

SALINITY OF SOIL AND IRRIGATION WATER ON RICE PRODUCTIVITY IN THE CANTON OF SAN JACINTO DE YAGUACHI, ECUADOR

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ABSTRACT

The surface of agricultural soils affected with salinity causes degradation and reduction of crop production, negatively impacting the economy of farmers. The objective of this research was to determine the effect of water quality and soil salinity on rice production in the sub-basin of the Yaguachi River, Ecuador. For this purpose, 99 soil samples were georeferenced and analysed over an area of 19 027 ha, as well as water samples representative of the area under study. Soil pH and electrical conductivity (EC) maps were produced and a regression analysis between EC and rice yield was performed on 34 producer plots. The predominant texture of the soils was found to be clayey, with an average pH of 6.73; The 38.4 % of the samples had an EC between 3.8 and 7.1 dS m⁻¹. Rice yield gradually decreased as it was grown in soils with higher salinity and 26.81 % of the yield loss was found to be attributed to the increase in EC. The salinity of the irrigation water and other quality indicators such as the percentage of soluble sodium (Na⁺) and the sodium adsorption ratio (RAS) classified the water as severely restricted for use. However, given that crop yields did not show as drastic a reduction as expected, it can be said that the rice plant responds to the conditions of the canton of San Jacinto de Yaguachi as moderately tolerant to salinity.

Keywords: electrical conductivity, Ecuador, sodium adsorption ratio - RAS, regression, Yaguachi.

INTRODUCTION

Soil salinity is one of the problems that most affects agroecosystems worldwide. Soil origin, use of saline irrigation water and excessive fertilization are described as the main causes of salinization (FAO, 2015). In Ecuador, the formation of saline soils has been reported by Pozo *et al.* (2010), especially in the flat areas of the coastal slope, with Guayas being the most affected province (INIAP, 2014).

Rice is sensitive to salinity, especially in the plantlet stages, end of the vegetative phase and initiation of the panicle until flowering (Munns and Tester, 2008). The plant is

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relatively tolerant during germination, as well as throughout the grain filling and ripening stages. Salinity delays spiking and flowering, which increases ear sterility, reduces weight and total carbohydrate content in the grain, and in the end decreases yield. Soil EC values above 3.8 dS m^{-1} can generate yield losses greater than 25 % (Willadino and Rangel, 2010).

In the San Jacinto de Yaguachi canton, Guayas province, Ecuador, 3000 ha of rice are cultivated under flooding. This surface is irrigated during the dry season (June to December) with water from the Yaguachi River. Its saline waters, due to the tides, extend towards the interior of the continent, up to 100 km through its tributaries; there is intrusion of saline water into the study area (Medina *et al.*, 2022).

The objective of this study was to determine the degree of salinity affectation on soils and the effect of irrigation water in the San Jacinto de Yaguachi canton, as well as the effect of salinity levels on the yield of rice production systems.

MATERIALS AND METHODS

The research was conducted in the San Jacinto de Yaguachi canton, Guayas province, Ecuador, between $2^{\circ} 5' 15'' - 2^{\circ} 6' 14'' \text{ N}$ and $79^{\circ} 40' 51'' - 79^{\circ} 42' 03'' \text{ W}$. The San Jacinto de Yaguachi canton has a tropical savanna climate (Aw) according to the Köppen climate classification. According to the records of the National Institute of Meteorology and Hydrology (Ecuador; INAMHI, 2021), precipitation is markedly seasonal, with an annual average of 1250 mm concentrated almost entirely in the months of January through May, and the average monthly temperature varies between 24.0 and 27.2 °C. The soils are classified as vertisols, characterized by a high content of expansive clay 2:1; they are poorly drained and when they are dry, wide and deep cracks are formed (Gardi *et al.*, 2014).

Soil and water sampling

Soil sampling was conducted in September 2018, a period without rainfall. The study area comprised 19 027 ha located on both banks of the Yaguachi River, where 99 agricultural plots were randomly selected. Sampling points within the study area are highlighted (Figure 1A).

Composite soil samples (15 subsamples) were taken in the 0–20 cm depth of each plot. For water sampling, five sites were selected distributed among the irrigation channels within the study area. Composite samples were taken in the center of each irrigation channel, 10 cm below the surface using polyethylene bottles. Samples were kept refrigerated at 4 °C until analysis. Both soil and water sampling points were georeferenced using a GPS.

