Region - Water Conservancy, 2025, Volume8, Issue2
DOI: 10.32629/rwc.v8i2.3734
ISSN Online: 2630-4902

Processes impacting irrigation water quality in several coastal wells of Center-Southern Cuba

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Abstract: Water quality is a variable to be controlled in irrigated agriculture. The objective of the research was to identify the main processes that impacted water quality for irrigation in wells located in the southeastern coastal area of Cienfuegos Bay. The data came from the company Recursos Hidráulicos and includes the concentrations of the majority components and the electrical conductivity (EC) of water from seven wells, during the 1983-2015 stage. To facilitate the treatment, a similarity analysis was applied and three groups of wells with different physical and chemical characteristics were obtained. The identification of the influent processes in each group was achieved through ionic relations and principal component analysis. The following indicators were used to characterize the water for irrigation: potential salinity (SP), permeability index (PI), sodium adsorption ratio (SAR), percent sodium possible (PSP), residual sodium carbonate (CSR), EC, total hardness (TD), Kelly ratio (KR) and magnesium adsorption ratio (RAM). The water in all three groups was calcium bicarbonate, with a higher proportion of these ions in the first group. The main processes identified were: rock washing, cation exchange, chloride and sodium input, and salinization of the water. The water met the established requirements for irrigation. However, in the wells of the second and third groups, an increase in TD and a decrease in PI linked to anthropic activities developed in the basins were observed.

Key words: potential salinity; permeability index; ionic relations; anthropic activities

1 Introduction

One of the important factors for the development of a region is the availability of water sources that meet the requirements for various purposes, both in quantity and quality. These aspects need to be considered for proper management of the resource (Choramin et al. 2015). Water resources worldwide are under enormous pressures due to the increasing demand for water with improved quality; this demand is conditioned by political, social and environmental factors (Moreno and Roldán 2013). Economic development associated with an accelerated increase in population has generated an increased demand for water for different purposes (Vasanthavigar et al. 2012).

The quality of irrigation water is of great importance for safety reasons, due to its potential effect on human and ecosystem health in general (Graczik et al. 2011). When water used for irrigation does not meet the requirements, pathogenic organisms may be present in vegetables such as tomato and lettuce. The concept of water quality for this purpose refers to characteristics that may affect soil and crops in their long-term use (Bosch et al. 2012).

To evaluate its quality, criteria such as salinity and sodicity must be defined (Ayers 1987, Asamoah et al. 2015). Salinity depends on the type and quantity of dissolved salts, so its measurement includes the determination of the concentration of total soluble salts, calcium ions (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na.), potassium (K.), sulfate (SO^{2-}), chloride (Cl.), carbonate (CO^{2-}), bicarbonate (HCO.) and electrical conductivity (EC) (Ayers and Wescot 1976, Arzola et al. 2013).

Sodicity is determined in relation to the relative concentration of Na. with respect to other cations. With the variables derived from the evaluation of the above criteria, indicators are calculated to determine the suitability of the water. These include Na. adsorption ratio (SAR), residual sodium carbonate (RSC), pH, EC, degree of acidity, percent sodium possible (PSS), effective salinity (ES), potential salinity (SP) and permeability index (PI) (Ayers 1987, Palancar 2006, Cortés-Jiménez et al. 2009, Lingaswamy and Saxena 2015).

In coastal communities, groundwater is the main source of supply for multiple uses. Its quality depends on factors such as soil characteristics, topography of the region, human activities, among others (Zghibi et al. 2013). Irrigation can modify the water quality of neighboring surface streams (Betancourt et al. 2012a) and groundwater, due to percolation of wash water from fertilized and pesticide-treated areas.

When coastal aquifers are exploited beyond their capacity, the balance between groundwater and seawater is broken and marine intrusion occurs (Lin et al. 2012). Climate change affects hydrogeological conditions, generates changes in water temperature and in the balance of salts present, and also favors marine intrusion (Kovalevskii 2007). Both the overexploitation of aquifers and anthropic activities in the feeding basins and climate change increase the variation in water quality in coastal aquifers.

