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Impact of Drought and Groundwater Quality on Agriculture in a Semi-Arid Zone of Mexico

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Abstract: This paper analyzes the behavior of drought in the face of the impact of climate change and groundwater quality and its implications for agricultural production in a semi-arid area of northeastern Mexico. The pluviometric information of two stations from 1961 to 2020 was analyzed, and the Standardized Precipitation Index was applied in the spring–summer period (SPI-6). Twenty-five samples from the Ahualulco aquifer were collected and analyzed, to which quality indices for agricultural use were applied. The results show that in the last 20 years there have been mild to moderate droughts, which have considerably affected rainfed farmers. The area under irrigation is affected by salinity conditions as the water goes from medium to high conductivities and low to medium sodicity, which indicates a medium sodicity risk but an excessive salinity risk.

Keywords: aquifer; water quality index; dry season; salinity; rainfed agriculture; agricultural irrigation

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1. Introduction

The phenomenon of drought can occur more frequently in aerated regions than in others [1]. There is no universal definition for drought. However, in all of them, the rainfall deficit occurs for a relatively long time. Some authors classify it into four types: meteorological drought, hydrological drought, agricultural drought, and socioeconomic drought [1–6].

From the point of view of hydrology and meteorology, drought occurs when precipitation is significantly lower than usual. Methods to estimate the duration, intensity, and spatial extent of drought are diverse, from hydrological methods [7–9] to spatial analysis and remote sensing [10,11]. These methodologies yield results used when establishing public policies and actions to mitigate the social, economic, and environmental impacts of drought. In Mexico, the socioeconomic effects of drought have been studied [12,13], such as in the case of San Luis Potosí, where studies that consider meteorological or hydrological aspects predominate [14,15]. However, the meteorological causes of drought have also been considered as in other countries and regions [16–18].

Depending on its magnitude and the strategies established to counteract it, drought can cause problems for agriculture (mainly seasonal), the hydroelectric sector, and industry, as well as a deficit in the drinking water supply, generating serious consequences for local populations [10,19,20]. In different areas, during droughts, irrigation is used to cover the water needs of other crops, but, increasingly, the limitations of irrigation water have to do with its quality, which in arid and semi-arid areas is underground and deteriorates with increasing extraction levels.

In arid or semi-arid regions, groundwater is the most critical water source and, in some cases, the only one [21]. In the development of agriculture, groundwater plays an important role [22]. Around 45% of the cultivated area is irrigated with groundwater worldwide [23]. One-third of the total groundwater in Latin America is used for agricultural activity. In Mexico, the primary source of water supply is underground, of which 1/3 is used for agricultural use.

Human development demands better quality in agricultural products [24]; this leads to stress in agriculture that requires better water quality (WQ) [18,23]. The evaluation of water quality is carried out through indices [25–27].

Poor irrigation water limits agricultural production [22,23].

The effects of sodium salinity, soil properties, and specific ion toxicity are aspects to consider when evaluating the quality of water used in agriculture [18]. This evaluation is addressed with indices such as sodium adsorption rate (SAR), magnesium absorption rate (MAR), percentage of soluble sodium (Na %), and residual sodium carbonate (RSC) [23,25–27].

Because both the quantity and the quality of water are essential to carrying out agricultural activities, this work aims to analyze the temporal behavior of drought in a semi-arid area of northern Mexico using the Standardized Precipitation Index and the influence of these climatic conditions on groundwater quality.

2. Materials and Methods

2.1. Location and Characterization of the Study Area

The Ahualulco municipality is located in the central part of Mexico, 20 km from the city of San Luis Potosí (Figure 1), between parallels 22°24′05.101″ north latitude and meridians 101°09′59″ west longitude. The altitude recorded for the municipal seat is 1902 m above sea level, with an average altitude of 1851 m above sea level.

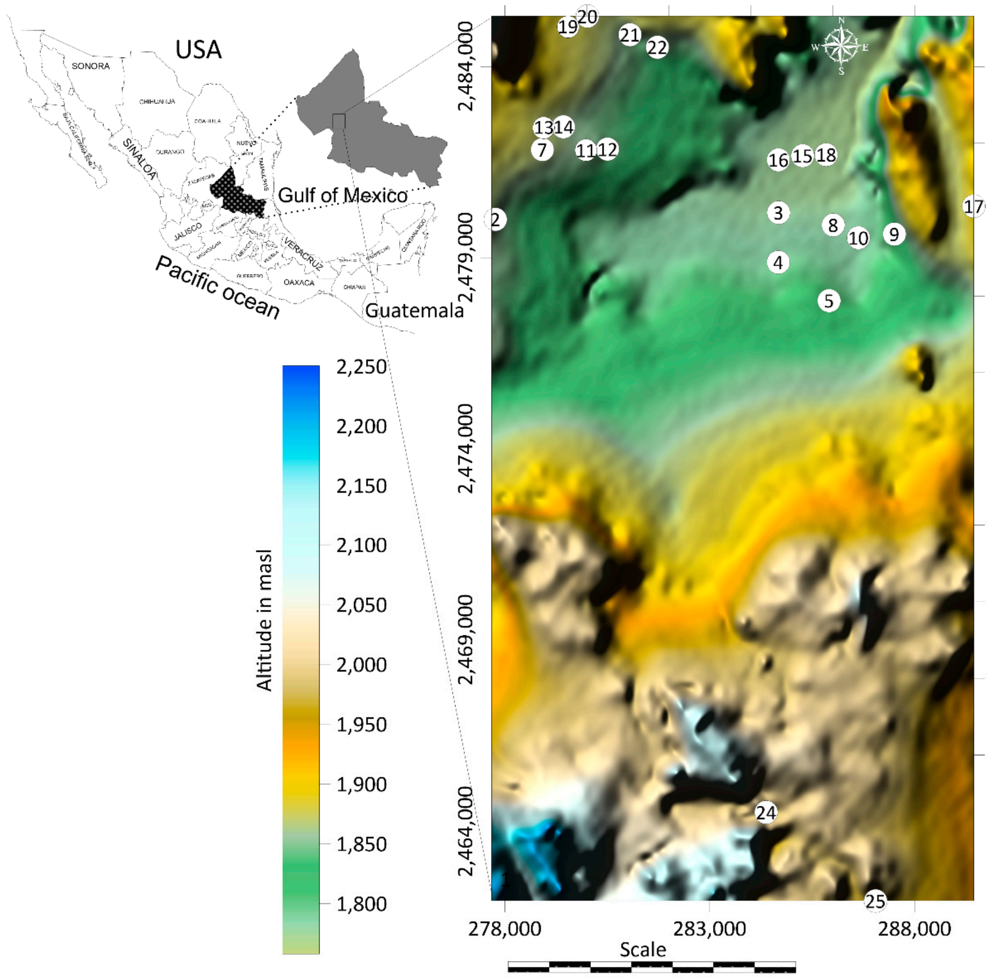


Figure 1. Location of the study area in northeast Mexico, and the locations of the sampling points.

2.2. Hydrogeological Framework

The Ahualulco aquifer is located in a syncline of carbonate rocks from the Cretaceous [28], which also constitutes the hydrogeological basement of the study area. On the Cretaceous rocks, volcanic rocks of rhyolitic composition are located, and in turn, the volcanic rocks are covered by conglomerates, sands, and silts.

