in the region.

In the region, two well-differentiated geomorphological environments can be recognized: one is clearly continental with a landscape that responds mainly to fluvial processes, and the other coastal, where the most significant modeling agent is the marine one. In both cases, wind processes have acted in a subordinate way [37]. In the continental environment, they are represented by fine eolian sediments, sandy deposits arising from wind action (dune fields), and colluvial, alluvial and evaporitic deposits. In the coastal environment, there are fine sediments corresponding to tidal plain and estuarine environments, sandy deposits that form beaches, beach barriers, coastal strands and barrier islands, and gravel deposits that form coastal strands [38]. The different rock types and the rock–water interaction of geological formations, combined with ion circulation, are main factors influencing the geochemistry of the river surface waters. The elemental composition in the Colorado river basin suggests that the major ions in the lower end of the VBRC are dominated by evaporite dissolution and silicate weathering [39–42].

2.2. Sample Collection and Laboratory Analysis

Water samples were extracted monthly between August 2015 and February 2021, which includes six irrigation periods in the above-mentioned four sampling sites (Figure 1). Water sample extraction was carried out following the general guidelines proposed, using standard methods for the examination of water and wastewater [43]. The water samples were collected directly from the river in high-density polyethylene bottles with a capacity of 500 mL. The river water samples were collected from each site at adepth of 20 cm beneath the surface. Prior to the sample collection, each sample bottle had been washed with nitric acid and then rinsed with distilled water. The bottles and caps were rinsed three times with sample water and filled to within one to two inches of the top. During sampling, an icebox cooler was used in the field to keep and transport the samples. The samples were transported to Hilario Ascasubi and the determination of anions and cations was carried out at the Laboratory Water Chemistry, Instituto Nacional de Tecnología Agropecuaria. In the laboratory, the water samples were immediately filtered through a 0.45 mm cellulose acetate membrane filter. All the samples were kept refrigerated at 4 °C before analysis. The samples were analyzed within 7 days. The parameters analyzed included: total dissolved solids (TDS), pH, electrical conductivity (EC), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), potassium (K^+), carbonates (CO_3^-), bicarbonates (HCO_3^-), chlorides (Cl^-), sulfates (SO_4^{2-}) and sodium adsorption ratio (RAS). The pH, EC and TDS were measured in situ with a multiparameter water quality meter (HI 9828, HANNA Instruments, Limena, Italy). Other measurements of the in situ parameters, such as rainfall and flow rate, were carried out using a standard rain gauge and a SIAP windlass, respectively.

2.3. Statistical Analysis of Data

Statistical analysis was applied to the data set using the Matlab® 2010a software for the hydrochemical dataset interpretation. The free Qualigraf 2017 water software was used to evaluate the dominant ions to establish quality analysis. The HCA and PCA were performed with the Matlab® 2010^a software.

2.4. IWQI Calculation and Development

To determine the suitability of water for irrigation (IWQI), we estimated the river water quality index (IWQI) using the methods outlined by Meireles et al. (2010) [44]. The calculation equation is as follows:

$$IWQI = \sum_{i=1}^{n} q_i * w_i \quad (1)$$

where n is the number of parameters, q_i is the quality parameter, and w_i is the standardized weighting unit for each parameter. First, the registered parameters were analyzed, and those that contributed the most to the irrigation variety were identified using tools such as principal components analysis (PCA) and factor analysis (FA), selecting the parameters: "Na^+", "Cl^-", "HCO_3^--CO_3^{2-}", "EC" and "RAS" for the corresponding sampling stations. The values of qi and wi were subsequently estimated for each parameter, obtaining an IWQI based on the irrigation water criteria obtained by the University of California Consultants Committee (UCCC) and Ayers and Westcot (1999) [45].

$$q_i = q_{max} - \frac{\left[\left(x_{ij} - x_{inf}\right) * q_{iamp}\right]}{x_{amp}} \quad (2)$$

where q_{max} is the maximum value of qi for each class, x_{ij} represents the observed value of each parameter, x_{inf} refers to the lower limit value of the class to which the parameter belongs, q_{iamp} presents the amplitude of the class and x_{amp} corresponds to the amplitude of the class to which the parameter belongs. The upper limit was considered to be the highest value determined in the analysis of the water samples required to evaluate the x_{amp} of the last class of each parameter.

According to the University of California Consultants Committee (UCCC), the values of q_i are estimated according to the amount of factor, the tolerance limit and the irrigation water quality parameters shown in Table 1. The water quality parameter, IWQI, is a dimensionless number, and as the value of the parameter increases, the water quality becomes better.

Table 1. Limit values of parameters for the calculation of q_i. The brackets [) includes data, and no brackets do not include data.

q_i	EC (µS cm^{-1})	SAR (mmol L^{-1})$^{1/2}$	Na$^+$ (mg L^{-1})	Cl$^-$ (mg L^{-1})	HCO$_3{}^-$ (mg L^{-1})
85–100	[200 750)	[2 3)	[46 69)	[35.5 140)	[61 91.5)
60–85	[750 1500)	[3 6)	[69 138)	[140 248.5)	[91.5 274.5)
35–60	[1500 3000)	[6 12)	[138 207)	[248.5 355)	[274.5 518.5)
0–35	EC < 200 or EC ≥ 3000	SAR < 2 or SAR ≥ 12	Na$^+$ < 46 or Na$^+$ ≥ 207	Cl$^-$ < 35.5 or Cl$^-$ ≥ 355	HCO$_3{}^-$ < 61 or HCO$_3{}^-$ ≥ 518.5

The parameter weight, w_i, used in the IWQI was obtained through (PCA/FA), by summing all the factors multiplied by the explained variance of each parameter. Finally, the values of w_i (Table 2) were normalized, so that their sum is in unity.

$$w_i = \frac{\sum_{j=1}^{k} F_j A_{ij}}{\sum_{j=1}^{k} \sum_{i=1}^{n} F_i A_{ij}} \quad (3)$$

Table 2. Relative weight (w_i) of each chemical parameter calculated based on the standard values reported by the Food and Agriculture Organization of the United Nations (FAO, 1994).

Parameters	FAO (1994)	Relative Weights (w_i)
Sodium (Na$^+$)	920 mg L^{-1}	0.204
Carbonate + Bicarbonate (CO$_3{}^{2-}$ + HCO$_3{}^-$)	640 mg L^{-1}	0.202
Chlorine (Cl$^-$)	1065 mg L^{-1}	0.194
Sodium adsorption ratio (SAR)	15 (mmol L^{-1})$^{1/2}$	0.189
Electrical conductivity (EC)	3000 µs cm^{-1}	0.211
-	-	$\Sigma w_i = 1$

According to this equation, w_i and F_j correspond to the relative weight of the parameter for the water quality index and the constant value of component j, respectively. A_{ij} defines the extent to which parameter i can be explained by factor j, i represents the number of the selected physicochemical parameters varying from 1 to n and j is the number of the factors chosen (varying from 1 to k). Table 3 shows the relative weight of each parameter chosen, and by applying (1), (2) and (3), the IWQI values for each class are obtained. The main characteristics of each of them can also be observed, considering the risks of salinization, decreased infiltration and plant toxicity, in addition to indicating the causes of water use restriction [44].