For an integrated management of water in agriculture, it is necessary to know the main processes influencing its quality. There is a group of wells located in the southeastern coast of the province of Cienfuegos in south-central Cuba that have different uses, however, the processes that are influencing the composition and quality of water for irrigation have not been identified. The objective of the present research was to identify the main processes that impacted the quality of irrigation water in these wells.

2 Materials and methods

The study used the results of physical and chemical parameters of seven wells located southeast of the province of Cienfuegos, in the section between the mouth of the Yaguanabo River to the east of Cienfuegos Bay (Figure 1). Physical and chemical data and information related to the use and exploitation of the wells during the stage from 1985 to 2015 were obtained from the Provincial Delegation of Hydraulic Resources (DPRH). Sampling was periodic but the stored data were irregular and as a result the number of measurements different in each well.

In order to know the geology present in the basins that feed the wells, the Geological Map at a scale of 1:50,000 and information from the DPRH archive were consulted. Soil characterization was based on Hernández-Jiménez et al. (2015), and soil uses were obtained using a map from the Provincial Delegation of Agriculture in Cienfuegos, which was corroborated with information obtained from surveys of the area and interviews with local officials and residents.

EC was measured by the conductimetric method. It was used as an indicator of salinity measurement because it indicates the total dissolved salts in water and is used to determine the damage produced by salinity (Tartabul and Betancourt, 2016). Na. and K. were determined by flame photometry, Ca^{2+} and Mg^{2+} by the volumetric method with ethylenediamine tetraacetic acid. HCO . and Cl. by volumetric method using dilute solutions of sulfuric acid and silver nitrate as standards. SO^{2-} was determined spectrophotometrically according to APHA (1980).

Wells with similar concentrations in the majority components and EC were identified by hierarchical clustering analysis according to the Euclidean distance between the variables. These variables were previously standardized by the expression: log (x+1). Each group, determined by hierarchical clustering, was subjected to descriptive analysis. To find the significant differences in EC and the proportion of ions between the three groups of wells studied, an analysis of variance (ANDEVA) was applied by the non-parametric method and according to the Kruskal Wallis criterion for $p \leq 0.05$. To perform paired comparisons between variables and establish differences, Dunnett's test was applied.

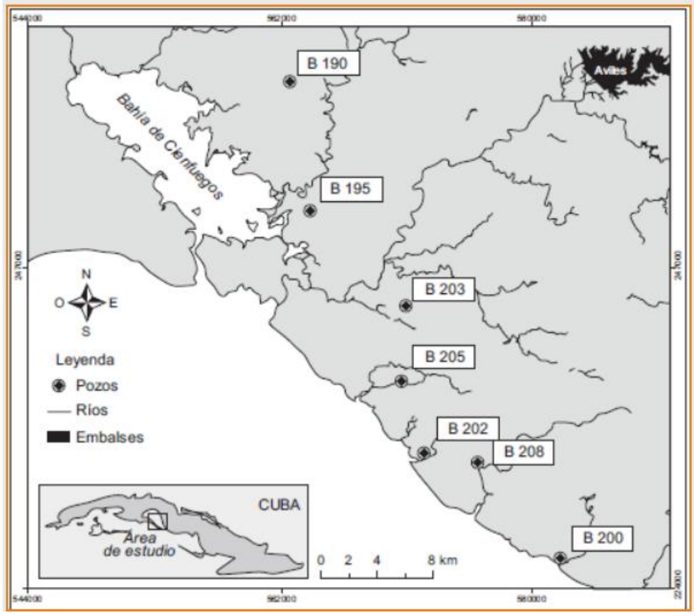

Figure. 1 Study area. The location of each well and the surface streams in the area are shown

The identification of the influential processes on water composition was carried out by means of principal component analysis (PCA). As many factors were extracted as eigenvalues greater than unity for each hierarchical group identified, which made it possible to reduce the variables under study and identify new variables related to the processes occurring. The ionic relationship between Cl and Na was used (figures where the ordinate is represented by the concentrations of the Cl ion and the abscissa by the Na ion). This relationship allows to establish how the geochemical processes have been in a given basin (Fernandez and Miretzky 2004, Pehlivan and Yilmaz 2005, Rajmohan and Elango 2007, Betancourt et al. 2012b).