The groundwater is extracted from the tertiary fill of volcanic rocks, which reach a thickness of 230 to 250 m, with flow rates greater than 30 l/s. The depths of wells range from 10 to 70 m. The shallowest levels are located to the west in the town of Ahualulco, while the deepest levels are located toward the east, in the Valle Umbroso. The flow goes from west to east, that is, from Ahualulco to Valle Umbroso.

2.3. Assessment of Drought and Agricultural Production

Precipitation follows a skewed frequency distribution, with most occurrences at low values and a rapidly decreasing probability of more significant precipitation totals. SPI algorithms analyze the input data to evaluate two significant coefficients that govern the transformation. The observed precipitation data are transformed into Gaussian (normal) equivalents.

The transformed precipitation data is then used to calculate the dimensionless SPI value, which is defined as the standardized precipitation anomaly:

$$\mathrm{SPI} = (P - P^*)/\sigma p$$

where

P = precipitation
P^* = mean precipitation
σp = standard deviation of precipitation

The Standard Precipitation Index (SPI) is a drought index based on the probability of precipitation for any time scale [2] and is widely used in several countries [29,30] and is the basis of the Drought Monitor in Mexico (DMM). The information registered in the Rincón del Porvenir station with code 24,061 with a registration period of 1961–2016 and from the Mexquitic station with code 24,042 with a registration period of 1943–2011 were used. Both are operated by the National Water Commission (CONAGUA) and are located inside the study area. The rainfall information was subjected to homogeneity tests using the Helmert, Student, and Cramer methods [29,31,32] and the independence test of Anderson [18,32]. Subsequently, the values were adjusted to the Gamma function, and the SPI-6 was determined for the spring–summer period [33], considering that the Pedj Drought Index (PDI) in scales of three and six months best describe the effects on agricultural production [4,28,34,35]. The results were plotted on an Excel sheet for the period 1961–2020.

The annual information on the planted and harvested area (hectares), agricultural production (tons), and the value of production (Mexican pesos) for the municipality of Ahualulco was obtained from the Agrifood and Fisheries Information Service (AFIS) of the Secretariat of Agriculture and Rural Development (SARD) of the government of Mexico. The period analyzed was 2000–2019; the data obtained from each of these variables were normalized [36] to analyze their behavior with respect to the SPI-6 and were graphed in the same Excel sheet.

2.4. Sampling and Activities Laboratory Measurements

Samples were taken from 25 dug wells in the dry season (Figure 1) to determine cations and anions in groundwater. Groundwater sampling was performed in accordance with APHA-AWWA-WPCF [37]. The samples were collected in high-density polyethylene bottles and washed with 10% hydrochloric acid to determine cations and trace elements. Physicochemical parameters (pH, EC, temperature, redox potential, dissolved oxygen, and alkalinity) were measured in situ for each collected sample. After collection, samples for cations and trace elements were acidified ultrapure nitric acid to $\mathrm{pH} < 2$. The samples were transported at a temperature of 4 °C. The main ions and trace elements were analyzed in the laboratory of the Center for Geosciences of the National Autonomous University of Mexico. Inductively coupled plasma atomic emission spectroscopy (ICP-AES) was used to determine concentrations of major cation ions (calcium, magnesium, sodium, potassium). Anions were analyzed using a Smart3 colorimeter (sulfate, nitrate, and chloride). Alkalinity and bicarbonate ($HCO_3{}^-$) were determined by in situ titration. The ion balance error (electroneutrality) in every 25 samples was considered less than 5%.

2.5. Classification of Water in Connection with Agricultural Use

In the analysis of water for irrigation, the conditions of acidity and alkalinity (pH) were considered, and indices such as the SAR, RSC, % Na, the soluble sodium percentage (PSS), Kelly ratio (KR), and permeability index (PI) were used [11,18]. Other indices used were electrical conductivity (EC), effective salinity (SE), salinity potential (SP), and osmotic potential (OP), which is closely related to total dissolved solids (TDS) and EC [38,39]. SP, SE, and OP allowed us to classify irrigation water (Table 1). The United States Department of Agriculture Salinity Laboratory plot and the Wilcox plot combine the SAR and EC indices. Water quality indices for agricultural use were evaluated using the equations shown in Table 1.

Table 1. Main equations to obtain the irrigation indices.

INDEX	Equation	Reference
sodium adsorption ratio (SAR)	$\frac{Na^+}{\sqrt{\frac{Ca^{2+}+Mg^{2+}}{2}}}$	[27]
Residual Sodium Carbonate (RSC)	$\left(CO_3^{2-} + HCO_3^-\right) - (Ca^{2+} + Mg^{2+})$	[26]
percentage Sodium Soluble (SSP)	$\frac{Na^+}{Ca^{2+}+Mg^{2+}+Na^+} * 100$	[26]
Sodium Percentage (% Na)	$\frac{Na^+ + K^+}{Ca^{2+}+Mg^{2+}+Na^+ + K^+} * 100$	[40]
Ratio Kelly (RK)	$\frac{Na^+}{Ca^{2+}+Mg^{2+}}$	[27]
permeability index (PI)	$\left(\frac{Na^+ + \sqrt{HCO_3^-}}{Ca^{2+}+Mg^{2+}+Na^+} * 100\right)$	[41]
Salinity Effective (SE)	$Ca^{2+} > \left(CO_3^{2-} + HCO_3^- + SO_4^{2-}\right)$ $Es = \sum cations - \left(CO_3^{2-} + HCO_3^-\right)$ $If\ Ca^{2+} > \left(CO_3^{2-} + HCO_3^- + SO_4^{2-}\right)\ but$ $Ca^{2+} > \left(CO_3^{2-} + HCO_3^-\right),\ then$ $Es = \sum cations - Ca^{2+}$ $If\ Ca^{2+} > \left(CO_3^{2-} + HCO_3^-\right)\ but$ $(Ca^{2+} + Mg^{2+}) > \left(CO_3^{2-} + HCO_3^-\right),\ then$ $Es = \sum cations - \left(CO_3^{2-} + HCO_3^-\right)$ $If (Ca^{2+} + Mg^{2+}) < \left(CO_3^{2-} + HCO_3^-\right),\ then$ $Es = \sum cations - (Ca^{2+} + Mg^{2+}$	[42]
Salinity Potential (SP)	$\left(Cl^- + \frac{1}{2}SO_4^{2-}\right)$	[42]
osmotic potential (OP)	$(OP(atm) \approx CE(\mu S.cm^{-1}) * 0.36$	[40]

3. Results

3.1. Drought and Sown and Harvested Agricultural Area

The pluvial precipitation data presented homogeneous and independent conditions, which coincided with what was determined in similar studies [13]. The PDI-6 showed similar trends for the two stations analyzed. In the period 1962–1966, it was observed that there were severe to mild droughts in the studied area, which were registered at the national level. Similar conditions were presented in the periods 1978–1980, 1996–2000, and in the years 1990 and 2003. In 2012, a mild drought was recorded, but the rainfall conditions recorded from that year at both stations were different. In the Mexquitic station, a moderate to mild drought was recorded; in the Rincón del Porvenir station, in 2013–2018, humidity conditions suitable for rainfed agriculture were observed. However, in the years 2019–2020, there were normal humidity conditions (Figure 2). Thus, in the last 20 years, only in 2003, 2005, and 2013 have there been moderate to mild droughts.

