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Articles

Risks of soil infiltration problems in the Javita river basin, Ecuador

Riesgos de problemas de infiltración de suelos en la cuenca del río Javita, Ecuador

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ABSTRACT: This study evaluates the potential risks of decreased permeability and infiltration problems in agricultural soils associated with groundwater quality in the Javita River basin (Santa Elena Peninsula, Ecuador), using three indicators: Doneen Permeability Index (PI), Sodium Adsorption Ratio (SAR/SARx), and Cation Ratio of Structural Stability (CROSS). Three sampling campaigns were conducted (May, August, and December 2024) in 25 wells (20 in December due to the dry season), following INEN standards 2196 and 2176. pH, Electrical Conductivity (EC), and cation/anion concentrations (Na^+, K^+, Ca^{2+}, Mg^{2+}, HCO_3^-, CO_3^{2-}, SO_4^{2-}, Cl^-) were determined in the samples. The results show high spatial and temporal variability (high coefficients of variation) and a PI classification of Class II (Good) in all three sampling periods (means: 50.9, 54.9, and 40.2 %), suggesting that these waters would not affect permeability. In the SAR/SARx/CROSS vs. EC evaluation, the “None” restriction category predominates, although nine wells present “Slight to Moderate” restriction in May and/or December. Several of these (P-14, P-16, P-17, P-22, P-23, and P-24) maintain this condition in both sampling periods. In December, the available observations are classified as having no restriction, but the absence of data for five wells requires caution in the handling of these waters. In summary, there is no current risk of sodicity or decreased permeability; monitoring of wells with “Slight to Moderate” restrictions and management measures to maintain effective wet-bulb salinity and minimize the potential for surface dispersion and sealing are recommended.

Key words: CROSS, electrical conductivity, SAR, sodicity, water quality.

RESUMEN: Se evalúan los posibles los riesgos de disminución de la permeabilidad y problemas de infiltración en suelos asociados a la calidad del agua subterránea en la cuenca del río Javita (Península de Santa Elena, Ecuador), mediante tres indicadores: Índice de Permeabilidad (PI), Relación de Adsorción de Sodio (SAR/SARx) Relación Catiónica de Estabilidad Estructural (CROSS). Se realizaron tres campañas de muestreo (mayo, agosto y diciembre de 2024) en 25 pozos (20 en diciembre por estiaje), bajo las normas INEN 2196 y 2176. A las muestras se les determinaron pH, Conductividad Eléctrica (EC) y cationes/aniones (Na^+, K^+, Ca^{2+}, Mg^{2+}, HCO_3^-, CO_3^{2-}, SO_4^{2-}, Cl^-). Los resultados muestran alta variabilidad espacial y temporal (coeficientes de variación elevados) y una clasificación del PI en la Clase II (Buena) en los tres muestreos (medias: 50,9; 54,9; 40,2 %), esto sugiere que esas aguas no afectarían la permeabilidad. En la evaluación SAR/SARx/CROSS vs. EC predomina la categoría de “Ninguna” restricción, aunque nueve pozos presentan restricción “Leve a Moderada”, en mayo y/o diciembre, varios de ellos (P-14, P-16, P-17, P-22, P-23, P-24) mantienen esa condición en ambos muestreos. En diciembre, las observaciones disponibles clasifican sin restricción, pero la ausencia de datos en cinco pozos exige cautela en el manejo de estas aguas. En conclusión, hay ausencia de riesgo actual de sodicidad o disminución de la permeabilidad, se recomienda el seguimiento de los pozos con restricción “Leve a Moderada” y medidas de manejo para mantener la salinidad efectiva del bulbo húmedo y minimizar el potencial de dispersión y sellado superficial.

Palabras clave: calidad del agua, conductividad eléctrica, CROSS, SAR, sodicidad.

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INTRODUCTION

Water is an indispensable resource for agriculture, and its quality is as important as the quantity available to ensure crop productivity and the long-term sustainability of soil resources. The presence and concentration of dissolved salts in irrigation water can directly influence plant growth. Furthermore, the continued use of water with an excess of dissolved salts can alter soil structure, leading to reduced permeability and aeration, aspects vital for crop root development and adequate drainage (1).