2.5. The Calculation and Development of HCA and PCA

The results of the water sample analyses for each monitored station were subjected to statistical methods such as multivariate analysis. The advantages are that they provide a useful method for establishing a comprehensive understanding of both spatial and temporal differences in physicochemical qualities over the study period for the Colorado river water. Pearson's correlation was first employed to establish the strength of the relationships between two or more of the parameters studied, and subsequently HCA, was applied based on Ward's algorithmic linkage method and Euclidean distance. Prior to running PCA, Kaiser–Mayer–Olkin (KMO) tests and Barlett's test of sphericity were applied to test the adequacy of the data significant at $p < 0.05$ for the PCA analysis to be appropriate, with an objective of classifying the samples according to their variation in the content of physicochemical parameters. The KMO sample adequacy measure tests whether the partial correlations between variables are sufficiently small. It allows for comparing the magnitude of the observed correlation coefficients with the magnitude of the partial correlation coefficients. The KMO statistic varies between 0 and 1; it is advised that if KMO $\geq$ 0.75, the idea of performing PCA is good. If 0.75 > KMO $\geq$ 0.5, the idea is acceptable and if KMO < 0.5 it is unacceptable. In our case, the KMO values obtained with the significance of 0.0 are indicative of the validity of the PCA application, as all of them meet the requirements for the analysis (Table 4). Therefore, our analysis meets the criteria of sampling adequacy. Bartlett's test of sphericity was significant (<0.05), rejecting the null hypothesis that the correlation matrix is an identity matrix, meaning that all the variables are uncorrelated. Furthermore, the test also shows that the Chi-square values are higher than 690.460, with a significant value of 0.000, so it can be said that the correlation matrix is not an identity matrix.

Table 3. IWQI categories and classifications.

Irrigation Water Quality Index (IWQI)			
Index Scale	**Water Quality**	**Soil**	**Plant**
85–100	No Restriction (NR)	Water can be used for almost all types of soil. Soil is exposed to lower risks of salinity/sodicity problems.	No toxicity risk for most plants.
70–85	Low Restriction (LR)	Irrigated soils with a light texture or moderate permeability can be adapted to this range. Soil leaching is recmmened to avoid soil sodicity in heavy textures.	No toxicity risk for most plants.
55–70	Moderate Restriction (MR)	The water in this range would be better used for soils with moderate-to-high permeability values. Moderate leaching of the salts is highly recommended to avoid soil degradation.	Plants with moderate tolerance to salts may be grown.
40–55	High Restriction (HR)	This range of water can be used in soils with high permeability without compact layers. A high-frequency irrigation schedule is required.	Plants with a moderate-to-high tolerance to salts.
0–40	Severe Restriction (SR)	Using this range of water for irrigation under normal conditions should be avoided.	Only plants with a high salt tolerance.

Table 4. KMO and Bartlett test results.

Station	**KMO Test**	**Bartlett Test (Chi-Square)**	**df.**	**Signif.**	**Evaluation Criteria**
S1	0.615	690.460 (73.312)	10	0.000	Acceptable
S2	0.807	1420.300 (73.312)	10	0.000	Good
S3	0.735	1522.400 (73.312)	10	0.000	Acceptable
S4	0.790	1417.300 (73.312)	10	0.000	Good

3. Results and Discussion

3.1. Hydrochemistry

The descriptive statistics of hydrochemical compositions relating the four sampling sites, including minimum, maximum, mean and standard deviation, are presented in Table 5. S1 is the sampling point located above the river at the water inflow to the VBRC, which is mainly used for irrigation water, while S2, S3 and S4 are water collectors, also called the drainage canals.

Table 5. Statistical values for the parameters quantified in the four stations.

		Station 1 Paso Alsina					Station 2 Colector II					Station 3 Cuenca 10					Station 4 Colector P				
Parameters	**Units**	**Min**	**Max**	**Mediane**	**Mean**	**Std**	**Min**	**Max**	**Mediane**	**Mean**	**Std**	**Min**	**Max**	**Mediane**	**Mean**	**Std**	**Min**	**Max**	**Mediane**	**Mean**	**Std**
Na^+	mg L^{-1}	119	211	158	158	23	454	1037	696	713	114	797	2592	1822	1832	429	494	2187	1474	1427	399
K^+	mg L^{-1}	3	5	4	4	0.5	5	13	8	9	2	7	84	60	57	19	7	29	14	14	5
Ca^{2+}	mg L^{-1}	73	158	129	129	18	143	339	250	252	38	232	1332	350	376	162	145	411	318	303	72
Mg^{2+}	mg L^{-1}	3	42	18	20	9	37	110	72	71	19	59	490	162	172	73	40	157	99	97	28
Cl^-	mg L^{-1}	171	325	226	235	36	511	1494	818	854	193	319	4255	2242	2435	788	625	3034	1684	1650	478
CO_3^{2-} + HCO_3^-	mg L^{-1}	91	159	117	118	15	173	307	224	226	30	145	351	261	255	49	144	289	210	212	39
SO_4^{2-}	mg L^{-1}	83	455	265	265	92	180	1603	885	909	320	649	2569	1359	1510	503	297	3212	1405	1404	592
HT	mg L^{-1}	330	484	403	403	41	686	1278	891	922	137	1028	5340	1546	1645	669	627	1540	1161	1158	240
EC	µs cm^{-1}	920	1940	1390	1416	202	3040	6850	4320	4436	892	5390	15,230	9995	9760	2152	3600	10,770	8105	7712	1946
pH	-	7.8	8.6	8.2	8.2	0.2	7.8	8.5	8.1	8.1	0.2	7.7	8.5	8.2	8.2	0.2	7.5	8.5	8.0	8.0	0.2
TDS	mg L^{-1}	700	1260	930	944	119	2040	4550	2995	3091	559	3200	9810	6585	6764	1652	2300	7800	5600	5349	1471
SAR	(mmol $L^{-1})^{1/2}$	2.5	4.5	3.5	3.4	0.5	7.5	12.8	10.2	10.3	1.2	7.9	25.5	20.9	20.0	3.9	8.6	25.0	18.6	18.0	3.7

In this study, the order of the predominance of the main ions for S1 and S2 follows the pattern of $Na^+ > Ca^{2+} > Mg^{2+} > K^+$, and $SO_4{}^{2-} > Cl^- > HCO_3{}^- + CO_3{}^{2-}$ for the anions. For S3 and S4, the order of predominance remains the same, except that Cl^- predominates over $SO_4{}^{2-}$. This may be due to the infiltrations of seawater, because it is an area near the mouth of the Atlantic Ocean or evaporite dissolution. The pH of the water was slightly alkaline, with a mean pH value between 8.0 and 8.2 for all stations. This value is within the FAO limit (range between 6.5 and 8.5). The slight difference in pH observed between the samples could probably be explained by the carbonate nature of the geological formations crossed by the waters. It should be noted that this distribution of anions and cations was only found in the Srou River and its tributaries [46], otherwise this ionic distribution is not very common.