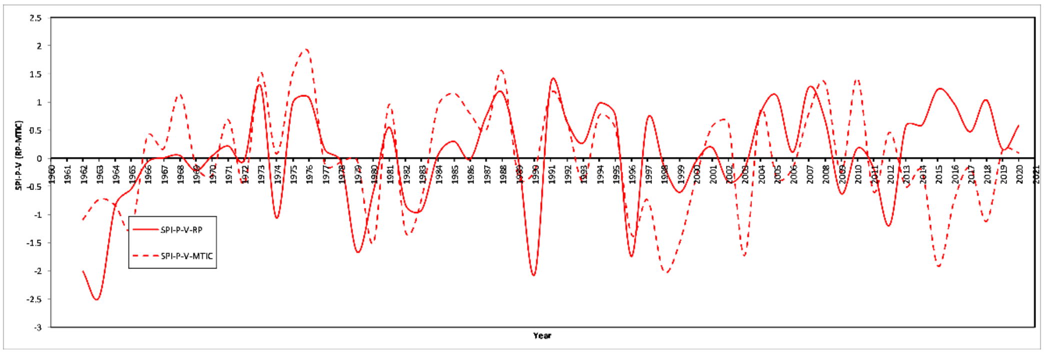


Figure 2. PDI-6 values for the spring–summer cycle in the Rincón del Porvenir (RP) and Mexquitic (MTIC) stations. Source: Author's elaboration based on CONAGUA (2020). SPI-P-V-RP = Rincon del Porvenir Station. SPI-P-V-RP = Mexquitic Station.

In the municipality of Ahualulco, rainfed agriculture is practiced, which is subject, in relation to the area sown and harvested, to the temporal variation of rainfall. In the 2003–2019 period, the average area sown and harvested in the spring–summer cycle was 2711.5 hectares and 1364.94 hectares, respectively, with a standard deviation of 890 and 887, respectively. The maximum value of planted area was 4500 hectares in 2007, and 2798 hectares were harvested. In the 2006–2008 period, there were conditions of rainfall superior to the average conditions, which in turn caused adequate humidity conditions for agricultural production. The maximum value of the harvested area was 3300 hectares in 2004, the year in which the humidity conditions were higher than average (Figure 3). The smallest planted area was 850 hectares in 2006, and the smallest harvested area was 500 hectares in 2005 [24].

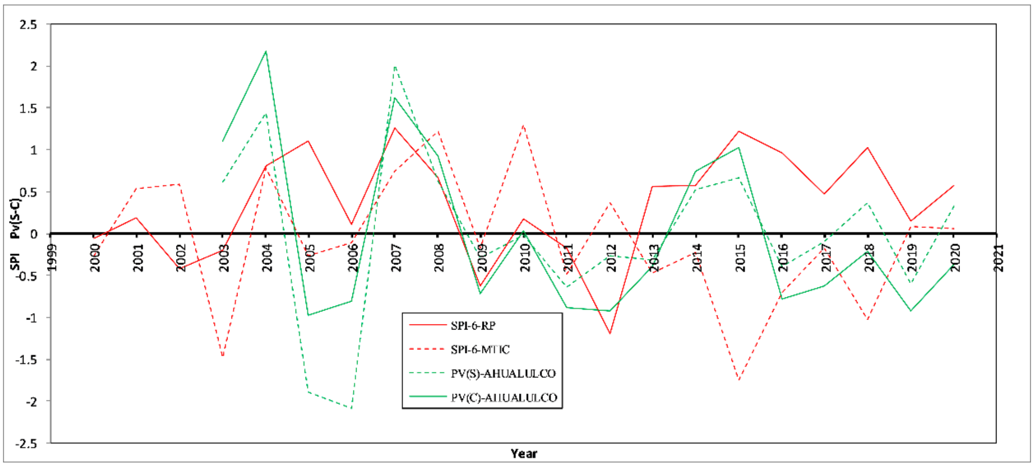


Figure 3. The behavior of the sown and harvested area vs. SPI-6. Source: Authors' elaboration based on statistical information from CONAGUA (2020) and SIAP (2020). SPI-6-RP = Rincón del Porvenir station. SPI-6-MITIC = Mexquitic station. PV (S)-AHUALULCO = normalized value of the area sown in the spring–summer cycle in the municipality of Ahualulco. PV (C)-AHUALULCO = normalized value of the harvested area in the spring–summer cycle in the municipality of Ahualulco.

Irrigated agriculture is also practiced in the studied area. The average sown and harvested area of irrigated crops was 287 hectares and 269 hectares, respectively (Figure 4). The autumn–winter cycle is sown, and in this, the predominant crop is green forage oats (*Avena sativa*). In the spring–summer cycle, maize (*Zea mays*) predominates. In perennial crops under irrigation, green alfalfa (*M. sativa*) predominates. In general, the area sown with irrigated crops is relatively equal to the area harvested; that is, the irrigation water, in terms of quantity (in this case), is not limiting.

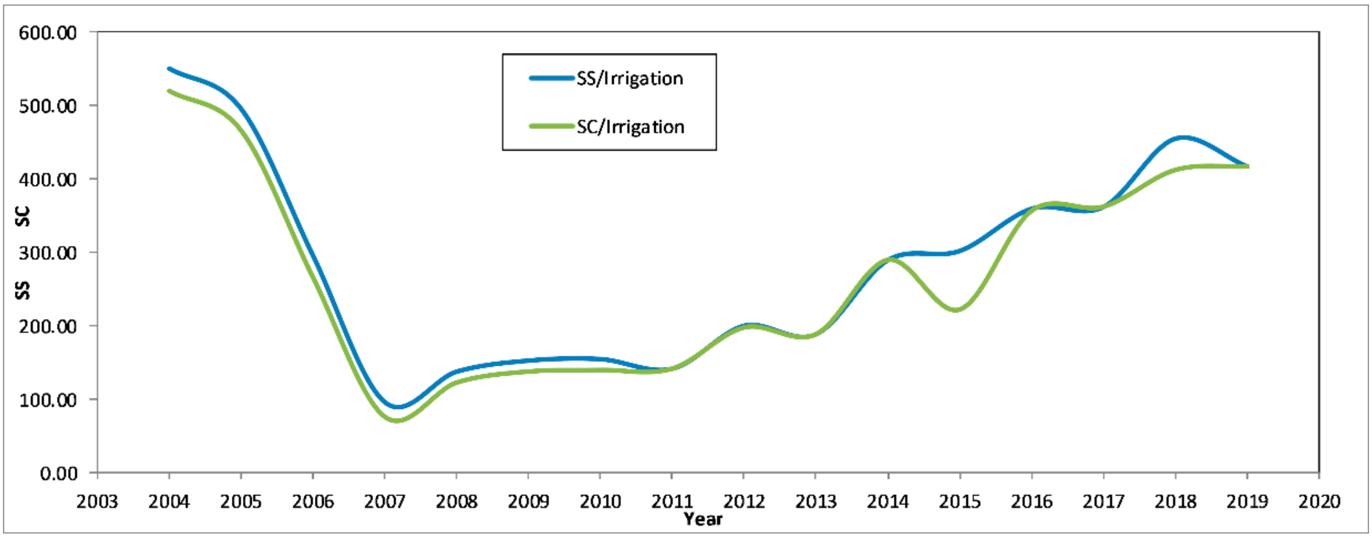


Figure 4. Sown and harvested area (in hectares) under irrigation in the studied area. Source: Authors' elaboration based on statistical information from SIAP (2020).