Soil and water analysis

Soil and water analyses were performed at the Chemical Laboratory of the Sugarcane Research Center of Ecuador (CINCAE). Physical and chemical properties of the soil were determined, texture, EC and pH in the saturated mix.

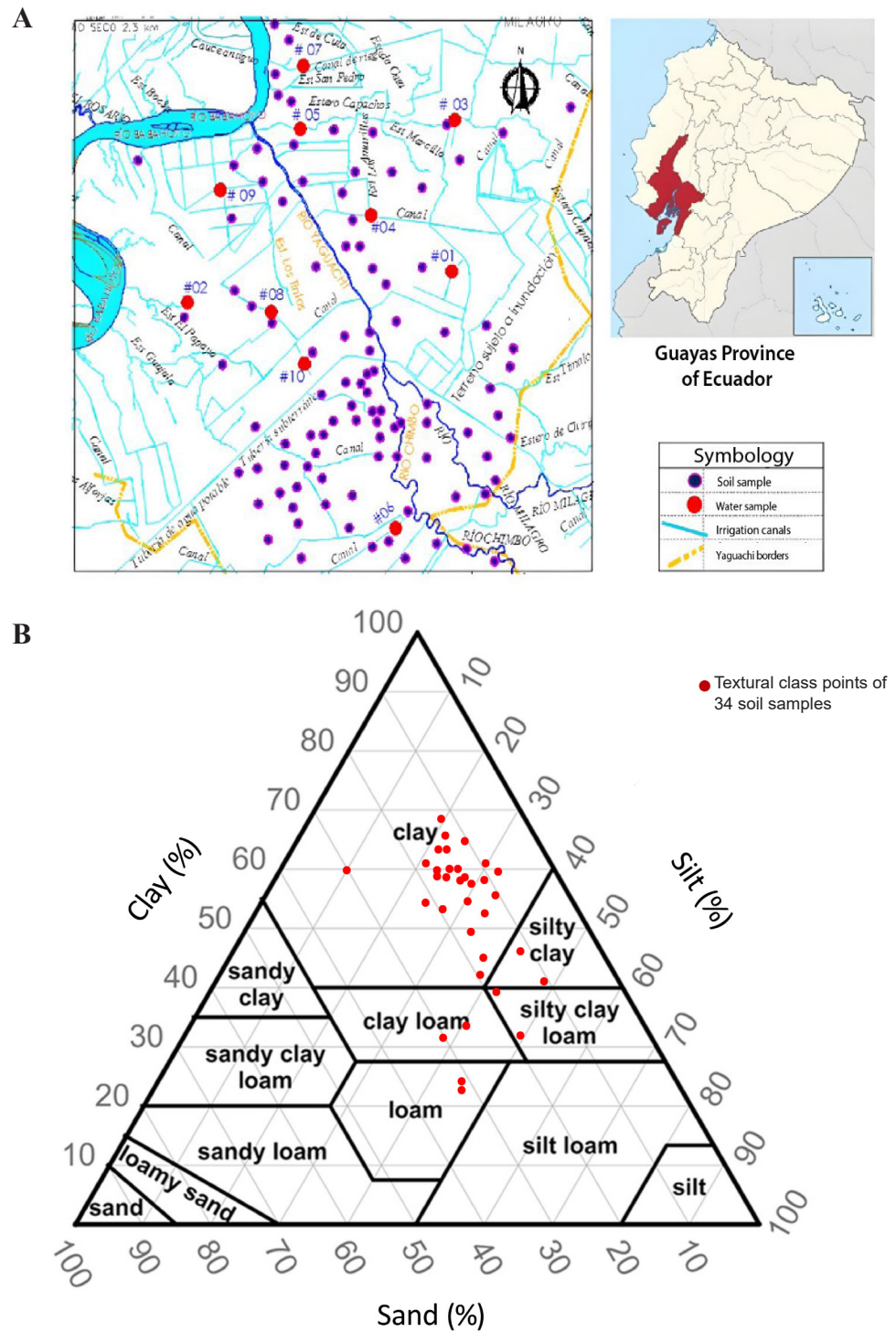


Figure 1. Samples from the canton of San Jacinto de Yaguachi, Guayas province, Ecuador. A. Location of soil and water sampling sites (blue and red dots, respectively). B. Location of soils within the textural triangle.