From the spatial characterization, it was found that S1 represents a natural condition in very few agricultural activities. In contrast, S2, S3 and S4 are mostly affected by agricultural activities, because they collect leachate runoff from the fields, either through irrigation runoff, flooding or rainfall. This could justify the increase in chemical parameters in S2, S3 and S4 with respect to S1. Additionally, the ionic concentrations in the river water tend to increase with the increasing watershed area.

The EC value of S1 oscillate is from 920 to 1940 µs cm^{-1}, with a mean value of 1416 µs cm^{-1}, and this value is within the FAO limit, i.e., <3000 µs cm^{-1}, while the mean values of S2, S3 and S4 were 4436 µs cm^{-1}, 9760 µs cm^{-1} and 7712 µs cm^{-1}, respectively. The substantially elevated EC concentrations in the semi-arid segment of the downstream region in the drainage canals are probably due to the agricultural runoff, and excessive chemical weathering and physical erosion, along with evaporation–crystallization processes, enhanced by the decreased upstream river flow.

The high SAR value reduces the hydraulic conductivity of the soil texture, and thus decreases irrigation efficiency. For S1 = 3.4, S2 = 10.3, S3 = 20.0 and S4 = 18.0; however, the water is considered unsuitable for irrigation if the SAR is greater than 15 $(mmol\ L^{-1})^{1/2}$, as per the FAO guidelines.

A piper diagram graphically provides chemical information on the ionic content of the water analyzed. The predominant ions in the water entering the VBRC were determined to be calcium or magnesium sulfates and/or chlorides, and the three drainage water collectors are classified as sulfate and/or sodium chloride containing waters, as shown in Figure 2 below.

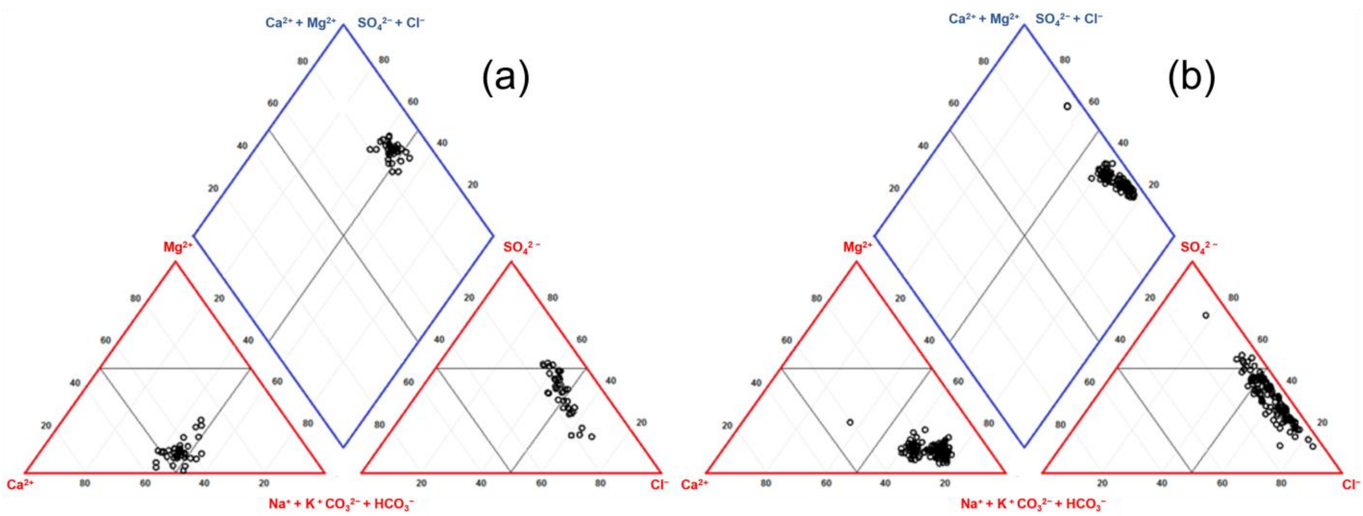

Figure 2. Piper diagrams. (**a**) Piper diagram for Station S1. (**b**) Combined Piper diagram for Stations S2, S3 and S4.

3.2. Relationship between Q, EC and Rainfall

Historically, the water flow entering the province of Buenos Aires is monitored at S1. This flow allowed for irrigating about 137.145 ha. However, a decade ago, the water level in the Casa de Piedra Dam was reduced due to the decrease in snowfall in the mountain range, possibly because of climate change and the increase in water consumption from productive activities [47,48]. Currently, during the 2019/2020 season, the irrigated area decreased to 81.400 ha, a significant loss of more than 59%, as a result of the water crisis and the successive migration of producers to other areas, looking for more favorable conditions for their production [49].

Since 1992, the Colorado river basin began to be regulated accordingly, and the average S1 flow during (1992–2014) reached 105.11 $m^3 s^{-1}$. Nevertheless, during the last six years, the river flow has become much weaker than before; 2015–2021 barely exceeded 53 $m^3 s^{-1}$.

Besides the problem of water scarcity, the reduction in flow has had an impact on the increase in water salinity, which endangers the sustainability of the irrigation system. The use of deficient quality irrigation water can trigger processes of physical–chemical degradation of the soil and/or loss of the crop yields [50].

Figure 3 shows the relationship between flow, rainfall and EC corresponding to the period studied in S1. Notably, in recent years, particularly since 2017, higher water conductivity values have been observed during the periods of low flow. However, this trend was not evident in previous years, likely due to the influence of external factors such as diffuse water inputs. On the other hand, the highest rainfall occurrence is recorded in the spring–summer, with fluctuating accumulated levels for each year (740 mm in 2015, 523 mm in 2016, 610 mm in 2017, 534 mm in 2018, 344 mm in 2019 and 365 mm in 2020), conforming to the data provided by the INTA Hilario Ascasubi.