The assessment of water suitability for irrigation is based on several criteria. These include salinity, commonly quantified by electrical conductivity (EC); the risk of sodicity, expressed through the sodium adsorption ratio (SAR) (2-6); the potential toxicity caused by specific ions such as chlorides, sulfates, and boron (7); and the damage that may result from clogging of irrigation system components (8-12). These interrelated factors help determine the suitability of water for agricultural uses and its potential consequences for soil health and crop yield.

The permeability index (PI) (13) is an analytical tool specifically designed to evaluate the long-term impact of irrigation water on soil permeability (14). Permeability is a critical attribute that ensures efficient drainage and adequate aeration in the plant root zone.

The permeability index considers the interaction of specific ions, such as sodium and bicarbonate, in relation to calcium and magnesium present in the water, which can influence soil structure. Prolonged use of water with an unfavorable PI can lead to soil particle dispersion, significantly reducing permeability and causing problems such as surface waterlogging and oxygen deficiency in crop roots (1).

$$PI = \frac{\left[Na^{+}\right] + \sqrt{\left[HCO^{3-}\right]}}{\left[Ca^{2+}\right] + \left[Mg^{2+}\right] + \left[Na^{+}\,\right]} * 100$$

Where: PI is the Permeability Index; Na^{+}, Ca^{2+}, Mg^{2+}, HCO_3^{-} are the concentrations of these ions in mEq·L⁻¹.

The PI focuses on soil permeability; for this reason, it is not commonly used as the sole indicator for assessing irrigation water quality. Together with the PI, the SAR (Sodium Adsorption Ratio) is used, which focuses on the risk posed by sodium. This observation leads to the need for a multidimensional assessment of irrigation water quality. Sustainable water management in agriculture should integrate a set of indices to understand the complex interaction of water chemical properties and their cumulative effects on soil health and crop productivity over time (15).

Soil permeability increases with rising salinity in irrigation water, while it decreases if such water contains high concentrations of sodium ions (16,17). If sodium concentration is very high, it can lead to the deterioration of soil hydraulic properties, such as the infiltration rate. As a consequence, surface crusting, soil erosion, and poor aeration may occur. Ultimately, soils would degrade and crop yields would decrease (18).

The Sodium Adsorption Ratio (SAR) (19) has been the primary indicator for assessing the sodicity risk posed by irrigation water. The SAR calculation involves the cations Na^{+}, Ca^{2+}, and Mg^{2+}. The latter two cations are considered to have a similar positive effect on soil permeability.

$$SAR = \frac{\left[Na^{+}\right]}{\sqrt{\frac{\left[\left[Ca^{2+} + \left[Mg^{2+}\right]\right]\right]^{2+}}{2}}}$$

Where: SAR is the Sodium Adsorption Ratio; Na^{+}, Ca^{2+}, Mg^{2+} are the concentrations of these ions in mEq·L⁻¹.

When determining the SAR using the above equation, the changes in calcium contents that occur after irrigation are not taken into account. Hence, the proposal to calculate an adjusted SAR that considers the expected equilibrium due to the effects of carbon dioxide, bicarbonate, and salinity, based on the assumption of the presence of calcium minerals in the soil and the absence of magnesium precipitation (16).

$$SARx = \frac{\left[Na^{+}\right]}{\sqrt{\frac{\left[\left[Ca_x^{2+}\right] + \left[Mg^{2+}\right]\right]}{2}}}$$

Where: SAR_x is the adjusted Sodium Adsorption Ratio; Na^{+}, Mg^{2+} are the concentrations of these ions in mEq·L⁻¹.

Ca_x^{2+} is the "final concentration of calcium remaining in the soil solution, considering water conductivity, bicarbonate content relative to calcium, and the partial pressure of carbon dioxide exerted in the first millimeters of soil" (20).