In the water samples, pH, EC, Na⁺, K⁺, Ca²⁺, Mg²⁺, bicarbonate, chloride and sulphate contents were determined. Furthermore, the original and adjusted RAS (RASaj) were calculated using the following formula (concentrations in meq·L⁻¹):

$$\text{RAS} = \text{Na} / [(\text{Ca} + \text{Mg}) / 2]^{1/2}$$

For the RASaj, the Ca concentration was replaced by the concentration expected to remain in the soil solution after reaching equilibrium conditions, according to the procedure described by Bower (1968). Additionally, the percentage of soluble sodium (PSS) in water was calculated according to Doneen's formula: PSS = 100 * Na⁺ / (Na⁺ + Ca²⁺ + Mg²⁺ + K⁺).

Soluble salts were composed based on the composition of the soluble ions and to estimate the precision of the chemical analysis of the water, the ionic equilibrium error equation was used, according to Matthes (1980): e = 100* (sc - sa)/(sc + sa), where e: percentage error, sc: sum of cations and sa: sum of anions (both in meq L⁻¹).

On the other hand, information was available from the farmers regarding the yields obtained in their rice plots. Within the 99 sampling points, 34 farms were found where accurate data on average rice yields were available. With this information, an exponential regression analysis between soil EC and crop yield was performed to express the trend of decreasing yields.

Elaboration of pH and EC maps

The geographic coordinates of each of the 99 sampling points and their corresponding pH and EC values were placed in an Excel table, which was added to the geographic information system (GIS). Interpolation was performed and the corresponding pH and EC isolines were plotted. Subsequently, the map of expected yield as a function of soil EC was elaborated using the reference values of Willadino and Rangel (2010). Regression analysis was performed using Costat (Cohort) version 6.4; whereas, ion concentrations were analysed with statistical descriptive techniques as measures of central tendency and dispersion in Minitab® version 19.

RESULTS AND DISCUSSION

Soil

Out of 34 rice plots, 76.5 % of the soil studied is of clay textural class, followed by 5.9 % as loam, clay loam, silty clay loam and silty clay (Figure 1B). With over 35 % plastic and sticky clay and 50 % of the expansive clay fraction (2:1) of montmorillonite type, the soils were classified as vertisols (the vast majority of soils had high to very high clay contents). Heavy soils, such as clay soils, usually have higher fertility and water retention capacity than light soils and their main limitation for crop growth is their low oxygen circulation. Since rice has the tissue known as aerenchyma, which can provide oxygen to the roots under flooding conditions, it is an ideal crop for this type of soils, particularly when the flood irrigation system is used. In this regard, Dou *et*

al. (2016) mentioned that on clay soils rice significantly increased its grain yield and biomass accumulation compared to those grown on loam or sandy soils.

pH and EC

The pH found had a mean of 6.73 within a range from 5.90 to 7.55; it was observed that 5766 ha (30.33 %) are slightly acid soils, while 66.67 %, corresponding to 13 261 ha, showed practically neutral pH from 6.5 to 7.5 (Figure 2A). It can be considered normal that the soils in the rice plots in the canton of San Jacinto de Yaguachi have pH values close to neutrality as a consequence of flood irrigation using water with pH close to 7, as may be seen below. The optimal pH for rice is 6.6, because at this value the microbial release of nitrogen (N) and phosphorus (P) from organic matter is high, while metals such as aluminum (Al), manganese (Mn) and iron (Fe) are below the toxic level. Outside this range, unfavorable conditions for plant growth are generated; since at low pH there are Ca and Mg deficiencies and high Al contents, as well as high P fixation, while at high pH there may be insufficiency of soluble micronutrients (Neina, 2019).

Regarding EC, 24.24 % of the samples (4612 ha) presented a value of 3.8 to 5.1 dS m⁻¹, and 14.14 % (2690 ha) ranged from 5.1 to 7.2 dS m⁻¹. According to Willadino and Rangel (2010), with the aforementioned salinity ranges, rice production would decrease by 25 and 50 %, respectively (Figure 2B).