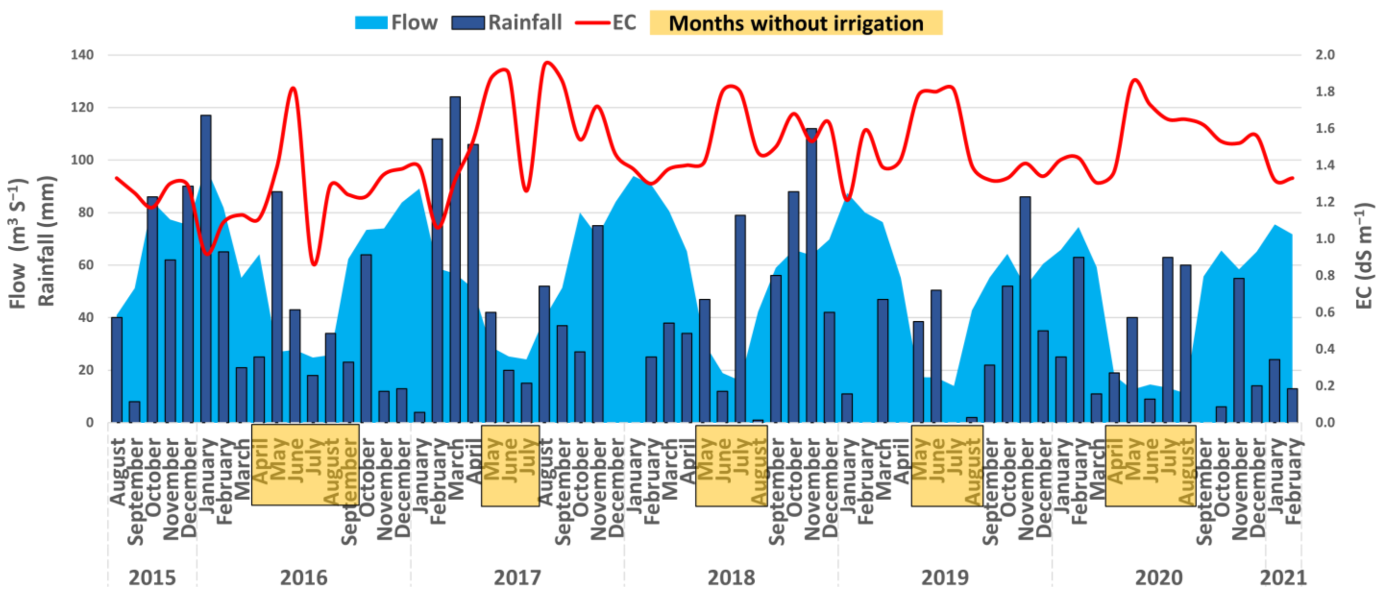

Figure 3. Hydrograph corresponding to S1.

It is important to note that the maximum floods shown in Figure 3 are directly related to the discharges from the Casa de Piedra reservoir located 420 km from S1. This reservoir regulates the river flow throughout the year, including the minimum flow of the water released by the dam. Therefore, reservoir discharges have a significant impact on the river flow and water level increases observed in the area. During the summer, this reservoir maintains an average flow of 56.71 $m^3 s^{-1}$, which sufficiently meets most of the water requirements of the main crops in the VBRC. It is significant mentioning that the amount of water circulating per unit of time in the system had a reduction of more than 45% during this period (2015–2021) in relation to historical values (1994–2021). Moreover, it should be considered that the flow expended at the Casa de Piedra is subject to the rainfall generated in the VBRC, evaluating the possibility of reducing the flows with the objective of maximizing the water reserves in the dam.

Nowadays, the Colorado river basin has been reported to have experienced one of the worst droughts recorded in the last 100 years. The entire VBRC irrigation system has been under water delivery restrictions for at least 10 years. These containment measures have made it possible to continue with irrigated production and at the same time, store water in the Casa de Piedra Dam, consequently providing predictability of the following campaigns.

3.3. Irrigation Water Quality Index

To simplify the interpretation of the recorded data, results have been adopted to assess the quality of a water course over the years. In simple terms, IWQI is a specific method used mainly for the evaluation of water quality for agricultural purposes, which expresses the water resource quality by integrating the measurements of certain water quality parameters.

For monitoring S1, 97.7% of the samples analyzed were classified as "unrestricted use" water. This means that there was no risk of toxicity in most plants (Table 3). The remaining 2.3% was classified as water with "low use restrictions".

Contrary to the data obtained in the S1 Paso Alsina, for S2 Collector II (Figure 1), 97.3% of the sample analyzed was classified as water with "high restrictions of use"; that is, there is a risk of toxicity for most plants. It should only be used by plants with a moderate-to-high salt tolerance. On the other hand, the rest of the samples were classified as water with a "moderate use restriction" and can be used to grow plants with a moderate salt tolerance.

Regarding S3 Cuenca 10 (Figure 1), 98.50% of the analyzed sample was classified as water with "high restrictions of use", indicating that for most of the plants, there is a risk of toxicity. It should therefore only be used for plants with a moderate-to-high salt tolerance. The rest of the samples were classified as water with a "severe restriction of use" and can only be used to grow plants with a high tolerance to salts (Table 3).

For S4 Collector P (Figure 1), 97.00% of the analyzed sample was classified as water with "high restrictions of use", i.e., not advisable for most plants/crops due to its severe toxicity; it should only be used on plants with a moderate-to-high salt tolerance. The rest of the samples were classified as water with a "moderate use restriction". This water can be used to grow plants with a moderate salt tolerance.

3.4. HCA (Class Hierarchy Analysis)

In order to characterize each region according to its physical and chemical properties (main ions) and determine groups that are internally homogeneous among themselves, cluster analysis was applied to the four monitoring stations using the hierarchical method. The temporal and spatial differences in the water and soil quality of an area are the base of distinguishing the groups from one another. This analysis was developed based on electrical conductivity, since the identification and development of salt-tolerant forage crops can help address the scarcity of good-quality water in many arid regions of the world where there are large reserves of saline and brackish water [28]. The resulting HCA dendrogram, statistically significant ($p < 0.05$) for the water quality data, is shown in Figure 4.

The dendrogram in Figure 4 shows that the clusters are grouped into two groups. Cluster 1 is formed from monitoring S3 and S4, which corresponds to water that does not have quality aptitudes for irrigation; in these drainage canals, important anthropogenic sources can be detected. In addition, in this area, contaminants due to soil leaching from intensive agricultural and livestock activities, are common sources of diffuse pollution. Group 2 consists of S1, corresponding to the Colorado river water and S2 drainage canal water, with relatively moderate levels of river pollution.

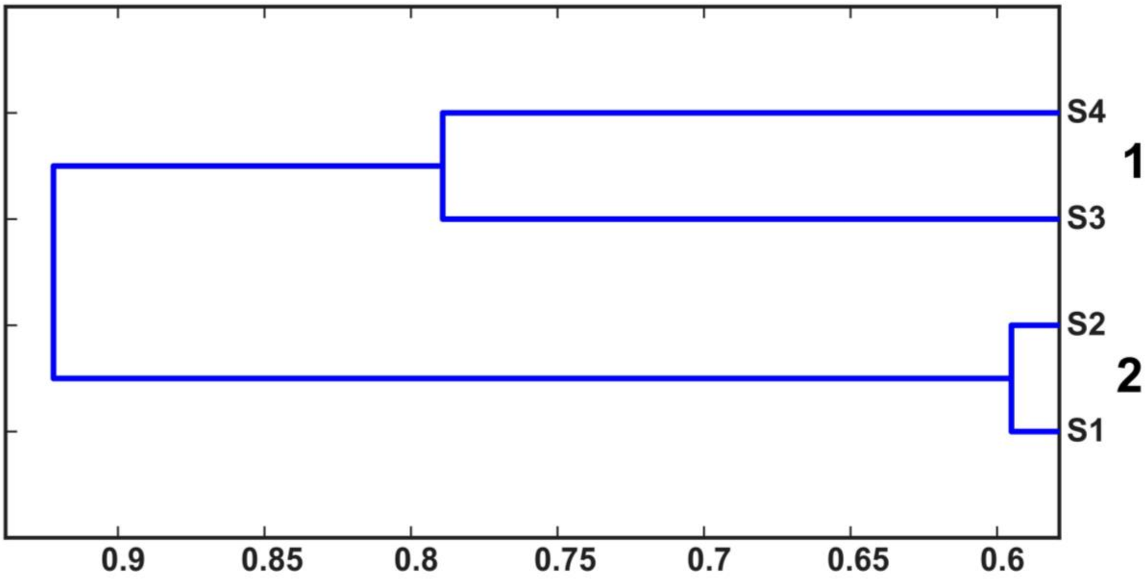

Figure 4. Dendrogram for the stations according to EC.