SAR does not consider the potassium ion as a cause of soil clay dispersion. Likewise, it does not differentiate between the flocculating power of calcium and magnesium. Various researchers have shown that potassium has a soil dispersing effect in the same way as sodium. Furthermore, it has been demonstrated that magnesium does not contribute to flocculation to the same extent as calcium. An alternative to overcome this situation is the Cation Ratio of Structural Stability (CROSS) (18,21,22), since the four fundamental cations (calcium, magnesium, sodium, and potassium) are present in irrigation water, in the soil solution, and on soil cation exchange sites, whether due to natural or anthropogenic factors (18).

$$CROSS = \frac{\left[Na^{+}\right] + 0{,}335\left[K^{+}\right]}{\sqrt{\frac{\left[Ca^{2+}\right] + 0{,}07_{58}\left[Mg^{2+}\right]}{2}}}$$

Where: CROSS is the Cation Ratio of Structural Stability; Na^{+}, K^{+}, Ca^{2+}, Mg^{2+} are the concentrations of these ions in mEq·L⁻¹.

CROSS is recommended as a replacement for SAR, primarily for waters with electrical conductivity (EC) below 4 dS/m, and where magnesium concentrations are higher than calcium concentrations (17).

The objective of this study was to evaluate the potential risks of reduced soil permeability in the Javita River basin, Santa Elena Peninsula, Ecuador, when using irrigation water. For this purpose, the following indicators were considered: Permeability Index (PI), Sodium Adsorption Ratio (SAR), and Cation Ratio of Structural Stability (CROSS).

MATERIALS AND METHODS

The study area, as shown in Figure 1, is constituted by the Javita River basin, located in the Colonche parish, Santa Elena canton, Santa Elena province. Its boundaries are: to the north, the Viejo River basin; to the south, the Grande, Zapotal, and Daular river basins; to the east lies the Chongón-Colonche mountain range; and to the west is the Pacific Ocean.

This is a coastal basin, i.e., on the Pacific slope. Its main characteristic is that it has poor, isolated aquifers of small extent. It belongs to the Zapotal hydrographic system, and its code according to the Hydrographic Division of Ecuador is 1244.

The terrain is undulating, with low-height elevations. Regarding climate, the study area is divided into two zones: in the eastern part, close to the Chongón-Colonche mountain range, it is classified as tropical megathermal dry, while the coastal zone is tropical megathermal semiarid.

The planar coordinates of the points defining the southwest and northeast extremes of the Javita River basin are 525,000, 9,760,000 and 580,000, 9,800,000 respectively, according to the UTM projection system, zone 17 south, WGS 84 datum.

The Javita River originates in the Chongón-Colonche Protective Forest mountain range and flows east-west; its flow is classified as intermittent because runoff occurs only during the rainy season. The original vegetation has been indiscriminately logged, mainly to use the wood for charcoal production.

Three samplings were carried out in May, August, and December 2024 at 25 wells located in the middle zone of the basin, where the main cultivation areas are concentrated, as shown by the blue points in Figure 1. It should be noted that during the December sampling, only 20 wells were analyzed, as five were dry due to low water levels (dry season).

The main crops in the study area are: corn, citrus, plantains, cocoa, watermelon, and passion fruit. These are sensitive to moderately sensitive to stress caused by soil salinity.

Sample collection was carried out according to the procedure set forth in the Ecuadorian Technical Standard 2176:2013 on sampling techniques (23). Amber glass containers with a capacity of one liter were used. Sample handling and preservation followed the Ecuadorian Technical Standard 2169:2013 (23).