CONAGUA, in the Ahualulco aquifer, has registered 466 concession titles for agricultural use, with a total volume of extraction from national waters of 7.4 mm^3/year. In 1999, there were 1183 dug wells and 33 deep wells [38]. In 2017, the same 1183 dug wells and 33 deep wells were reported, and three springs were added [43]. The water quality with which this agricultural area is irrigated has essential effects on the soil and the crops themselves, so it is important to know their physical–chemical conditions and infer their impact on the soil and crops.

3.2. Groundwater Quality and Limitations on Its Use

Twenty-five samples were collected and analyzed in the laboratory. They met the electro-neutrality conditions necessary to obtain irrigation indices and their effects on agricultural productivity under irrigation (Figure 5a). The quality of the water is a function of the content of dissolved salts. Osmotic processes are affected by the presence of salts in the water; the content of toxic substances such as boron can affect plant metabolism. Thus, sodium, salinity, and specific ion toxicity are considered when assessing water quality.

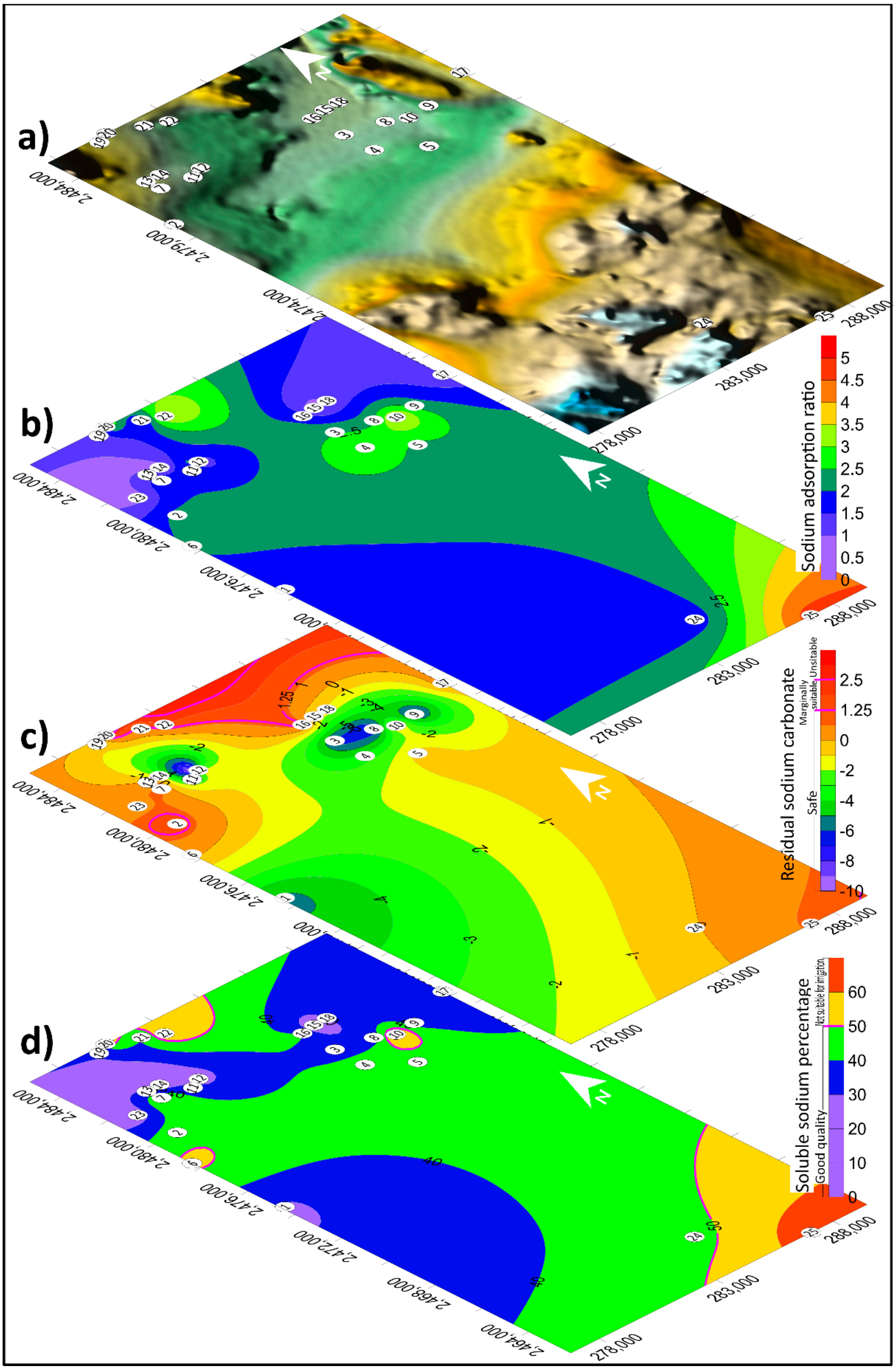


Figure 5. (**a**) Topographic relief of the study area; spatial distribution of (**b**) SAR, (**c**) RSC, and (**d**) SSP.

3.2.1. Acid and Alkaline Conditions

The maximum pH value was 8.1 (sample 20), while the minimum value was 6.76 (sample 1). Of the 25 samples, none had pH values above 8.5, and all were above 6. Water with pH values of 6 to 8.5 can better assimilate different nutrients, such as phosphorus and certain micronutrients.

3.2.2. Sodicity Conditions

Permeability is affected by high concentrations of sodium in the water; infiltration rate and soil cultivation are also affected [44]. The high sodium content concerning the calcium concentration causes a decrease in infiltration due to the dispersion of soil aggregates [45]. The evaluation of sodium in water is studied with the RAS, CSR, PSS, % Na, KR, and PI indices. When the proportion of sodium is higher than calcium and magnesium, the danger of sodification will be great [46].

In the study area, the maximum value of RAS was 4.8 (sample 25), and the minimum was 0.72 (sample 15) (Figure 5b). This index showed no danger of sodicity in the Ahualulco aquifer. All samples were classified as S1, meaning that they presented a low risk of sodification, when the presence of $(CO_3{}^{2-} + HCO_3{}^{-}) > (Ca^{2+} + Mg^{2+})$ can form ($NaHCO_3$), causing soil deflocculation [42,46]. These sodium waters reduce soil fertility [23].

The hazard of sodium carbonate is evaluated with the RCS index; when calcium and magnesium cations have already reacted with CO_3 and $HCO_3{}^{-}$, they are used to identify the risk of precipitation of these cations in the soil when highly carbonated water is used.

Four samples (samples 2, 16, 20, and 22) presented RCS values greater than 1.25 meq/L (Figure 5c). The rest had values below that limit and were suitable for agricultural use. The maximum values were 3.22 (sample 20), and the minimum was −7.36 (sample 8) (Figure 5c).

The percentage of soluble sodium depends on ions such as Ca, Na, and Mg. The cation exchange process begins when the sodium content in the soluble is more significant than 50%, and the calcium and magnesium cations are displaced [4,47]. When the percentages are higher than 50% of sodium in the water used, it reduces the permeability of the soil and limits the growth of crops [19]. The maximum value was 65.79 (sample 9), and the minimum was 18.14 (sample 15). Six samples (samples 6, 7, 10, 20, 22, and 25) presented values above the limit of 50; these values suggest that the water is not suitable for irrigation (Figure 5d). SSP values below 50 indicate good quality water [48].