The suitability of water for irrigation was determined by the variables of greatest international use and according to the criteria of the authors who defined these variables (Table Ⅰ). In the statistical processing as well as in the construction of the figures to represent the ionic relationships, the annual means of the corresponding variables in each hierarchical group were used. Statistical analyses were performed with the SPSS version 15 statistical package.

Table I. Variables used, equations for their determination and authors who define the criteria of water quality for irrigation

Variable	Equation*	Authors
SP	$SP = [Cl^{-}] + ½[SO^{2-}]$ 4	Balmaseda (2006)
IP	(IP) = [(Na+ + H2CO3 -)/ $(Ca^{2+}+ Mg^{2+} + Na^{+})]*100$	Balmaseda (2006)
RAS	$RAS = [Na^{+}] / [(Ca^{2+} + Mg^{2+})/2]$ ½	Richards (1954)
CSR	CSR) = (CO $^{2-}$+ H CO $^{-2}$) - $(Ca^{2+} + Mg^{2+})$ 3 2 3	Richards (1954)
PSS	PSS= Na^{+} + K+ $Ca^{2+} + Mg^{2+} + Na^{+} + K^{+}$	Wilcox (1955)
Total hardness	HT= (Ca+Mg)*50 (mg/L)	Durfor y Becker (1964),
RAM	RAM = [Mg/ (Ca+Mg)]*100	Ayers y Westcot, (1976)
RK	RK=Na/ (Ca+Mg)	Kelly (1963)

*Ionic concentrations in meq/L were used in the equations. SP: potential salinity, IP: permeability index, RAS: sodium adsorption ratio, CSR: residual sodium carbonate, PSS: percent soluble sodium, RAM: magnesium adsorption ratio, RK: Kelly's ratio.

To classify water according to its salt content, the criteria of Arslan and Demir (2013) were used (Table II).

Table II. Classification of water salinity according to the values of electrical conductivity

Value range	Criterion on salinity
< 250 µS/cm	Low
250-750 µS/cm	Medium
750- 2 250 µS/cm	High
CE > 2 250 µS/cm	Very high

3 Results and discussion

3.1 Characterization of the study area

The lithology is primarily composed of sedimentary rocks (conglomerates, sandstones and limestones of diverse grain size, detrital limestone, breccia, and biogenic-sandy textures) and metamorphic rocks such as schists, thin layers of foliated marble, and eclogitic rocks. Volcanic igneous rocks such as basalt, andesites, tuffs, and quartz are also present.

The wells are located in the southeast of Cienfuegos Bay in south-central Cuba at an elevation above sea level ranging from 4.49 to 36.87 m. The area is poor in groundwater so they are located close to neighboring surface streams. The extracted water was used for agricultural irrigation, animal husbandry and human consumption.

The largest extraction volumes were made in wells B203 and B205.

The soil is generally used for livestock farming, seasonal crops, and settlements, although irrigation activity was limited in the areas fed by well B208. Both settlements and animal husbandry (primarily cattle) were sources of contamination for the studied wells.

3.2 Grouping of wells according to the similarity of their majority components

Hierarchical clustering analysis of the wells studied yielded three groups: the first group comprised well B208; the second group comprised wells B190, B195, B200, and B202; and the third group comprised wells B203 and B205. The dendrogram shows the dashed lines for the cluster structure in which the wells were similar ($p > 0.05$). The solid lines represent the divisions between wells that were different ($p \leq 0.05$) (Figure 2).