3.5. FAO Limits

Comparing the results obtained from the different sites showed a high content of the ion concentrations in both S3 and S4 samples that exceeded the limits established by the Food and Agriculture Organization of the United Nations [51]; therefore, they do not have enough aptitudes for irrigation. A different case was found for S2, where only three parameters (Mg^{2+}, K^+, TDS) exceeded the FAO values for good-quality irrigation water (Figure 5).

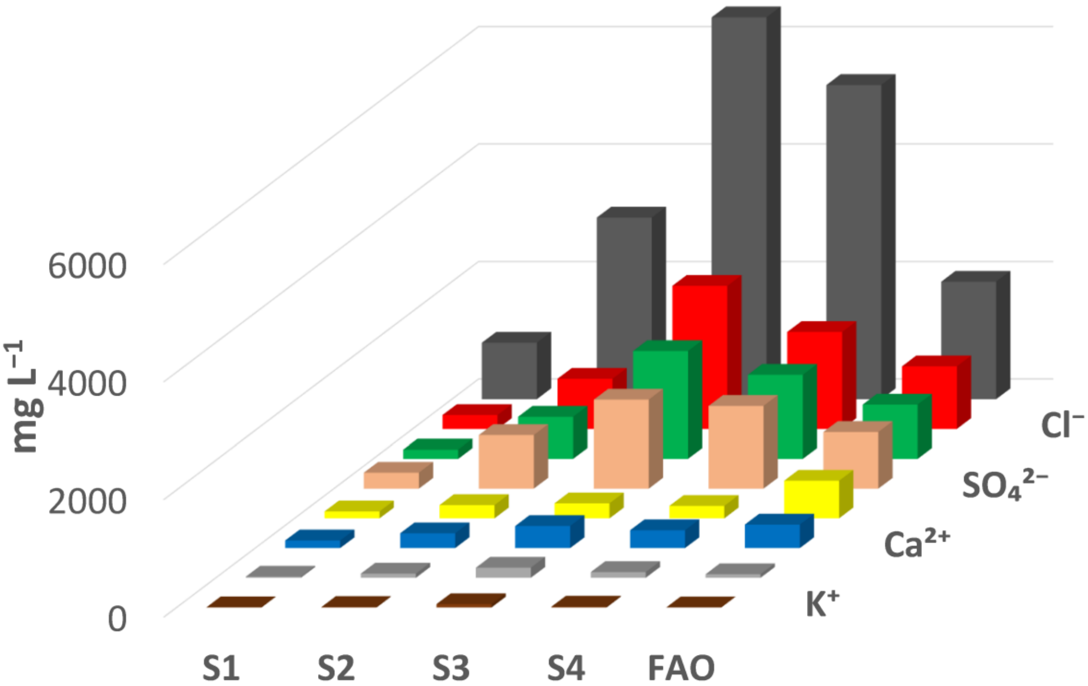

Figure 5. Mean values of ion concentration of S1, S2, S3 and S4, and the standards established by the FAO.

3.6. EC and SAR

The system proposed by the USDA Salinity Laboratory [52] classifies the water into five salt concentration categories (ECs) and four alkalinization risk categories (SARs), resulting in twenty water quality categories (Table 6 and Figure 6).

Table 6. Group Richard classification.

Class	Water Quality for Agriculture
C1	Low-salinity water, it can be used to irrigate most crops in most soils, with little risk of soil salinization incidents.
C2	Medium salinity water. It should be used with caution and can be used in sandy, loamy or clay soils when soil leaching is moderate. Crops with a low salinity tolerance can still be grown in most cases.
C3	High-salinity water. It can only be used in well-drained soils. Even in well-tended soils, special precautions must be taken to avoid salinization.
C4	Very-high-salinity water. It is generally not suitable for irrigation, but can be exceptionally used in permeable sandy soils, are well-tended and with abundant irrigation.
C5	Extremely-high-salinity water. This water can only be used in excessively permeable and very well-tended soils.
S1	Low-sodic waters. It can be used in almost all soils with little risk of forming detrimental levels of exchangeable sodium.
S2	Medium-sodic waters, with risk of sodicity for fine-textured soils and a strong cation exchange capacity. It can be used in coarse-textured soils or soils rich in organic matter, with good permeability.
S3	High-sodic water. There is a danger that harmful levels of sodium will form in most soils. They require special soil treatment (good drainage, leaching and the presence of organic matter).
S4	Very-high-sodic water, generally not suitable for irrigation, unless the overall salinity is low or at least medium. It can be used in very well drained soils rich in carbonates.

The water of S1 belongs to class C3 S1, i.e., high-salinity water that can be used for irrigation in well-drained soils using excess water volumes to wash the soil, and salinity-tolerant crops and low-sodium water, suitable for irrigation in most situations. In the case of S2, most of the samples correspond to section C4 S3, which indicates that only the plants with a high salinity tolerance, well-drained soils and leaching can be grown. Additionally, about 25% of the samples fell into the C5 category, which indicates that water can only be used in excessively permeable and very well-maintained soils.

3.7. Current Situation and Impacts on Agriculture

The VBRC economy depends mainly on irrigated agriculture. The influence of water resources directly affects the regional economy. The water crisis in the Colorado river basin, mainly caused by a significant reduction in snowfall in Cordillera de los Andes, has resulted in a reduction in productivity of the area.

At present, producers are looking for a palliative to the emerging shortage of water in the months of most demand due to the decrease in the flow of the Colorado river, through the adaption to use alternative sources of water for irrigation purposes, such as the use of water that is not normally used because it has a high concentration of salts. The same comes from main drainage canals, which the final stretch culminates in the Atlantic Ocean.

In order to evaluate the different agricultural campaigns, CORFO, together with the Economics Department of the Universidad Nacional del Sur, developed socioeconomic reports for the agricultural activity of the area from 1984 to 1985, to the present time [53].