Rice yield gradually decreased as it was grown in soils with higher salinity following an exponential trend (Figure 3) and it was found that 30.15 % of the yield loss could be attributed to the increase in EC. In other words, almost one third of the yield decrease is caused by soil salinity. Although this degree of association between yield and salinity is apparently not very high, at least two considerations must be accounted for. The first is that the association between the two variables was highly significant ($p \leq 0.01$), this is that the association between them really exists. Second, there are other factors involved in the process that were pointed out by the different producers, such as differences in crop management, use or not of certified seed, intensive or scarce pest and disease control, among others. Additionally, other improper cultural practices such as inadequate fertilization, low or no incorporation of organic matter, excessive applications of nitrogen fertilizers, failure to perform soil analysis, and inadequate weed control may also have an impact. Nevertheless, the regression line in the figure shows that plants maintained a yield close to 2.5 Mg ha⁻¹ at an EC higher than 12 dS m⁻¹.

The rice plant is highly tolerant to waterlogging, which may favour its performance in the saline soils of the study because flood irrigation, where standing water is maintained, can produce salinity reduction in the root zone by washing and dilution of salts (FAO, 2015). The above observations suggest that the rice plant behaves as moderately tolerant to salinity in the conditions of the canton of San Jacinto de Yaguachi.

Giao (2021) found a reduction of up to 30 % in the average yield of different rice varieties when soil salinity reached a value of 3.87 % (approximately 6 dS m⁻¹) due to