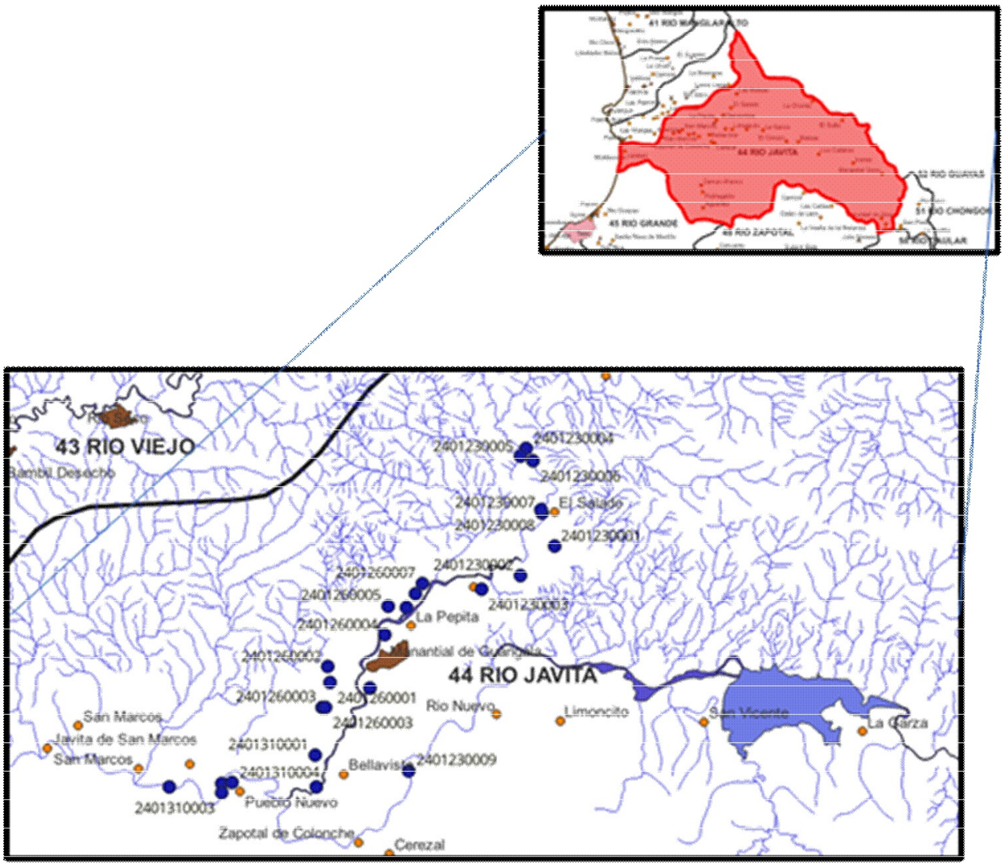

Figure 1. Location of the Javita River basin, the project's study area. Authors' own elaboration.

In the laboratory, the determinations shown in Table 1 were performed, where the techniques used in each case are also presented.

Table 1. Analytical procedures for water chemical analysis

Determination	Technique
pH	Potentiometry
Electrical conductivity (EC)	Conductometry
Sodium (Na^+)	Atomic Absorption Spectrophotometry
Calcium (Ca^{2+})	
Magnesium (Mg^{2+})	
Potassium (K^+)	
Sulfates (SO_4^{2-})	Turbidimetry
Carbonates (CO_3^{2-})	Volumetry
Bicarbonates (HCO_3^-)	
Chlorides (Cl^-)	

Source: Authors' own elaborationos autores

The ionic balance error was calculated as part of the analytical quality control. A margin of ±5 % is considered acceptable in hydrogeochemical studies (24). All samples from May and August were valid, with error values of 2.37 and 2.30 %, respectively. The December sampling showed 12 valid balances (the remainder lacked balance due to missing anions); the error for these was -0.38 %.

Using the InfoStat statistical package (25), statistical parameters for anions and cations from each sampling were determined, including mean, standard deviation, and maximum and minimum values.

The assessment of the risk of soil infiltration problems caused by water quality was carried out using the Doneen Permeability Index (PI), the Sodium Adsorption Ratio (SAR and SAR_x), and the Cation Ratio of Structural Stability (CROSS).

The classification used for the Permeability Index (7,26,27) is presented in Table 2.

Table 2. Permeability Index (PI) classification

PI (%)	Suitability	Class
> 75	Suitable	Class I
25 - 75	Good	ClassII
< 25	Unsuitable	Class III

The use restrictions for irrigation water according to SAR are defined in correspondence with the EC values determined in the water (16,26-28). For this purpose, the criteria shown in Table 3 are used. The same SAR criteria are used to classify CROSS (18,21).