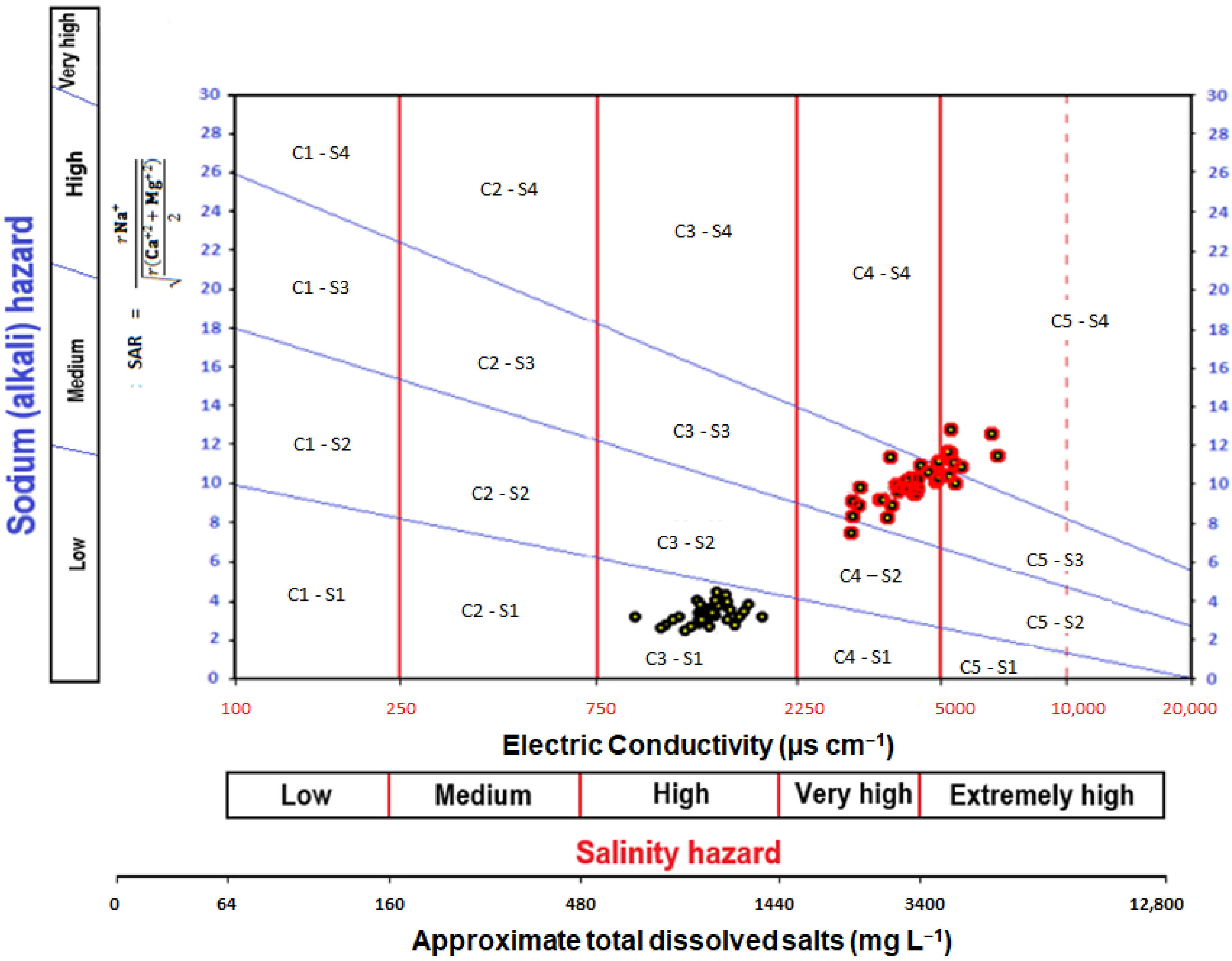

Figure 6. Richard's nomogram for S1 (**black**) and S2 (**red**).

These reports provide information on the gross value of irrigated production, which is adversely affected by the decrease in the irrigated area due to the water crisis. The scarcity of water could not only affect the irrigation map and extending irrigated area, but also businesses, the local metal–mechanic industry, dairy farms, and seed companies in the area, which would lead to the greater unemployment and emigration of producers to other areas with more favorable conditions for their production.

The quality of the irrigation water available to farmers in the basin has an important impact on the potential yield of the main crops grown in the VBRC. The crops under irrigation present different levels of sensitivity to salinity, defining Ayers and Westcot [45], the concept of relative tolerance to compare and select crops, in addition to establishing guidelines that allow for the classification into categories according to their degree of use restriction and in relation to certain potential problems. Therefore, it is important to emphasize that plants do not respond to salinity in a similar way. As shown in Figure 7, we can infer an order of tolerance from which the potential yield of the crops developed in the VBRC is restricted.

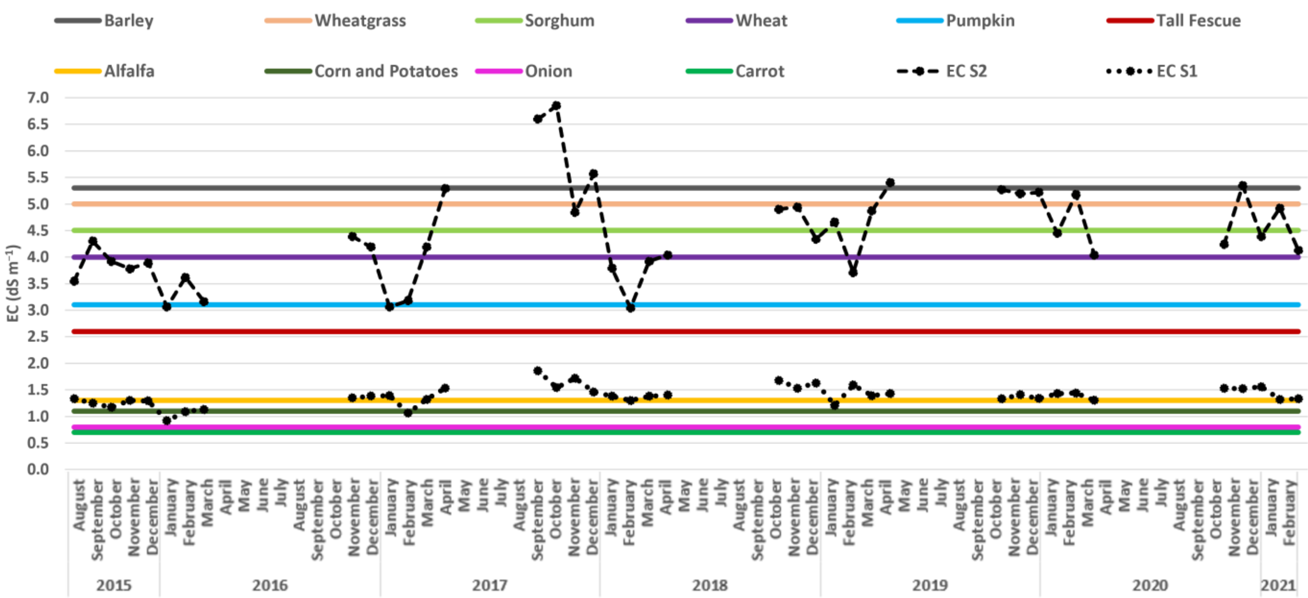

Figure 7. Salinity threshold value for crops produced in the VBRC in relation to the EC measured during the months of irrigation within the study period, for S1 and S2.

According to the classification proposed by Maas [54], for crops with higher tolerance thresholds (e.g., tall fescue, pumpkin, wheat, sorghum, wheatgrass and barley), in the absence of soil salinization problems, S1 irrigation water will not be a limiting factor (Figure 7). In contrast, some crops produced on a large scale in the VBRC, such as alfalfa, corn, potatoes, onion and carrot, show a high sensitivity to the presence of salts. This salt-induced oxidative stress causes significant yield losses in these crops, as seen in Table 7. For example, alfalfa can experience losses ranging from 2.33 to 2.78%, while corn and potatoes can lose between 2.0 and 7.17%. Onion and carrot, on the other hand, show even more significant losses, ranging from 10.50 to 18.75% and 12.25 to 18.44%, respectively. It is worth noting that the results for S3 and S4 are not included in Table 7 due to their high levels of EC (Table 5), which would practically result in the complete loss of crop yields [54,55].