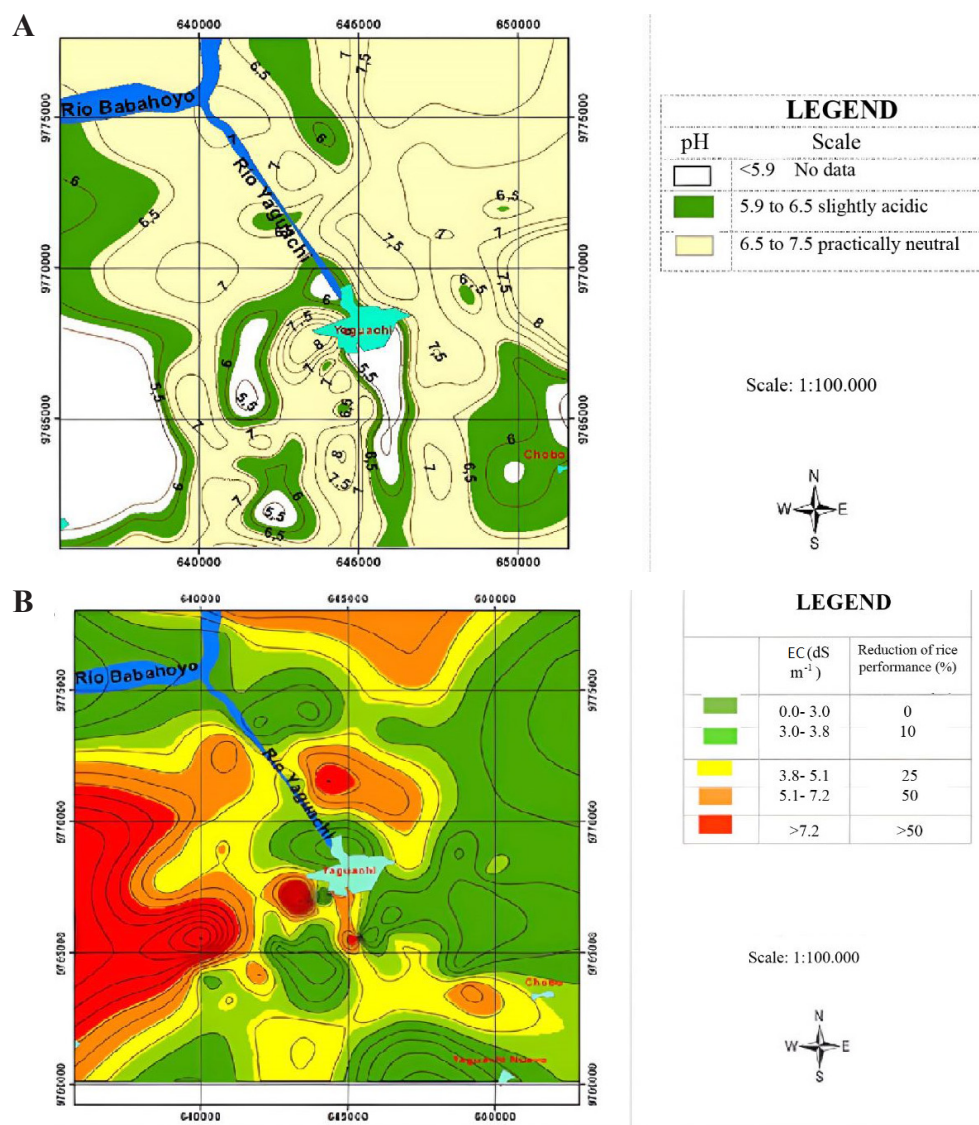


Figure 2. Distribution of soil chemical characteristics in the farms within the study area in the canton of San Jacinto de Yaguachi, Guayas province, Ecuador (n = 99 samples). A. pH. B. Electrical conductivity (EC) and estimated rice yield reduction (according to Willadino and Rangel, 2010).

saline intrusion, indicating that in that study there were moderately acceptable yields despite the high salinity value. In contrast, Lan (2021) detected in variety H78 a yield reduction of 58.6 % when the EC of the medium reached approximately 4.7 dS m⁻¹ and no yield when the EC approached 8 dS m⁻¹.

This indicates that there are different salinity tolerance indices associated with varietal differences in rice plants, as stated by Cristo-Valdés *et al.* (2018). Differences in yield attributed to salt stress are mainly observed in the number of panicles and stems per plant (Khanam *et al.*, 2018). Rodriguez *et al.* (2019) mentioned that the mechanisms that

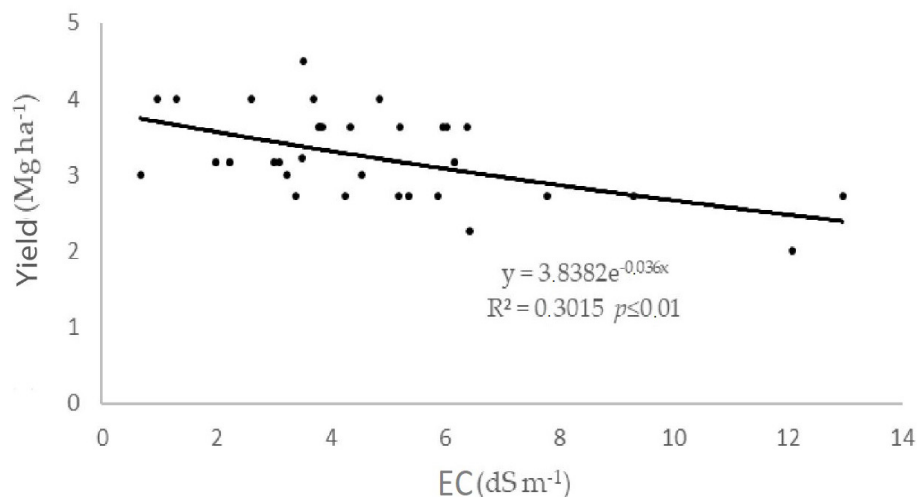


Figure 3. Exponential regression analysis between irrigation water EC and rice yield in 34 farms in the study area in the canton of San Jacinto de Yaguachi, Guayas province, Ecuador.

explain the differences in the response to salt stress in rice varieties are associated with differences in their osmotic adjustment capacity.

In a recent review, Chen *et al.* (2021) summarized information on the major molecular mechanisms underlying salinity tolerance in rice and highlighted that numerous gene families and interaction networks are involved in regulating the response. In this regard, Pundir *et al.* (2021) recently identified quantitative trait loci (QTL) for salt stress tolerance in rice that may be advantageous in breeding programs for the development of salinity tolerant varieties at the reproductive stage.

Water

On the values of the chemical characteristics of irrigation water (Table 1), it was observed that in all samples the total concentration of negative ions (anions) exceeded that of positive ions (cations). Which suggests that perhaps some important cation, such as K^+ or Fe^{+2} (ferrous ion), was not included in the analysis; although it is known that these ions are usually found in low concentrations in natural waters. For this reason, when evaluating the precision of the water analysis based on its ionic balance, an analysis that complied with a balance error slightly higher than usual, but always within a range percentage restricted to one digit (this is, less than 10 %) was considered acceptable. The average error obtained was 7.15 % (Table 2).