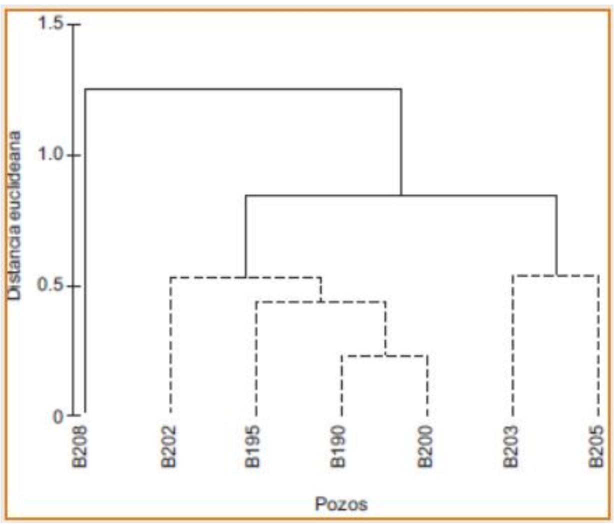

Figure 2. Dendogram of Euclidean distances between wells. Solid lines indicate groups of wells separated ($p < 0.05$) by the SIMPROF test

3.3 Physical and chemical composition of the water from the wells studied

The descriptive statistics of the majority components of the water in each of the groups obtained through the dendogram revealed that, in general, the highest values of the majority components and EC corresponded to the wells included in the third group (B203 and B205) (Table III). Significant difference ($p \leq 0.05$) was found when comparing the EC and the proportions of the ions of the three groups of wells, except for the proportions of SO^{2-} and K. ions, which were similar ($p > 0.5$). The EC was highest in the third group, followed by the second, while the first recorded the lowest values ($p<0.05$).

The water was classified as calcium bicarbonate, however in Figure 3 it is observed that a significant increase in Na. ratios occurred in the third and second groups, with the lowest value for the first ($p \leq 0.05$). One of the sources of these ions is marine aerosols (Jha et al. 2009). The proximity of these wells to the coastal zone could have caused the increase in Na. proportions, either by aerosols or by intrusion, combined with the use and management of these water sources that also make contributions. When this same comparison was made, the proportions of Ca^{2+} and HCO. were higher in the first group ($p \leq 0.05$). When the salt composition of water is determined by rock weathering, it is characterized by a predominance of these ions (Pehlivan and Yilmaz 2005, Jha et al. 2009).

3.4 Identificationof processes influencing water quality ionic relationships

The relationship established between Cl. and Na. ions revealed that in the first group of wells studied the greatest number of observations were located above the 1:1 line, which infers Cl. concentrations higher than Na. In the rest the opposite occurred (Figure 4), when Na. concentrations are higher than Cl, it is associated with the influence of anthropic processes on water quality (Giussani et al. 2008, Omo-Irabor et al. 2008, Jha et al. 2009).

These wells are located in areas of temporary crops where agricultural irrigation is systematically applied. Areas dedicated to cattle raising were also located, and in the case of the wells of the third group, the largest quantities of water were extracted, so that some penetration of saline waters from the coast could have occurred. Similar results were found in four Cuban reservoirs affected by this type of anthropogenic activities (Betancourt et al. 2012a).

3.5 Principal component analysis

The application of PCA to the three groups of wells studied revealed that the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy was above 0.500, Bartlett's test of sphericity was

Table III. Values of the descriptive statistics of the variables for each group of wells studied. Electric conductivity (EC) is expressed in µmhos/cm and all ions in meq/L

	Variables evaluated	Minimum	Maximum	Media	Standard deviation
First group Well 208	EC	401	786	487	66
	pH	6.71	8.20	7.50	0.201
	HCO^{-3}	2.57	6.30	3.88	0.851
	Cl-	0.29	1.09	0.53	0.176
	SO_2^{-4}	0.05	2.11	0.34	0.346
	Ca^{2+}	2.10	6.65	3.51	0.772
	Mg^{2+}	0.38	2.42	1.01	0.484
	Na+	0.13	0.77	0.40	0.150
	K+	0.01	0.08	0.08	0.013
Second group Wells B190, B195, B200 and B202	EC	435	1292	841	172
	pH	6.58	8.03	7.36	0.211
	HCO^{-3}	3.55	9.69	6.09	1.020
	Cl-	0.38	2.93	1.38	0.560
	SO_2^{-4}	0.10	2.74	0.69	0.410
	Ca^{2+}	3.00	8.80	5.68	1.360
	Mg^{2+}	0.10	5.00	1.30	0.810