According to the sodium content in % Na in groundwater for use in agricultural irrigation, it is classified as excellent with values below 20%, good with 20–40%, admissible with values of 40–60%, doubtful with percentages of 60–80%, and not adequate with values higher than 80%. The maximum value was 71.67%, and the minimum was 20.22% in the Ahualulco aquifer. Fourteen samples were classified as of good quality for agricultural use. Six water samples were classified as admissible quality.

Three water samples (10, 22, and 25) had a classification of doubtful use for agriculture (Figure 6a).

The KR is related to the sodium content between the calcium plus magnesium ratio. Excess sodium is considered when KR is greater than 1, and the water is suitable for agricultural use when KR is less than 1 [16]. The maximum value was 1.92 (sample 25), and the minimum 0.22 (sample 15). For the Ahualulco aquifer, five samples (6, 7, 10, 20, 22, and 25) presented values more significant than one (Figure 6b).

PI is affected by irrigation with water rich in sodium, calcium, magnesium, and bicarbonate. This index was classified into Class I, Class II, and Class III. If it has a PI greater than or equal to 75%, this type of water is considered good for irrigation use. If it has a PI lower than 25%, it is not suitable for agriculture (39, 35, 59). In the present study, the maximum contents were 104.83% (sample 7), and the minimum 39.08% (sample 11) (Figure 6c); therefore, the aquifer water is of good quality for irrigation.

Generally, calcium and magnesium remain in equilibrium in water. When magnesium is present in high concentrations, it affects agricultural production in some crops sensitive to this element [49]. Groundwater has low magnesium levels; however, when it interacts with dolomites, magnesium concentrations are high. For agricultural use, magnesium is evaluated with the MAR in percentage values. The values above 50% cause harmful effects on the soil [21,50,51]. In this study, the maximum value was 34.53% (sample 12), the minimum was 0.0015 (sample 4), and none of the samples presented values higher than 50% (Figure 6d).

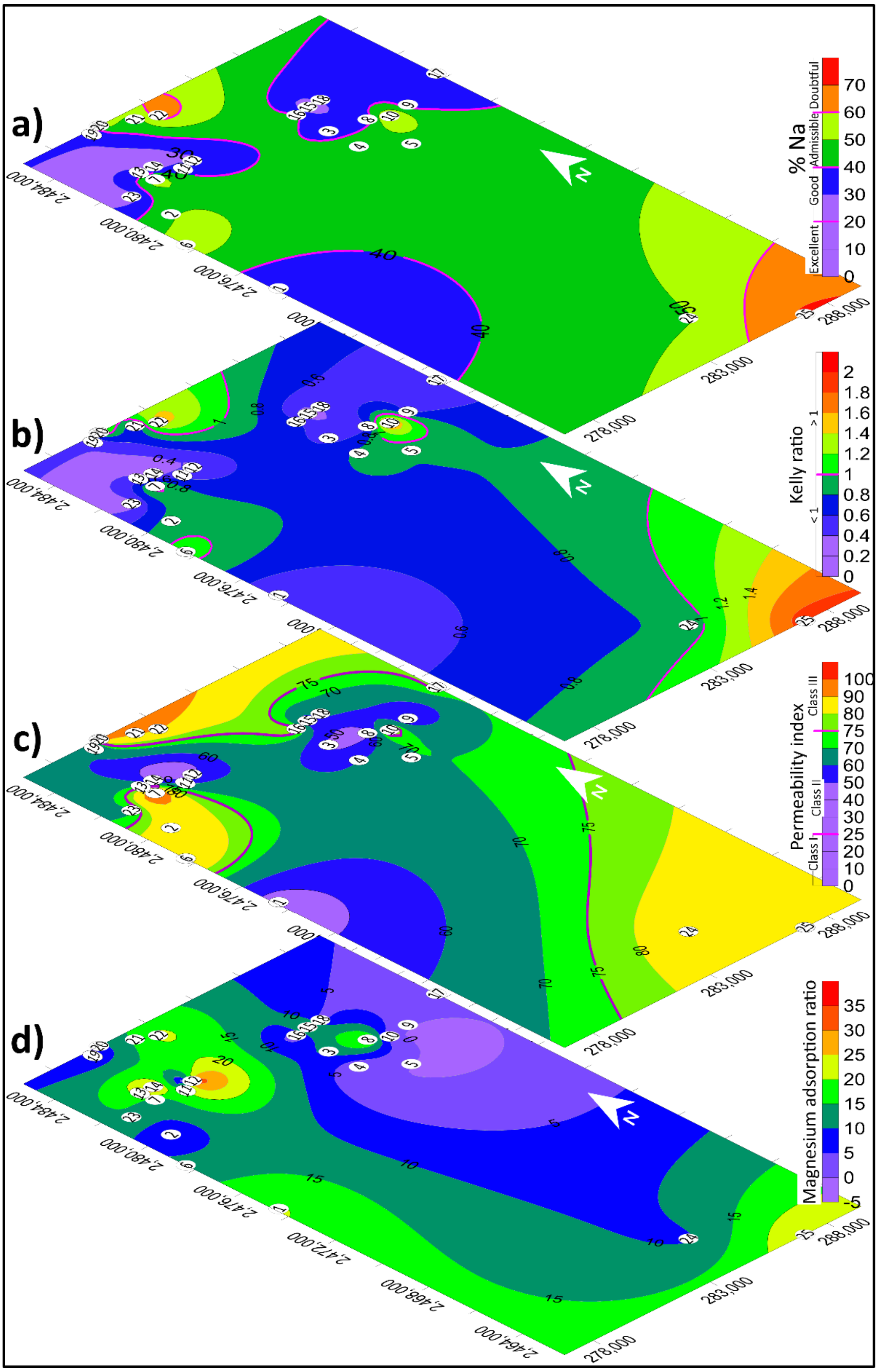


Figure 6. Spatial distribution of the indices in the study area (**a**) % Na, (**b**) KR, (**c**) PI, and (**d**) MAR.

3.2.3. Salinity Conditions

Irrigation water with high concentrations of salts can cause an accumulation in the soil profile and in the root zone, reducing the growth and development of agricultural production [11,44,45]. Since salts in solution are directly proportional to EC, it can be used for evaluation. Other indices to evaluate salinity in water are ES, PS, and OP, which are also related to EC and TDS [11,42,46,51]. The last three indices classify irrigation water. The PO is affected by the presence of salts, which causes a decrease in agricultural production. Salinity is the most important criterion for classifying irrigation water [47], which causes a reduction in agricultural productivity [47]. The EC indicates the degree of salinity, and its excess reduces osmotic activity [46,49,50]. The EC influences the nutrition of the soil and the absorption of water in the plant; however, the higher the EC, the lower the water available to plants [44,47,50,52,53]. According to the EC content, water is classified as excellent (CI) when it is less than 250 µmhos/cm at 25 °C; 250–750 is classified as good (C2); 750–2000 (C3) is allowable; 2000–3000 (C4) is doubtful, and it is considered inadequate with values higher than 3000 µmhos/cm at 25 °C (C5), which causes the soil salinity to increase [54,55]. In some cases, the concentration of salts in the soil can be two to six times the conductivity of the irrigation water [54,56].