The pH of the five samples showed values close to each other and ranged from 6.44 to 7.01, with an average of 6.77, which means classifying it practically as neutral water (Table 2). From this point of view, it does not pose problems to be used for irrigation according to the classification criteria from Ayers and Westcot (1994).

The EC of water did not present important variations, showing values between 2.32 and 2.84 $dS m^{-1}$, with a coefficient of variation of 7.47 % (Table 2). This indicates that

Table 1. Concentration of ions and soluble salts in rice irrigation water in the canton of San Jacinto de Yaguachi, Guayas province, Ecuador.

Sample	Ions (meq L ⁻¹)						Salts (meq L ⁻¹)					
	Na ⁺	Ca ⁺²	Mg ⁺²	Cl ⁻	HCO ₃ ⁻	SO ₄ ⁻²	Ca(HCO ₃) ₂	Mg(HCO ₃) ₂	CaSO ₄	MgSO ₄	Na ₂ SO ₄	NaCl
1	20.85	2.76	6.22	19.45	2.43	10.72	2.43	0	0.33	6.22	4.17	16.68
2	22.39	1.25	4.79	20.13	1.27	9.92	1.25	0.02	0	4.77	5.15	17.75
3	19.25	2.48	5.61	19.04	2.08	12.21	2.08	0	0.4	5.61	6.6	12.65
4	21.12	2.86	6.18	20.40	2.44	12.36	2.44	0	0.42	6.18	6.18	20.4
5	19.55	1.09	4.28	18.64	1.76	9.41	1.09	0.67	0	4.28	5.13	18.64
Mean	20.63	2.09	5.42	19.53	2.00	10.92	1.86	0.14	0.23	5.41	5.45	17.22
Maximum	22.39	2.86	6.22	20.40	2.44	12.36	2.44	0.67	0.42	6.22	6.6	20.4
Minimum	19.25	1.09	4.28	18.64	1.27	9.41	1.09	0	0	4.28	4.17	12.65
SD	1.27	0.85	0.86	0.73	0.49	1.33	0.65	0.30	0.21	0.86	0.96	2.90
CV	6.16	40.78	15.86	3.76	24.74	12.16	26.52	44.41	50.62	13.87	14.54	14.20

Na⁺: sodium ion; Ca⁺²: calcium ion; Mg⁺²: magnesium ion; Cl⁻: chloride; HCO₃⁻: bicarbonate; SO₄⁻²: sulphate; Ca (HCO₃)₂: calcium bicarbonate; Mg (HCO₃)₂: magnesium bicarbonate; CaSO₄: calcium sulphate; MgSO₄: magnesium sulphate; Na₂SO₄: sodium sulphate; NaCl: sodium chloride.

Table 2. Water quality indicators in rice irrigation and estimation of the analytical error in the canton of San Jacinto de Yaguachi, Guayas province, Ecuador.

Sample	pH	EC (dS·m ⁻¹)	PSS	RAS	RASaj	Error (%)
1	6.91	2.49	69.90	9.84	19.09	4.44
2	6.44	2.84	78.75	12.88	17.78	4.84
3	6.78	2.53	70.41	9.57	18.19	9.87
4	6.7	2.63	70.03	9.93	19.87	7.71
5	7.01	2.32	78.45	11.93	23.03	8.93
Mean	6.77	2.56	73.51	10.83	19.59	7.15
Maximum	7.01	2.84	78.75	12.88	23.03	
Minimum	6.44	2.32	69.90	9.57	17.78	
SD	0.22	0.19	4.66	1.48	2.08	
CV	3.23	7.47	6.33	13.69	10.64	

EC: electrical conductivity, RAS and RASaj: original and adjusted sodium adsorption ratio, respectively.

water would present light to moderate use restriction if it is considered that it stays within the range 0.7 to 3.0 dS·m⁻¹ (Abdallah and Mourad, 2021). However, according to Salinity Laboratory Staff criteria (El-Aziz, 2017), the water was classified as of very high salinity that should be used in well-drained soils for crops with high-tolerance to salinity; which means it would not be recommended for the rice crop under study. Water EC, as an indicator of salinity risk, is the most important quality parameter for crop productivity. First above all, water with high salinity causes physical problems

due to high ionic concentration that results in a decrease of useful water for plants due to the reduction of their osmotic potential. Which means that even if the soil has high humidity, plants suffer water stress due to the difficulty of the roots to absorb water. Simultaneously or afterwards, chemical or toxic problems caused by specific ions such as chlorine or sodium may occur in the plant (Fipps, 2003).