RESULTS AND DISCUSSION

Characteristics of the studied waters

Table 4 shows the mean, minimum, maximum, and standard deviation values of the variables used to determine the risks of permeability problems in soils irrigated with the studied waters. In all cases, a high coefficient of variation is observed, indicating the spatial and temporal variability in the quality of these waters. An example of this is electrical conductivity, with values ranging from close to 0.7 dS m to values above 8 dS m.

Permeability Index

Table 5 presents the main statistical summary measures related to the Permeability Index. In all cases, the water classification falls under Class II, defined as "Good" (Table 2); that is, 100 % of the studied water sources are considered unlikely to affect soil permeability. The coefficient of variation values confirm the spatial and temporal variability of water quality in the wells of the Javita River basin.

A more detailed analysis of the PI can be seen in Figure 2, where several wells, specifically those identified with numbers P-15 to P-24, show a trend toward decreasing PI values between 30 and 40 %, close to the upper limit of Class III (Unsuitable). This could be related to the end of the dry season in the area, which increased the salt concentration in some wells, while others were completely dry.

Risk of sodium accumulation in the soil

The risk of sodicity in the soils was determined using the SAR, SAR_x, and CROSS indicators in combination with electrical conductivity (16,26-28). However, as can be seen in Table 6, for the conditions studied there were practically no differences in the classifications obtained among the indicators.

Magnitude of the risk

"No restriction" conditions predominate in all three samplings. Nevertheless, nine wells show "Slight to Moderate" restrictions in May and/or August, associated with combinations of low EC and SAR_x/CROSS between 3 and 5. In the December sampling, all available observations classify as no restrictions; this could be explained by a decrease in sodium content and an increase in calcium and magnesium in the waters.

Table 3. Classification of irrigation water use restrictions: SAR/CROSS vs. CE

SAR/SARx/CROSS	Use restrictions: None	Use restrictions: Slight to Moderate	Severe
	CE in dS m	CE in dS m	CE in dS m
0 - 3	> 0.7	0.7 - 0.2	< 0.2
3 - 6	> 1.2	1.2 - 0.3	< 0.3
6 - 12	> 1.9	1.9 - 0.5	< 0.5
12 - 20	> 2.9	2.9 - 1.3	< 1.3
20 - 40	> 5.0	5.0 - 2.9	< 2.9

Table 4. Descriptive statistics of the variables involved in the indices studied for the three samplings

Sampling	Descriptive statistics	EC (dS m)	Ca^{2+}	Mg^{2+}	Na^{+} (mEq L)	K^{+}	$HCO3^{-}$
May	n	25	25	25	25	25	25
	Mean	2.14	9.34	3.07	9.99	0.32	1.98
	S.D.	1.69	5.69	2.42	10.49	0.16	0.66
	Min.	0.74	2.20	0.92	2.90	0.16	1.28
	Max.	8.14	24.80	10.74	51.93	0.84	4.35
	C.V.	79 %	61 %	79 %	105 %	50 %	33 %
August	n	25	25	25	25	25	25
	Mean	1.96	7.76	2.94	8.93	0.24	2.44
	S.D.	1.12	4.37	1.96	6.37	0.09	0.62
	Min.	0.77	2.45	0.90	3.34	0.12	1.50
	Max.	4.90	18.75	8.12	26.80	0.54	3.36
	C.V.	57 %	56 %	67 %	71 %	39 %	25 %
December	n	20	20	20	20	20	20
	Mean	1.94	9.89	2.76	6.89	0.25	2.48
	S.D.	1.57	4.28	1.83	7.23	0.15	1.04
	Min.	0.76	5.86	1.08	2.36	0.09	1.15
	Max.	7.00	20.37	6.82	30.72	0.85	5.38
	C.V.	81 %	43 %	66 %	105 %	62 %	42 %

Source: Authors' own elaboration

Table 5. Descriptive statistics of the Permeability Index

Sampling	n	Mean	S.D.	Min.	Max.	C.V.
May	25	50.90	12.09	27.72	74.52	24%
August	25	54.92	9.40	34.12	69.01	17%
December	20	40.20	7.18	32.24	58.66	18%