In this study, the maximum 2204.0 µmhos/cm was found at 25 °C and a minimum of 376.0 µmhos/cm at 25 °C EC values (Figure 7a). Samples 2, 6, 9, 12, 17, 19, 20, 21, and 22 presented values between 250 and 750, or medium salinity. The other samples presented values between 750 and 2250, or high salinity. In a study carried out in 1998 for the Ahualulco aquifer, researchers found EC greater than 1500 µmhos/cm but less than 2500 µmhos/cm [47]. Twenty-five data samples were analyzed to determine the danger of medium to high salinity (Figure 7a). For PS and ES, 13 of the 25 sampled points had their water conditioned (with ES values of 3 to 15).

The PS index is considered a good estimator of the effect of salts on plants. It indicates the salinity risk when there is low moisture content in the soil [57]. Agricultural production is limited by increased osmotic pressure by precipitating chloride and sulfate salts [48,52,53]. The maximum value was 7.48 (sample 11) and the minimum 0.48 (sample 21). Seven of the 25 samples (samples 1, 3, 4, 8, 9, 11, and 25) fell into the conditioned water classification (Figure 7b).

ES estimates the danger of salinization considering the water's soluble salts when used for irrigation. It considers the precipitation of calcium and magnesium carbonates and calcium sulfates, which are less soluble salts [48,53,58]. The maximum ES value was 7.98 meq/L (sample 8), and the minimum was 1.16 meq/L (sample 23). Of the 25 water samples, 12 presented ES values lower than 3, which is the upper limit to classify the water as good quality (Figure 7c).

The OP depends on the EC. When the OP values are less than 0.1 atm, it indicates low saline water and excellent quality; values between 0.1 and 0.3 indicate good quality water, between 0.3 and 0.7 the quality is permissible, and between 0.7 and 1.10 poor quality due to high-quality salinity in the water. Saline water with increasing problems and OP above 1.10 atm indicates that the water is highly saline with significant issues. In the study area, seven samples (1, 3, 4, 7, 8, 10, and 18) were classified as highly saline with significant problems (Figure 7d).

When the TDS values are between 0 and 1000 mg/L, the water is classified as freshwater; if it is between 1000 and 3000 mg/L, the water is classified as slightly saline; if the values are between 3000 and 10,000, the water is moderately saline; and values greater than 10,000 mg/L indicate that the water is highly saline. The minimum values were 182 mg/L and a maximum of 1057 mg/L. All groundwater samples were classified as freshwater. It is worth mentioning that the presence of excess ions dissolved in water causes physical and chemical effects on the soil and plants [2], limiting the ability of plant roots to extract water from the soil.

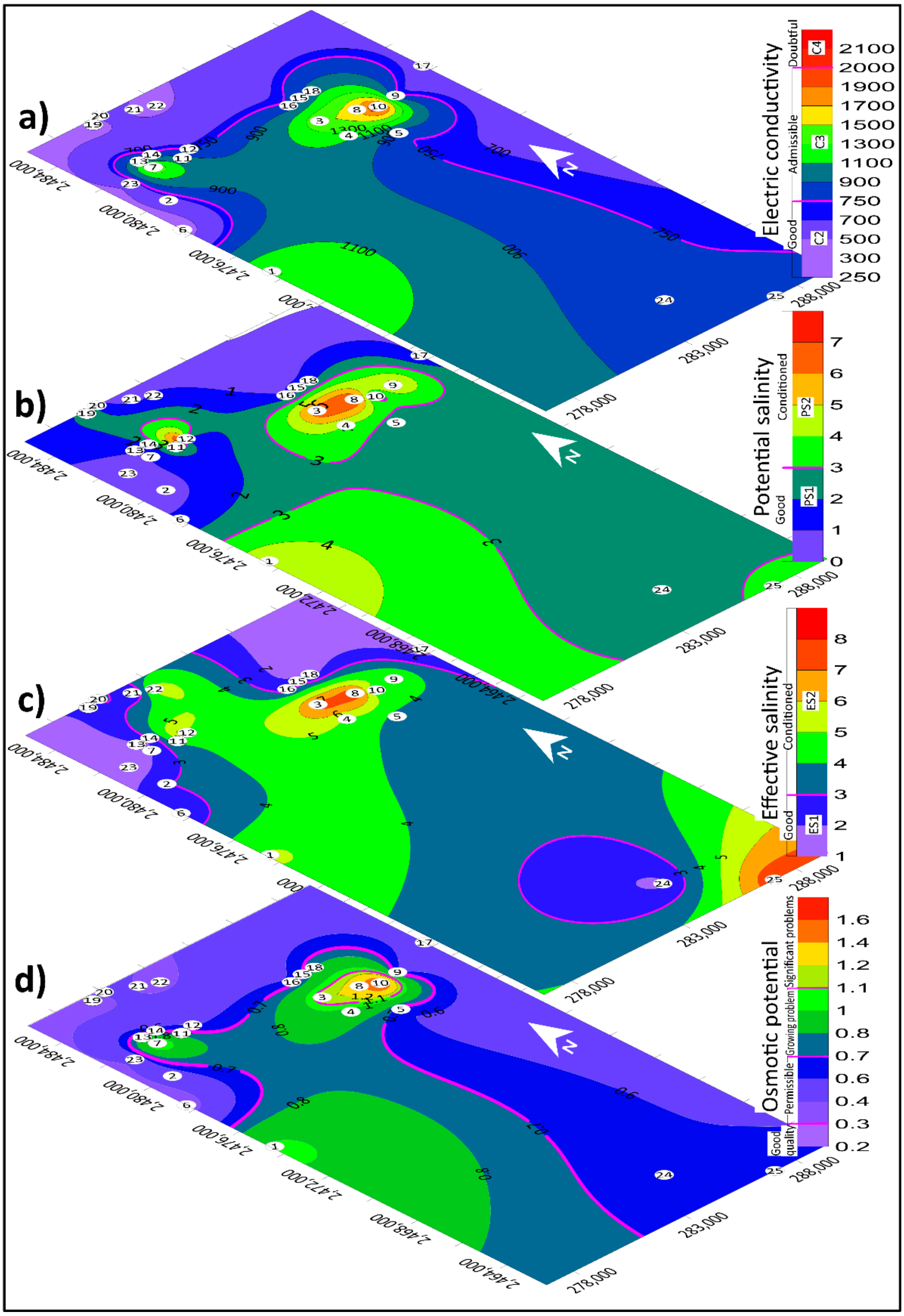
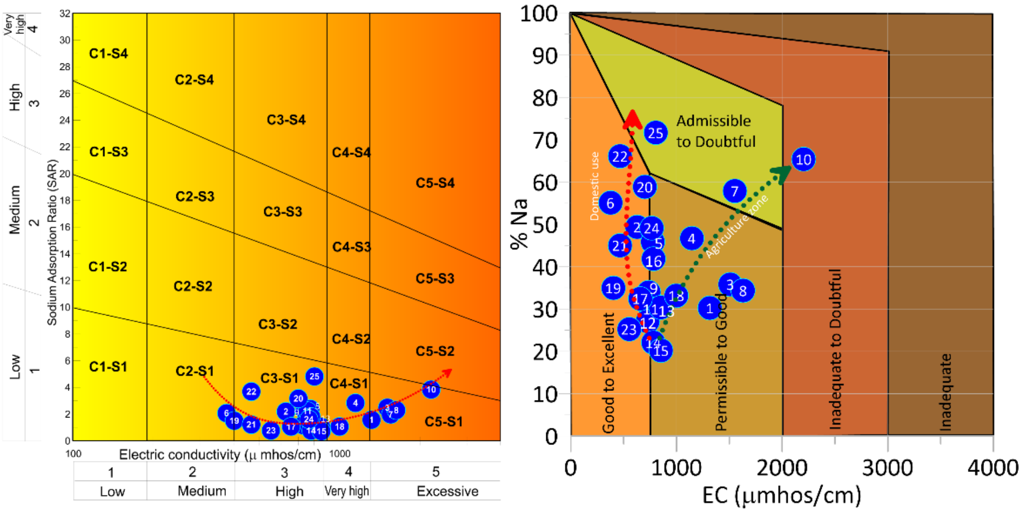