The moderately high EC recorded in the water of the study area may reflect the enrichment by some salts as there is saline intrusion in the Yaguachi River as a result of tidal inflow, such as calcium sulphate, magnesium sulphate, sodium sulphate, and sodium chloride.

The RAS reached a mean of 10.83 (Table 2), a value that is considered a risk of toxicity to crops according to the criteria indicated by Ayers and Westcot (1994). The RAS value is a useful index for estimating the risk posed by the sodium level of water for both crops and soils.

The use of this water for irrigation purposes is not considered a high risk for the soil since it is used in many light soils, but in vertisols as those in the area under study, with more than 50 % of expansive clays (montmorillonite), the risk of affecting permeability due to the effect of sodium is magnified. In this case, according to the previous criterion, severe soil dispersion problems could exist when RAS values are reached, higher than nine.

Continued use of water with a high RAS values can lead to a deterioration of the physical structure of the soil, as Na⁺ binds to the clays, breaking up the soil aggregates, whose particles will clog the pores and make soils increasingly impermeable to water and air penetration (Fipps, 2003). However, in a research implemented with different rice varieties subjected to different salt concentrations and values of RAS in the growth medium, Bajwa (1982) found that salinity damage was less when there were high values of RAS in the irrigation water. Thus, he concluded that rice, although considered moderately sensitive to saline conditions, proved to be very tolerant to sodic conditions. This suggests that the level of damage caused by salinity in rice depends on a close interaction between EC and RAS in the growth medium.

The percentage of soluble sodium in the water samples was quite high and ranged from 69.90 to 78.75, with a mean value of 73.51 (Table 2). This is a high value as compared to the critical limits of Doneen (Loera-Alvarado *et al.*, 2019). In natural waters, sodium content is a common parameter to evaluate their suitability for irrigation purposes, since this element can affect soil permeability, as mentioned above. Excess sodium combined with carbonate ions leads to the formation of alkaline soils, while with chloride it participates in the formation of saline soils. Irrigation water containing large amounts of sodium is of particular concern not only because of the effect on the soil but also because of its possible toxic effect on the plant. The Wilcox plot (Peinado *et al.*, 2011) which relates the percentage of sodium and EC, indicates that all water samples were classified as inappropriate or of doubtful acceptance (Figure 4).

The concentration of the rest of the ions in the water indicates average values of Ca⁺² and Mg⁺² of 2.09 and 5.42 meq L⁻¹, respectively (Table 1). Thus, according to the

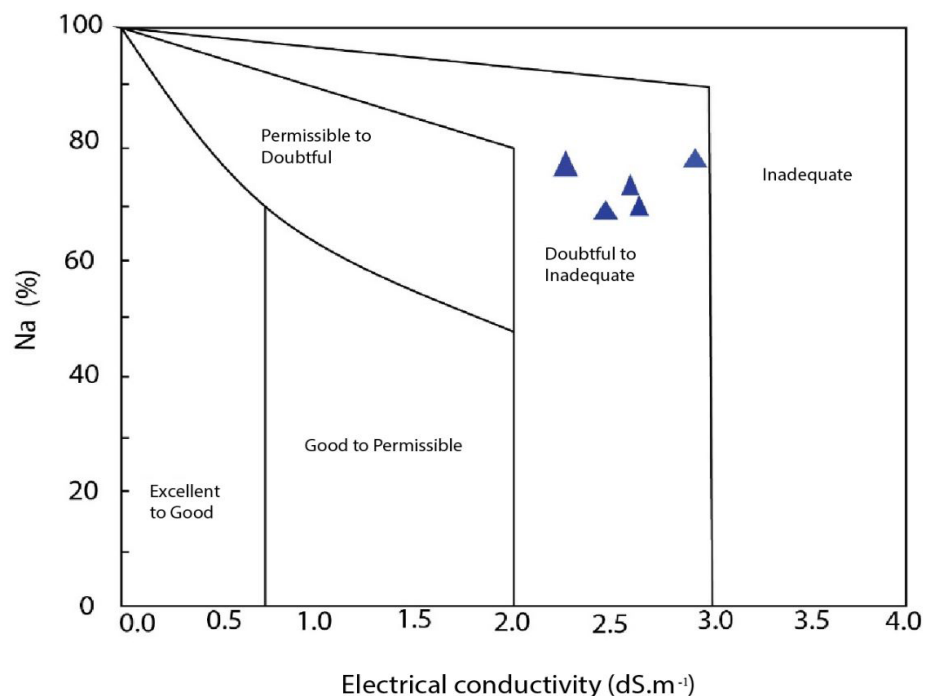


Figure 4. Wilcox nomogram with values of five irrigation water samples from the study area in the canton of San Jacinto de Yaguachi, Guayas province, Ecuador.