	Na^{+}	0.31	4.00	1.59	0.778
	K^{+}	0.01	0.95	0.07	0.092
Third group Wells B203 and B205	EC	620	1400	1022	163
	pH	6.97	8.06	7.39	0.218
	HCO^{-3}	5.57	10.17	8.27	0.848
	Cl-	0.60	2.89	1.44	0.536
	SO_2^{-4}	0.03	2.10	0.91	0.374
	Ca^{2+}	2.60	7.40	5.25	0.789
	Mg^{2+}	0.42	5.60	3.36	0.927
	Na^{+}	0.18	4.45	2.34	0.940
	K^{+}	0.00	0.55	0.07	0.092

Significant ($p \leq 0.05$) and the determinant had an acceptable value for this analysis.

In the first group of wells (B208) three components were extracted that explained 73.9 % of the variance of the data. The first factor explained 34.5 % (Table IV) and was identified as the contribution of limestone washout to the chemical composition of the water. The second factor explained 24.5 % and was related to silicate and gypsum rock washout. The third factor contributed the least with a value of 14.9 % and was related to the contribution of fertilizers containing Cl. and K. From these results, it can be inferred that the water quality of this well is mainly determined by natural processes (washing of the rock or weathering action) represented by 59 % of the total variance of the data.

In the second group of wells, three components were extracted that explained 72.8 % of the variance of the data, each factor found had a similar weight (24.7 %, 21.5 % and 21.5 %) (Table V).

The first factor explained 24.7% and grouped EC and HCO , SO^{2-} and Mg^{2+} ions, which according to the geology described, are present in the feed basins of these wells. This factor was identified as the contribution of rock weathering.

The second factor explained 21.5 % of the variance of the data and was related to the contribution of sodium chloride (NaCl) generated by cattle raising and runoff water from irrigation areas. The area that feeds these wells contains stables belonging to the Sierrita livestock company, which was created in the 1980s. In recent years, the company has raised 930 heads of livestock, combined with sheep and goats. Bananas, rice and vegetables are also grown, with a high frequency of irrigation. Several authors (Giussani et al. 2008, Omo-Irabor et al. 2008, Jha et al. 2009) have reported similar results due to the contribution of agricultural waste and runoff from agricultural irrigation areas to natural waters.

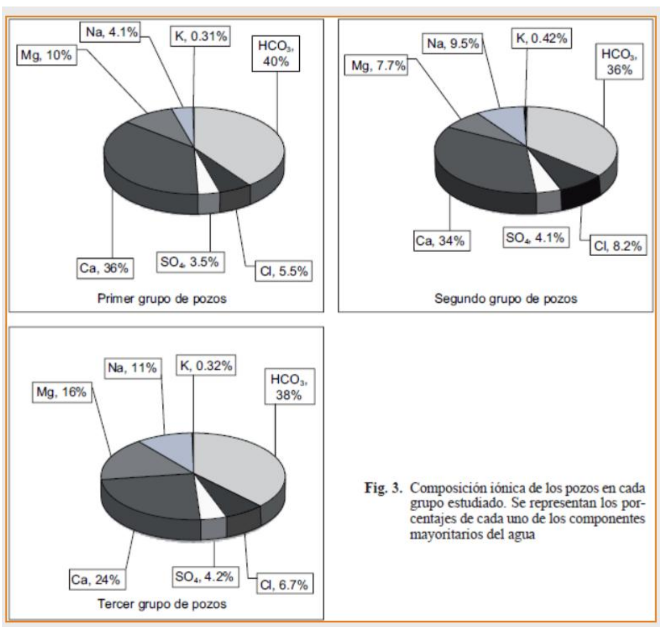

Figure 3. Ionic composition of the wells in each group studied. The percentages of each of the major components of the water are represented.