Figure 7. Spatial distribution of the indices: (**a**) EC, (**b**) PS, (**c**) ES, and (**d**) OP.

3.2.4. Classification of Water Considering % Na, RAS, and EC

The combination of RAS and EC generates a diagram developed by the United States Salinity Laboratory (Figure 8a). This graph is one of the most used for the classification of irrigation water. Of the 25 samples collected, two samples were classified as medium salinity risk and low sodium risk (C2-S1). Fifteen water samples were classified as high salinity hazards and low salinity hazards (C3-S1). Two were classified as very high risk for salinity and one as low risk for sodicity (C4-S1). Four samples fell into risk of excessive salinity and low sodium (C5-S1). The graph showed a tendency to increase the danger of salinity from medium to excessive and a low to medium risk for sodicity.



(**a**) (**b**)

Figure 8. Water classification for the Ahualulco aquifer according to (**a**) Wilcox and (**b**) EC vs. % Na.

Sodicity levels in samples 20, 22, and 25 conditions groundwater use in Ahualulco. Samples 1, 3, 4, 7, 8, and 10 require monitoring due to their salinity levels (Figure 8b). The problems associated with sodicity in the aquifer are not severe and occur in specific areas. However, issues related to salinity may increase as groundwater evolves.

The % Na is plotted together with the EC. Nine samples collected fell in the good–excellent classification, 12 were considered as permissible–good, two fell in the admissible–doubtful category, and one sample was classified as inadequate–doubtful. Figure 6b shows that the water for domestic use evolved from good–excellent to admissible–doubtful, while water for agricultural use evolved from good–excellent to inadequate–doubtful.

With the EC and OP indices, a classification table is constructed with 16 areas [51,55]. The first area (C1-OP1) is classified as good quality, low-saline. The second area (C2-OP1) is classified as permissible, low saline. The third area (C3-OP1) is classified as a low-saline growth problem. The fourth area (C4-OP1) is classified as a low-saline problem. The fifth area (C1-OP2) is classified as medium saline and good quality. The sixth area (C2-OP2) is classified as medium permissible saline. The seventh area (C3-OP2) is classified as a problem of medium growth of saline. The eighth area (C4-OP2) is classified as significant problems of medium saline solution. The ninth area (C1-OP3) is classified as high salinity and good quality. The tenth area (C2-OP3) is classified as highly permissible saline. The eleventh area (C3-OP3) is classified as a problem of high growth of saline. The twelfth area (C4-OP3) is classified as a problem of high saline significance. The thirteenth area (C1-OP4) is classified as very high saline of good quality. The fourteenth area (C2-OP4) is classified as very high, allowable saline. The fifteenth area (C3-OP4) is classified as very high saline growth problems. The sixteenth area (C4-OP4) is classified as very high saline problems. In general, the samples showed an increasing linear trend that started from C1-OP1, which is classified as a low-saline solution of good quality, and ended in C3-OP4, which is classified as a very high saline growth problem (Figure 9a).

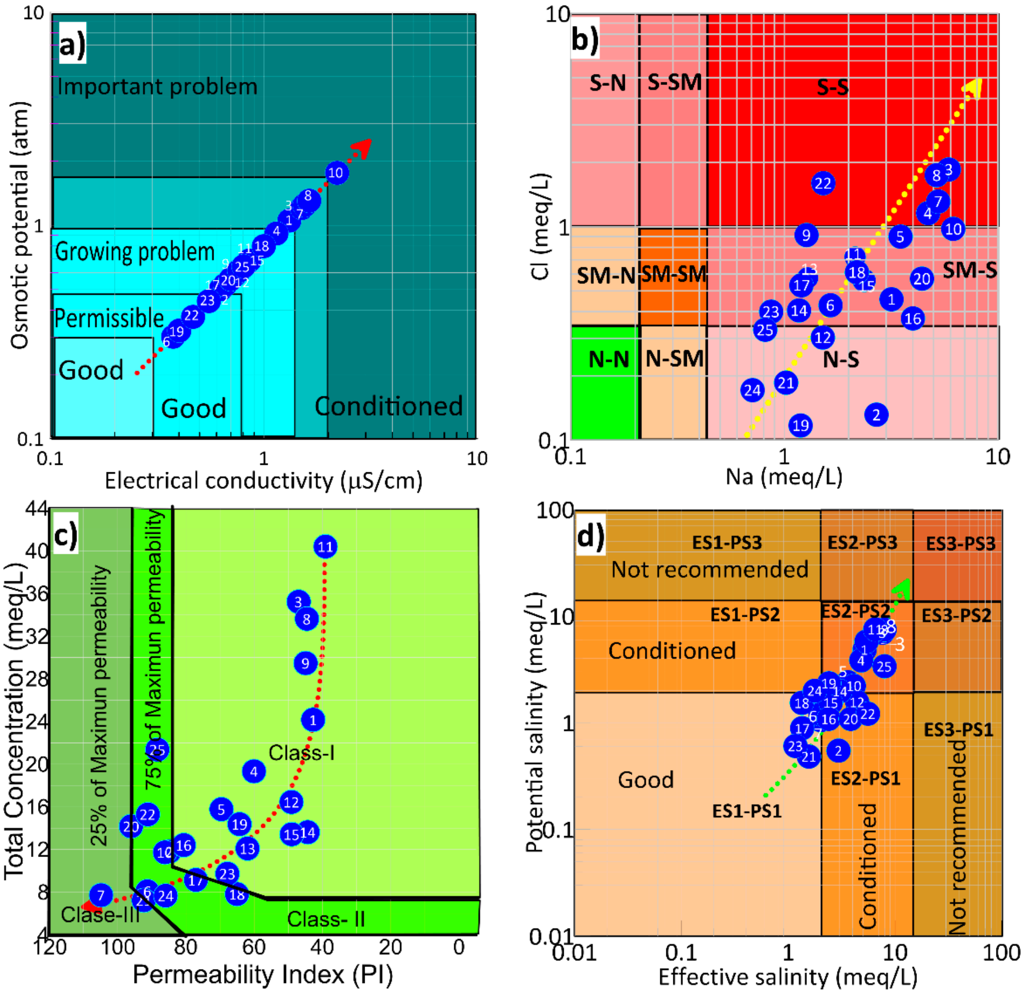


Figure 9. Spatial distribution of the indices: (**a**) EC vs. OP, (**b**) Na vs. Cl, (**c**) PI vs. TC, and (**d**) ES vs. PS.