interpretation patterns of Monge (2018) for irrigation water, Ca would be at normal concentrations and Mg slightly high. Ca⁺² and Mg⁺² ions can help counteract the effects of Na⁺ and help maintain soil properties. On the other hand, excessive amounts of Ca²⁺ can restrict the availability of phosphorus (P), boron (B) and iron (Fe) for plants (FAO, 2015).

The chloride anion showed an average value of 19.53 meq L⁻¹ (Table 1), which highlights the saline condition of the water. According to the Ayeseedlnirs and Westcot (1994) classification, concentrations above 10 meq L⁻¹ create severe irrigation water use restrictions for many crops, including rice.

The sulphate anion showed a mean concentration of 10.92 meq L⁻¹ (Table 1) which is considered acceptable. In very high amounts, its salts can affect sensitive crops by limiting Ca²⁺ uptake and increasing Na⁺ and K⁺ uptake, leading to a disturbance of the cation balance within the plant.

For bicarbonates, in the water analysis, a mean value of 2.0 meq L⁻¹ was detected, with a minimum of 1.27 and a maximum of 2.44 meq L⁻¹ (Table 1). Although this ion is not normally toxic to the plant, it presents a mild to moderate degree of restriction for sprinkler irrigation, according to Ayers and Westcot (1994). This is due to the fact that when the water evaporates, a whitish precipitate of calcium bicarbonate remains on the leaves, which limits light uptake for the plant.

The presence of bicarbonates in irrigation water causes the precipitation of calcium ion (Ca^{2+}) and thus increases the risk of Na^+ in the soil. This is why, in our study, when calculating the adjusted RAS, we obtained a value of 19.59, which almost doubles the value of the original RAS of 10.83 (Table 2). This is a further highlighted risk of using this water.

The distribution of soluble salts in the water indicates that there was a predominance of sodium chloride with values greater than 17 meq L^{-1} (Table 1), followed in order of abundance by sodium and magnesium sulphates, with values of approximately 5 meq L^{-1} each, and finally by calcium bicarbonate with a low value (1.86 meq L^{-1}). Calcium sulphate (gypsum) was only present in three of the samples and showed a very low average value (0.23 meq L^{-1}). Irazoke *et al.* (2021), evaluating rice performance under saline conditions, indicated that sodium chloride was more toxic than sodium sulphate, and it was the common salt which most affected plant yield.

It should be noted, then, that the soil and water characteristics do not seem adequate for good rice productivity. However, the yields shown by the crop do not reflect such a drastic decrease as expected according to the salinity reduction tables. A possible explanation could be based on the type of irrigation that keeps the salts diluted and does not allow them to concentrate at their most damaging levels, and at the same time, by keeping the soil flooded, there is water available for the plant at all times.

The high availability of water in the soil corresponds to a scarce supply of oxygen to the roots, but as already mentioned, the rice plant has an aerenchyma tissue that allows it to overcome this disadvantage. In turn, the salinity of the water helps to compensate for the risk against soil permeability due to high Na^+ contents. On the other hand, it is to be expected that responses of the materials to the environmental conditions, such as soil salinity or water studied here, are influenced by the genotype, and their adaptation is expressed as a function of their intrinsic capacity for growth and root development, as well as fresh matter production.

CONCLUSIONS

A high percentage of the soils in the Yaguachi, Ecuador sub-basin, dedicated to rice cultivation, have high levels of salinity. In turn, the water used for irrigation has a moderately high electric conductivity and high sodium levels that can affect soil permeability. Nevertheless, the plant behaves in the conditions of the canton of San Jacinto de Yaguachi as moderately tolerant to salinity, which is attributed to the flood irrigation system, characteristic in the management of rice.

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