Table 7. Theoretical reduction in the yield potential for the VBRC crops.

Crops under the Influence of Salinity (FAO)		Yield Reduction According to EC (dS m^{-1})					Estimated Yield Loss (%) Station 1					Estimated Yield Loss (%) Station 2				
							Campaign					Campaign				
		0%	10%	25%	50%	100%	2015–2016	2016–2017	2017–2018	2018–2019	2019–2020	2015–2016	2016–2017	2017–2018	2018–2019	2019–2020
Cereals	Wheat	4	4.9	6.3	8.7	13	-	-	-	-	-	-	11.71	4.44	8.56	10.92
	Corn	1.1	1.7	2.5	3.9	6.2	2	7.17	6.83	7.5	6.83	45.18	75.21	60.87	68.91	72.61
	Barley	5.3	6.7	8.7	12	18	-	-	-	-	-	-	-	-	-	-
	Sorghum	4.5	5	5.6	6.7	8.7	-	-	-	-	-	-	11.49	-	5.4	8.8
Pastures	Alfalfa	1.3	2.2	3.6	5.9	10	-	2.56	2.33	2.78	2.33	25.54	51.07	39.29	45.89	48.93
	Tall Fescue	2.6	3.6	5.2	7.8	13	-	-	-	-	-	10.32	25.64	18.57	22.54	24.36
	Wheatgrass	5	6.6	9	13	21	-	-	-	-	-	-	0.37	-	-	-
Horticultural	Onion	0.8	1.2	1.8	2.9	5	10.5	18.25	17.75	18.75	17.75	67.38	100	85.71	94.52	98.57
	Potatoes	1.1	1.7	2.5	3.9	6.7	2	7.17	6.83	7.5	6.83	45.18	70.71	58.93	65.54	68.57
	Carrot	0.7	1.1	1.9	3	5.4	12.25	18.06	17.69	18.44	17.69	63.12	92.92	79.17	86.87	90.42
	Pumpkin	3.1	3.8	4.9	6.7	10	-	-	-	-	-	7.57	27.22	18.18	23.23	25.56

Calculations were made based on the average EC for each irrigation season.

Regarding the analysis of the main drainage canals and their use by the VBRC producers, S2 is included in Figure 7. This does not justify the use of low-quality drainage water, rather it can be used in the exceptional cases of irrigation water scarcity.

The drained saline water available in the subsurface drainage systems can be a source of water for irrigation and agricultural production in the VBRC, being applied as irrigation management strategies to use this water for salinity-tolerant crops (e.g., barley, wheatgrass, sorghum, etc.) or crops that require fewer irrigations for their development [56]. The results of crop yield loss for S2 are presented in Table 7. When focusing on the most tolerant crops (Figure 7), it can be observed that the wheatgrass crop only experienced a loss of 0.37% during the 2016–2017 season. Alongside that, sorghum showed losses ranging from 5.40% to 211.49%. In contrast, the barley crop did not show any yield loss.

Another alternative consists of mixing the saline water S2 with the regular irrigation water S1 to reduce the applied salinity. This option would not only decrease the saline concentration of S2, but would specifically help to reduce the parameters Mg^{2+}, K^+ and TDS, as mentioned in [51], which can be observed in Figure 5.

The findings of this study suggest that irrigation with drainage water has promising potential as an adaptation to the water crisis and climate change in the Colorado River basin. Although more research is needed to determine its effect on crop yields, the results suggest that the use of drainage water could be a valuable alternative in water-scarce areas.

The use of drained saline water as a source of supplemental irrigation water has been widely studied [57]. Rhoades et al. [58] found that the use of saline water with a low-to-moderate salt content, along with good-quality water, is an effective method for using saline water for supplemental irrigation without producing negative effects on the yield and soil quality. Other studies have evaluated the impact of irrigation with drainage water on crop yield, but the results have been inconsistent. For example, Mahmoud et al. [59] found that irrigation with drainage water improved the crop yield in northern Egypt. Similarly, Li et al. [60] reported that irrigation with drainage water led to higher yields in the Manas River valley in China. In contrast, Dotaniya et al. [61] found that irrigation with drainage water reduced crop yields in India. The variability in results can be attributed to several factors, including the differences in drainage water quality, soil type, crop type and management practices.

Furthermore, this study found that the water quality in the Colorado river basin varies spatially and seasonally, highlighting the need for the continuous monitoring and management of water resources. The drainage water quality is often poor due to high salinity levels, which can have detrimental effects on soil and crop health. Adequate management practices, such as soil amendments and crop selection, may be necessary to optimize the use of drainage water for irrigation.

Overall, this study provides important insights into the potential of drainage irrigation as a solution to water scarcity and climate change in the Colorado river basin. However, more research is needed to fully assess the impact on crop yields and develop sustainable management practices that can ensure the long-term viability of this approach. The variability in the results from different regions suggests that local factors need to be taken into account when considering the feasibility of irrigation with drainage water as an alternative water resource.

3.8. PCA (Principal Component Analysis)

Principal component (PC) is a linear combination of observable water quality variables. PCA of the normalized variables (water quality dataset) was performed to extract significant PCs and further reduce the contribution of variables with a minor significance. The principal components were applied to sites S1 and S2 in conjunction with Pearson's correlation. In the selection of the principal components, the eigenvalues greater than the unity were used once the matrix was rotated by the varimax method. In turn, the variables of each component are correlated in a strong, moderate or weak way, considering the classification of correlation coefficients according to the following values: very strong (>0.75), moderate (0.75–0.50) and weak (0.50–0.30).

Eleven parameters (Mg^{2+}, HT, K^+, pH, Cl^-, TDS, Na^+, $SO_4{}^{2-}$, Ca^{2+}, $HCO_3{}^-$ + $CO_3{}^{2-}$ and EC) were used to determine the PCs for Stations 1 and 2.

The data in Figure 8a show the first four rotated principal components (varimax). PC1 posed 76.22% of the total variance and is responsible for 40.4%, with strong positive loadings of Na^+, Ca^{2+}, HT, EC and TDS, and a moderate one of Cl^-. PC2 represents about 16.27% of the total variance and had a moderate positive loading for Mg^{2+} and SO_4^{2-}, together with a moderate negative loading of $HCO_3^- + CO_3^{2-}$. PC3 accounts for about 10.54% of the total variance and had a moderate positive loading of K^+ and pH. Finally, the PC4 component (9.02%) had a moderate positive and negative loading of Mg^{2+} and pH, respectively. Regarding S2 (Figure 8b), the first two rotated PCs (varimax) explained 79.78% of the total variance. PC1 was responsible for 68.61% of the total variance with strong positive loadings of Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, HT, EC and TDS, and a moderate one of $HCO_3^- + CO_3^{2-}$ and SO_4^{2-}. PC2 accounted for about 11.17% of the total variance and had a strong positive loading of pH, a moderate negative of $HCO_3^- + CO_3^{2-}$ and a weak one of SO_4^{2-}.