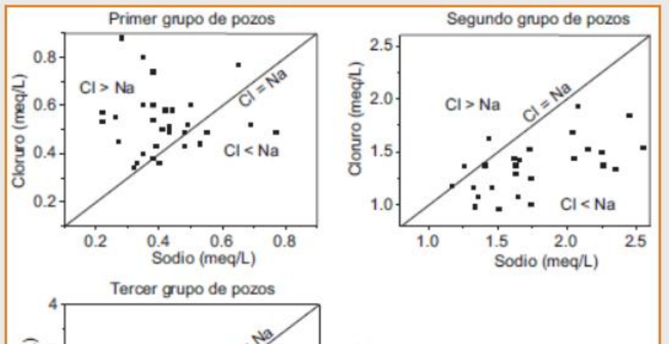

Fig. 4. Relación entre el cloruro y el sodio. El primer grupo representa al pozo B208, el segundo grupo a los pozos B190, B195, B200 y B202 y el tercer grupo a los pozos B203 y B205

Figure 4. Relationship between chloride and sodium. The first group represents well B208, the second group represents wells B190, B195, B200 and B202 and the third group represents wells B203 and B205

Table V. Loading factors of the variables measured in the second group (Wells B190, B195, B200 and B202) for the first three axes. Variables included in each component are shown in bold.

Variables	Componente		
	1	2	3
CE	**0.660**	0.597	0.308
HCO_3^-	**0.818**	0.215	–0.010
Cl^-	0.123	**0.874**	0.197
SO_4^{2-}	**0.613**	0.081	0.344
Ca^{2+}	0.100	0.369	**0.847**
Mg^{2+}	**0.778**	–0.071	–0.466
Na^+	0.121	**0.777**	–0.386
K^+	–0.003	0.245	**–0.619**

The third factor explained 21.5 % of the variance of the data and was linked to base exchange. This newly obtained variable was positively related to Ca^{2+} and negatively related to K. Part of the K. in solution can return to the solid phase and Ca^{2+} passes into water (Chapman 1996). This author points out that base exchange is one of the processes that regulates the chemical composition of water (incorporation of Ca^{2+} and loss of K.).

In the third group of wells studied, two components were extracted (Table VI) that explained 57.33 % of the variance of the data, indicating that there were other processes affecting water quality that could not be identified by PCA. The first factor explained 39.7% and was identified as the increase in water salinity. These wells are used for human consumption (supplying the towns of La Legua and Gavilán) and are farther from the coast than most of those included in the second group, but other factors such as crop irrigation, animal husbandry and the extraction of a greater volume of water were influential. Well B203 is at 36.87 masl, with a depth of 24.63 m and close to the Arimao River in the estuarine zone. B205 at 14.26 masl and 6.12 m deep is located in the estuarine zone of the Gavilanes River.

Table VI. Loading factors of the variables measured in the third group (Well B203 and B205) for the first two axes. Variables included in each component are shown in bold.

Variables	Componentes	
	1	2
Conductividad eléctrica	0.921	0.140
HCO_3^-	**0.783**	0.018
Cl^-	**0.542**	0.188
SO_4^{2-}	**0.721**	–0.046
Ca^{2+}	0.296	**0.857**
Mg^{2+}	**0.582**	–0.481
Na^+	**0.690**	–0.257
K^+	–0.017	**0.565**

The extraction of high daily volumes may have generated the influx of water with high saline content from the estuarine zone. Agricultural irrigation is also recognized to increase the saline content of receiving waters (Rajmohan and Elango 2007, Miyamoto and Anand 2008, Betancourt et al. 2012b) due to the increased salt concentration in the drained waters and the presence of leached fertilizers and pesticides, as well as other ionic contaminants.

Table III also shows that these wells had the highest salinity values ($p \leq 0.05$), expressed as EC. Their chemical composition (Figure 3) shows a decrease in the proportions of Ca^{2+} with an increase in those of Mg^{2+} ($p \leq 0.05$), which may be due to the entry of water from the estuarine zone from the rivers located nearby. Wetzel (1975) reported that in areas of rivers close to their mouths it is characteristic to find a decrease in the proportions of Ca^{2+} with an increase in those of Mg^{2+}. The low altitude in relation to sea level that exists in the estuarine zone causes the entry of marine waters into that area at high tide. It is advisable for wells located close to the coastal zone to extract water at low tide.