Source: Authors' own elaboration

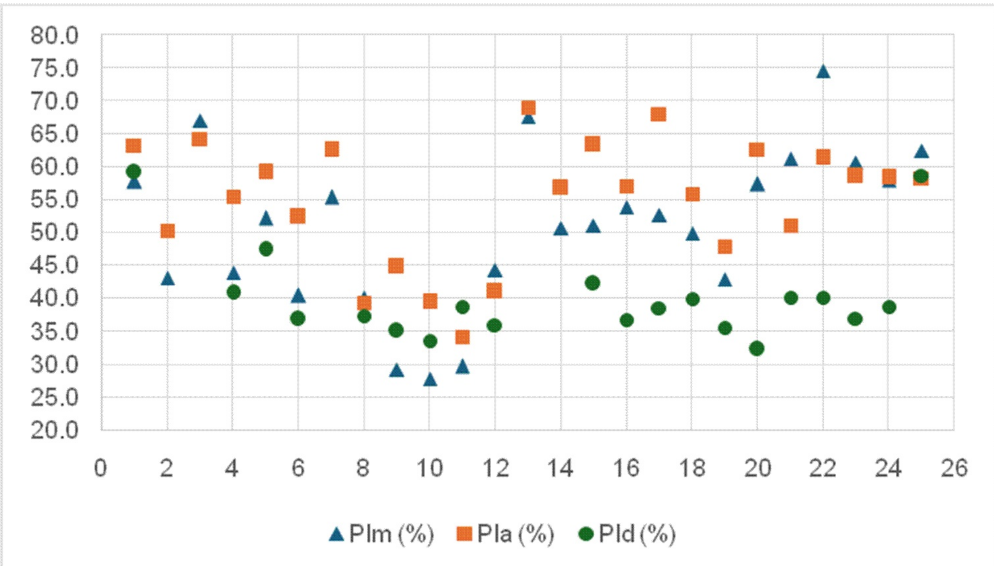

Figure 2. Permeability Index values for the three sampling periods (PIm: May; PIa: August; PId: December)

Table 6. Sodium accumulation risk in the studied soils

Wells	Use restrictions								
	May sampling			August sampling			December sampling		
	SAR	SARx	CROSS	SAR	SARx	CROSS	SAR	SARx	CROSS
P-01	N	N	N	N	N	N	N	N	N
P-02	N	L to M	L a M	N	N	N	SD	SD	SD
P-03	N	N	N	N	N	N	SD	SD	SD
P-04	N	N	N	N	N	N	N	N	N
P-05	N	N	N	N	N	N	N	N	N
P-06	N	N	N	N	N	N	N	N	N
P-07	N	N	N	N	N	N	SD	SD	SD
P-08	N	N	N	N	N	N	N	N	N
P-09	N	N	N	N	N	N	N	N	N
P-10	N	N	N	N	N	N	N	N	N
P-11	N	N	N	N	N	N	N	N	N
P-12	N	N	N	N	N	N	N	N	N
P-13	N	N	N	N	N	N	SD	SD	SD
P-14	L to M	L to M	L to M	L to M	L to M	L to M	SD	SD	SD
P-15	N	N	N	L to M	L to M	L to M	N	N	N
P-16	L to M	L to M	L to M	L to M	L to M	L to M	N	N	N
P-17	L to M	L to M	L to M	L to M	L to M	L to M	N	N	N
P-18	N	N	N	N	N	N	N	N	N
P-19	N	N	N	N	N	N	N	N	N
P-20	N	N	L to M	L to M	L to M	L to M	N	N	N
P-21	L to M	L to M	L to M	N	N	N	N	N	N
P-22	L to M	L to M	L to M	L to M	L to M	L to M	N	N	N
P-23	L to M	L to M	L to M	L to M	L to M	L to M	N	N	N
P-24	L to M	L to M	L to M	L to M	L to M	L to M	N	N	N
P-25	N	N	N	N	N	N	N	N	N

SAR_{Corr}.: SAR_x; N: None; L a M: Slight to Moderate; SD: No data. Source: Authors' own elaboration

Persistence of the conditions

Wells P-14, P-16, P-17, P-22, P-23, and P-24 show consistency in the "Slight to Moderate" category in May-August, thus requiring differentiated management if used to irrigate soils sensitive to dispersion. These wells also show a decrease in Permeability Index in December.