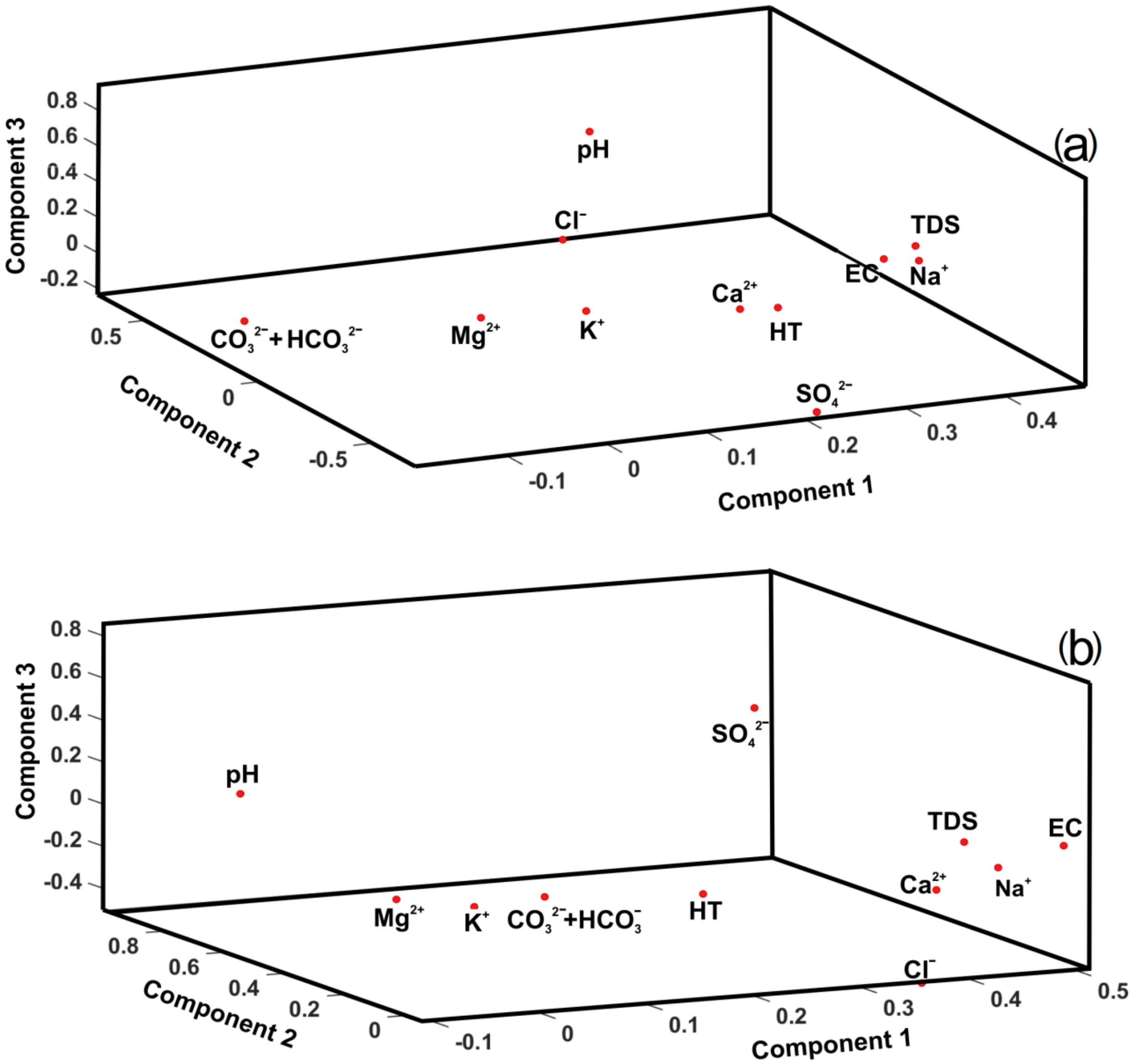

Figure 8. PCA analysis for the studied parameters: (**a**) S1 and (**b**) S2.

4. Conclusions

Based on the results of this study, irrigation with drainage water could be a potential adaptation strategy to cope with water scarcity and climate change scenarios in the Colorado river basin. However, its effect on crop yields varies greatly in the literature, making it challenging to thoroughly assess its role in global food security.

This study investigated the water quality of the Colorado river basin as the main resource for irrigation purposes, as well as the estimation of the yield losses of the crops grown in the VBRC, and a quality assessment on drainage water to analyze its potential reuse as irrigation water.

According to the physicochemical results, the cation dominance of S1 follows the pattern $Na^+ > Ca^{2+} > Mg^{2+} > K^+$, while the order of anions is $SO_4{}^{2-} > Cl^- > HCO_3{}^- + CO_3{}^{2-}$. The increased ionic concentrations were observed in drainage canals, which could be due to leachate runoff from fields from the irrigation runoff, flooding or precipitation. The drainage canals are derived from a large intensively cultivated agricultural area, in a system that is fed primarily by the seasonal fluctuations in water levels due to the reservoir regulations. Multivariate statistics, such as Pearson's correlation, PCA and HCA, were used to evaluate spatial and seasonal variations of the river water quality data.

It is worth noting that the indices used for water quality assessment can be useful for managers and administrative organizations (CORFO, INTA, etc.). According to the IWQI, the water quality of S1 is suitable for unrestricted use for irrigation, while the rest of the stations have restrictions. With this water quality, a theoretical yield loss was estimated for crops considering the salinity variable, with vegetables showing the greatest losses.

The historical drought in the basin highlights the extreme need for optimization and use of other irrigation alternatives. Faced with low flow scenarios and increases in EC values, the possibility of reorienting production toward crops with greater tolerance to salinity could be considered in the future, along with politically evaluating the possibility of using the water available in surface drainage systems as a source for irrigation and production in the VBRC, as has been observed in the case of S2.

Further studies and long-term evaluations are a priority, since background information is scarce. The data provided are important tools for implementing strategies for the sustainable management and use of natural resources. These have an impact on global agricultural sustainability and production, which will ensure the future of agricultural activity. It is necessary to understand the ecosystemic processes, and it is essential to have the knowledge and technology to ensure equitable, efficient and sustainable management of water resources, establishing tools for decision making.

Author Contributions: Conceptualization, J.O.P.; Data curation, M.T. and F.D.V.; Formal analysis, M.T., J.O.P. and F.D.V.; Funding acquisition, M.F.P.; Investigation, M.T. and F.D.V.; Methodology, M.T. and J.O.P.; Project administration, J.O.P., L.D.G. and M.F.P.; Resources, L.D.G.; Supervision, J.O.P. and F.D.V.; Writing—original draft, M.T. and F.D.V.; Writing—review and editing, M.T. and J.O.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data are included in the manuscript.

Acknowledgments: The Argentine authors are grateful for the support from the Universidad Nacional del Sur (Dpto. de Química—INQUISUR). M. Trillini, J.O. Pierini and M. F. Pistonesi are also grateful to (CIC) Comisión de Investigaciones Científicas de la Provincia de Buenos Aires. F.D. Vallese thanks the Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET, Argentina). A special thanks is given to the INTA (Instituto Nacional de Tecnología Agropecuaria) and CORFO Río Colorado (Corporación de Fomento del Valle Bonaerense del Río Colorado) for providing important data for the development of this work.

Conflicts of Interest: The authors declare no conflict of interest.

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