The second factor accounted for 17.61% and was related to the dissolution of rocks present in the basin. The lithological description of these wells revealed a zonation of volcanic series (igneous rocks) in the area surrounding the well, ranging from tholeiitic volcanites to the calc-alkaline series (different types of basalt; andesites, dacites, and rhyolites), with increased Ca^{2+} and K levels.

3.6 Determination of the quality of water for irrigation

Assessment of irrigation water quality in group one (Well B208) revealed that the water met all the requirements for use in agricultural irrigation. The RAS decreased significantly during the assessed stage (Figure 5), as did the SSP values. This well recorded the lowest concentrations of the major components and EC ($p \leq 0.05$) (Table III). The average EC classified the water as having medium salinity, according to the criteria used, and of good quality for irrigation. However, it was very hard, which can interfere with the lifespan of irrigation systems.

The analysis of the main processes influencing water quality reported that approximately 50% (49.4 %) of the variance of the data was related to natural processes, and only 14.9 % to anthropogenic activities (fertilizer input, leached water from irrigation, livestock waste, among others), which justifies the pattern observed in the variables evaluated in this section. In this well the lithology is represented by igneous rocks, which are more resistant to weathering and therefore justifies its lower saline content. In addition, in its supply basin, the arable areas were less extensive, so the contribution of salts from the return water of the irrigation areas was lower.

The analysis of the second group of wells verified that their waters were suitable for irrigation (Figure 6). However, the PI decreased significantly during the study period, which apparently does not match the significant decrease in the SSP. This lack of concordance is explained by the increase in the DT, which generated an increase in the proportion of Ca^{2+} and Mg^{2+}, with the consequent decrease in the SSP. The hardness values classified the water as very hard, which is detrimental to the useful life of irrigation systems due to the deposition of Ca and Mg salts. The CE criterion used classified the water as highly saline and acceptable for irrigation. The PCA applied to this group of wells revealed that the second component contributed 24.7% to the data variance and was related to the contribution of Cl and Na, which explains the observed decrease in the PI.

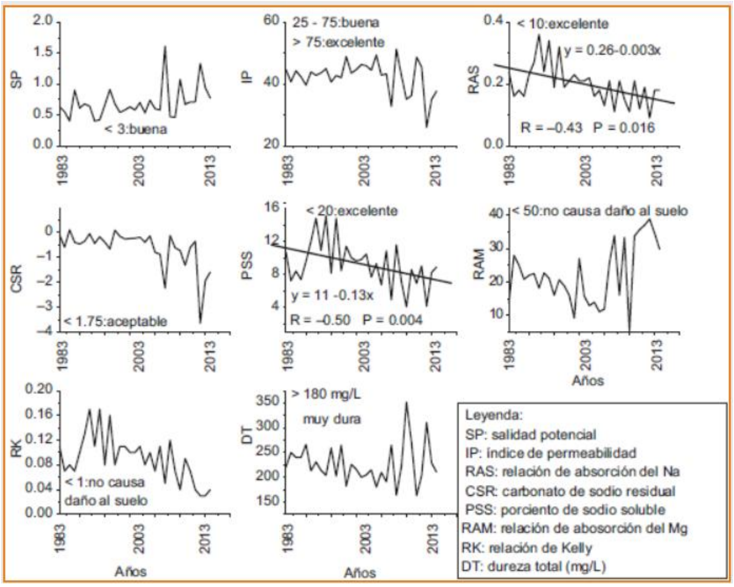

Figure 5. Behavior of the variables used in the determination of water quality for irrigation in the first group of wells (B208)