3.2.5. Presence of Toxic Ions (Chlorides and Sodium) for Plants

Some ions can be toxic (phytotoxic elements) to crops; generally, these elements accumulate in the leaves. These phytotoxic elements are usually chlorine, sodium, and boron [6]. A high concentration of chlorides causes the burning of the leaves until the death of the tissues. If the content of this element is less than 4 meq/L, the water is classified as good; if it is between 4 and 10 meq/L, it is classified as conditioned; and if the concentration is higher than 10 meq/L, it is classified as non-recommended water. The maximum value found in this study was 1.85 meq/L (sample 3), and the minimum was 0.11 meq/L (sample 20). The 25 sites presented values below 4 meq/L, which indicates that the aquifer water does not present problems due to this phytotoxic element and is classified as good and is suitable for agriculture.

Sodium often causes damage similar to that caused by chlorides and nutrient deficiencies in plants. Na concentrations below 3 meq/L are indicators of low risk of toxicity, concentrations between 3 and 9 meq/L indicate medium risk, and concentrations greater than 9 meq/L imply a high risk of sodium [20]. The maximum value was 6.16 meq/L (sample 10), and the minimum was 0.7 meq/L (sample 24). The concentrations between 3 and 6.16 meq/L obtained in samples 1, 3, 4, 5, 7, 8, 10, 16, and 20 related to medium risk. These values were similar to those reported in another study [39].

Cl and Na were used to classify the water with respect to these phytotoxic elements. The graph indicates nine regions. The first, N–N, indicates no toxicity problems for either element (Figure 9b). The second region, N–SM, shows no toxicity problems for Cl, but for Na, the risk is slight to moderate. The third region, N–S, indicates that there are no toxicity problems for Cl, but the risk is severe for Na. The fourth region, SM–N, indicates no toxicity problems for Na, but the chance for Cl is slight to moderate. The fifth region, SM–SM, indicates that the risk is slight to moderate for both elements. The sixth region, SM–S, indicates that the risk is slight to moderate for Cl, but the risk is severe for Na. The seventh region, S–N, establishes that the risk is severe for Cl, but there are no toxicity problems for Na. The eighth region, S–SM, establishes that the risk is severe for Cl, but the risk is slight to moderate for Na. The ninth region, S–S, indicates that the risk is severe for both elements. In the study area, 16% of the water samples were located in SM–S, with slight to moderate risk for Cl and severe risk for Na, and evolved to SS, where 84% of the samples were classified as severe risk for both elements (Figure 9b).

The combination of PI and total concentration (TC) was presented by [41]. Figure 9c shows Class I and II water, considered good and suitable for irrigation, while Class III corresponds to water not suitable for irrigation. In general, 100% of the samples were in Class I and are suitable for irrigation. However, the general trend was to evolve towards Class II, so monitoring is recommended to establish when it reaches Class III. At this point, it is no longer suitable for irrigation (Figure 9c).

When classifying the ES and PS indices, a classification table with nine regions was used. The first region was rated as good–good (ES1-PS1). The second region was classified as well-conditioned (ES2-PS1). The third region was classified as not recommended–good (ES3-PS1). The fourth region was classified as well-conditioned (ES1-PS2). The fifth region was classified as conditioned–conditioned (ES2-PS2). The sixth region was classified as a non-recommended conditioner (ES3-PS2). The seventh region was rated good–not recommended (ES1-PS3). The eighth region was classified as a non-recommended conditioning factor (ES2-PS3). The ninth region was classified as not recommended–not recommended (ES3-PS3) (Figure 9a).

4. Discussion

The previous analysis allows us to point out that the farmers of the studied region, as in the other areas with rainfed agriculture, respond to the conditions of rainfall and, therefore, to the humidity conditions of the area. The main seasonal crops for the spring–summer cycle in Ahualulco are corn (*Zea mays*) and beans (*Phaseolus vulgaris*). In different regions of the planet, it has been found that areas with rainfed agriculture are the most affected by droughts [41,59], so crop yield is highly variable and depends on rain [31,57].

It has been found that droughts can cause changes in cultivation or management activities or improvements to irrigation systems [10,57,60,61], and the effects of water deficit can be seen in crops such as alfalfa (*Medicago sativa*) [62] and maize *(Zea mays)* [11,43,63], as well as in agricultural impacts in general [28,46]. In general, the indexes for agricultural use indicate that the water is suitable for agriculture; only at some points is it classified as doubtful or inadequate; however, the combination of these indices reveals the water quality trend for agricultural use in the aquifer. In the Wilcox case, there is a slight variation in the SAR; however, the electrical conductivity (EC) shows a significant increase, so its tendency is to be classified as excessive [51,57].

The combination of % Na and EC indicates that the groundwater has two paths of evolution; in one, it has significant increases in % Na, starting from good to excellent to reach admissible–doubtful. Another evolutionary route starts from good–excellent to inadequate–doubtful [42,46].

The combination of OP and EC indicates a direct correlation between both indices. When the EC increases, the OP also increases, and the water starts with a good classification. It ends up as conditioned with essential problems [51,55].

The relationship between Cl and Na reveals a direct correlation between both chemical components, starting at no toxicity (N) and ending at S–S, indicating that the risk is severe for both elements [56,61].

The combination of CT in (meq/L) and PI has a non-linear correlation; it goes from Class I with high values of CT and PI, and as it evolves, these indices drastically decrease, to be placed in Class III; that is, it can be interpreted that there is a decrease in ions and a decrease in permeability due to the precipitation of some soluble salts [11].

The relationship between PS and Es shows a direct correlation between both indices; when one increases, the other also increases. In such a way, groundwater starts good and evolves into conditioned for both indexes [40,53].

The water quality can be good for one index, but it is not adequate for other indices, so it must be analyzed globally. The combination of the quality indices is vital because it reveals the generally negative trend that the groundwater in the aquifer will have as it evolves.

5. Conclusions

Drought conditions significantly affect farmers who practice rainfed agriculture. In the years of drought, farmers plant areas below the average. In contrast, there is no interannual variation between the sown and harvested areas in the irrigated areas, since they are the same as the sown areas. Another factor limiting irrigated agriculture is water quality. The Ahualulco aquifer presents punctual and specific sodicity conditions only in three sites. Salinity conditions are local and occur in six sites, so they must be observed.

The agricultural indices generally showed acceptable water quality conditions, but there is also a tendency to deteriorate its quality. The Wilcox diagram offers a trend towards an EC classification in such a way that the water goes from medium conductivity and low salinity to medium risk of sodicity and excessive risk of salinity (C2S1 to C5S2). The % Na varies from good to inadequate or doubtful. The EC–OP also indicates that the water evolves from good to salinity conditions and with a significant problem in osmotic permeability. Phytotoxic elements such as Na and Cl suggest that the water also becomes light to moderate in Cl and severe in Na, to severe in both elements. Finally, the ES–PS relationship also indicates changes in the water such that the water varies from good to conditioned for both indices. The foregoing, added to the edaphic, climatic, and physiographic conditions, such as rainfall of 350 mm/year, can affect the soil and, therefore, the yield of crops planted in the studied region. In addition, the water quality trend shows an increase in its deterioration for agricultural use.

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