Physicochemical interpretation

According to FAO guidelines, infiltration problems depend on the EC-SAR pair: for the same SAR, higher EC tends to mitigate soil dispersion; at low EC, the same SAR increases the risk (EC-SAR_x criterion) (16,17). SAR_x integrates the effects of carbonates/bicarbonates and the Ca^{2+} cation in solution, and is preferred for evaluating infiltration when there are relevant contents of HCO_3^- and CO_3^{2-} (29).

Cation Ratio of Structural Stability (CROSS)

This index incorporates the dispersive power of the K^+ cation, in addition to that known for Na^+, and the contrast in flocculation caused by Mg^{2+}, which is not considered to have the same influence as Ca^{2+}. CROSS offers a more comprehensive measure of soil structural stability under irrigation water and is used as an alternative to SAR (18,21,30). However, in this study, its classification results did not differ from those obtained with SAR_x.

Determination of use restrictions to avoid infiltration problems

Based on laboratory data and the criteria for defining restriction classes shown in Table 3, the following is proposed:

- "None" category: These are waters from this basin with EC ≥ 1.3-1.5 dS/m and SAR/SAR_x/CROSS ≤ 5-6; they are suitable for loamy-sand to silt-loam soils, with no evidence of sealing, as long as the effective salinity of the wetting bulb is maintained (avoiding abrupt dilution due to rainfall or water mixing).
- "Slight to Moderate" category: These require caution in irrigation management on soils with swelling clays or with low-EC irrigation water. Recommended measures include raising Ca^{2+} (calcium amendments, e.g., agricultural gypsum as a carrier or controlled acidification to dissolve carbonates), avoiding EC decreases due to water mixing, and adjusting irrigation depths and scheduling.

All available samples from the December sampling fall into the "None" category; however, the absence of data from five wells imposes caution in interpreting these results. During prolonged dry periods, salts in the soil profile may increase; therefore, irrigation management must maintain soil electrical conductivity compatible with the electrolyte threshold of the local soil-water system (31).

The classification of several wells in the "Slight to Moderate" category for infiltration problem risk indicates that these waters can be used for irrigation, but with caution, as they may promote clay dispersion, surface sealing, reduction of macropores, and consequently, lower infiltration rates and less uniform water distribution in the soil profile. This process reduces irrigation efficiency and limits salt leaching. For crops such as corn and watermelon, this will cause emergence problems and water stress during critical developmental stages. In citrus, the effect may be more severe and cumulative, since reduced infiltration and salt concentration in the root zone limit vegetative vigor and commercial fruit quality. For plantains, due to their high water demand and sensitivity to soil physical degradation, reduced infiltration can affect growth, leaf area development, and bunch weight. Overall, these results suggest that, although a widespread severe limitation is not evident, wells with a "Slight to Moderate" restriction require monitoring and management practices aimed at preserving soil structural stability and irrigation efficiency, particularly for perennial crops or those with high water requirements (32-36).

To maintain stable electrical conductivity in the wetting bulb and minimize low-concentration peaks, localized irrigation systems (e.g., drip or micro-sprinkler) are recommended.

Sudden dilutions of the irrigation water electrical conductivity (i.e., through mixing with very low salinity water or rainfall-interleaved irrigation) should be avoided. Leaching fractions should be moderate, applied when the soil is at adequate moisture and structurally stable, so as not to exceed the dispersion threshold.

To improve surface porosity and resistance to sealing, organic cover (crop residues, green manures) and minimum tillage should be maintained. These practices do not replace ionic control but help buffer the reduction in infiltration.

CONCLUSIONS AND RECOMMENDATIONS

1. According to the indicators used and the data obtained from the three samplings, the waters of the studied wells do not represent a current risk for sodium accumulation in soils or the consequent reduction in soil permeability.
2. Wells that remain in the "Slight to Moderate" category should be monitored due to the potential decrease in their Permeability Index during dry periods (low water levels).
3. To complement the physical chemical evaluation of irrigation water quality, physical characterization studies of the soils in the basin are recommended.

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