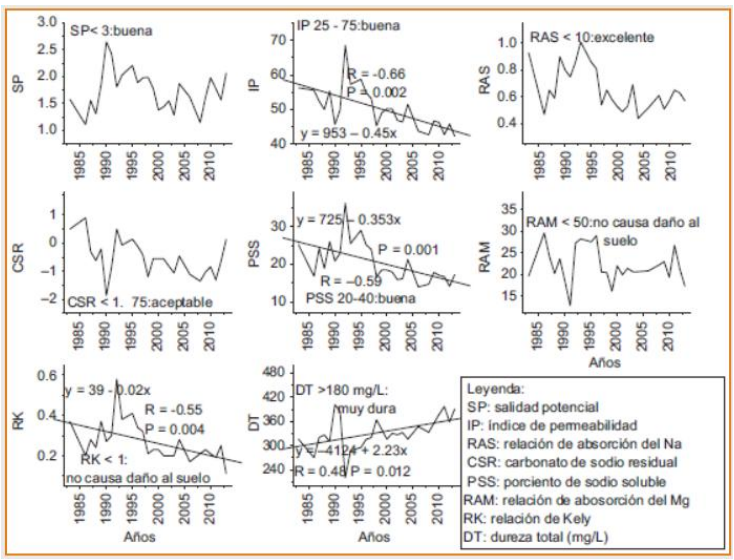

Figure 6. Behavior of the variables used to determine irrigation water quality in the second group of wells (B190, B195, B200, and B202)

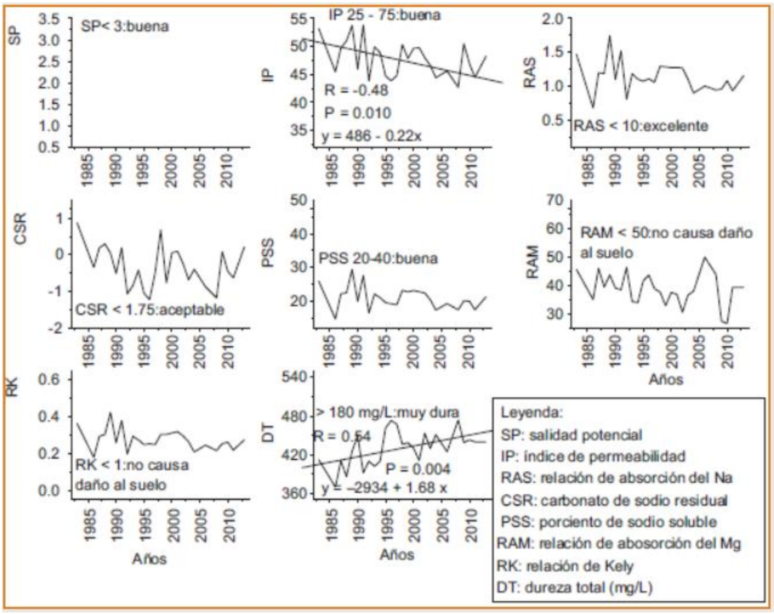

Figure 7. Behavior of the variables used to determine irrigation water quality in the third group of wells (B203 and B205)

The results obtained for the third group of wells (B203 and B205) revealed that all variables evaluated indicated good quality for irrigation (Figure 7), except for the EC, which classified the water as highly saline and acceptable for irrigation (similar to the second group of wells). The trends observed in the DT and IP revealed a deterioration in the quality of their waters over time. The identification of the processes influencing water quality revealed that the greatest contribution to the data variance was verified in the first component, which was related to water salinization, consistent with the downward trend in the IP.

The results obtained by applying three different methods to assess water quality and the influential processes (ionic ratio, ACP and irrigation water quality assessment) constitute an early warning that allows the development of management strategies in relation to the use and exploitation of these water sources in agricultural irrigation.

4 Conclusion

The application of cluster analysis allowed the identification of three groups of wells with different characteristics, which facilitated the identification of the main processes that impacted irrigation water quality.

Wells B203 and B205 extracted higher volumes of water than the other wells, which was related to the salinization of their waters. Land use, water withdrawals, and the lithology of the feeding basin were related to water quality. Similar results have been found in Cuban reservoirs regarding the influence of land use on water quality.

The main processes influencing water quality that were identified are: rock washing, cation exchange, NaCl input from livestock farming and runoff from irrigation areas, as well as water salinization.

A negative trend in the IP, combined with an increase in the DT, was observed in the second and third groups of wells studied, which raises concerns about the potential impact on irrigation water quality. This deterioration was most pronounced in the third group, where the salt content was higher than in the rest.

Conflicts of interest

The author declares no conflicts of interest regarding the publication of this paper.

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