EARTH SCIENCES
RESEARCH JOURNAL

Earth Sci. Res. J. Vol. 21, No. 3 (September, 2017): 117 - 127

UNIVERSIDAD NACIONAL DE COLOMBIA
SEDE BOGOTÁ
FACULTAD DE CIENCIAS
DEPARTAMENTO DE GEOCIENCIAS

HIDROGEOLOGY

Quality Indices of Groundwater for Agricultural Use in the Soconusco, Chiapas, Mexico

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ABSTRACT

In Soconusco, Chiapas, in spite of the high availability of surface water, it is resorting to the use of groundwater. Knowledge about the quality of surface or groundwater used to irrigate crops in that region is low. This paper aims to contribute to the knowledge of the quality of groundwater for agricultural use through the characterization of the spatial variability. Assuming a random spatial distribution of 45 samples which were collected in situ were determined: acidity and alkalinity (pH), electrical conductivity (EC), Total Dissolved Solids (TDS), cations and anions and trace elements; in addition to the agricultural index: Sodium Adsorption Ratio (SAR), Residual Sodium Carbonate (RSC), Soluble Sodium Percentage (SSP), Sodium Percentage (% Na), Kelly Ratio (KR), Magnesium Adsorption Ratio (MAR), Permeability Index (PI), Effective Salinity (ES), Salinity Potential (SP) and Osmotic Potential (OP). In general, SSP, % Na, KR, PI are low, there is only one anomalous point (9) with high values at W of the study area. Similarly, PS, ES, Cl, Na and SAR are low except point 16 and conversely, RSC and pH are high, except at this point located in the center of the study area. The results allow us to infer that the water in that aquifer presents no problems or sodicity toxic ions. In 27 sites sampled values above 250 µmhos/cm were found at 25°C, classified as medium to high risk of salinity, unsuitable for agricultural use. Analysis of the combined effect of the presence of sodium (SAR) and salinity (EC or TDS) shows that 27 of analyzing sites have restricted water medium at very high for use in irrigation.

Keywords: Salinity; sodicity; osmotic pressure; sodium adsorption ratio; electrical conductivity; irrigation; aquifer.

Índices de calidad del agua subterránea para uso agrícola en el Soconusco, Chiapas, México

RESUMEN

En el Soconusco, Chiapas, a pesar de la alta disponibilidad de agua superficial, se recurre al uso del agua subterránea. El conocimiento de la calidad del agua superficial o subterránea utilizada para el riego de los cultivos en la región es bajo. Este trabajo contribuye al conocimiento de la calidad del agua subterránea para uso agrícola a través de la caracterización de su variabilidad espacial. Asumiendo una distribución espacial aleatoria, se colectaron 45 muestras, a las que se les deteminó: acidez y alcalinidad (pH), conductividad eléctrica (CE), Sólidos Totales Disueltos (TDS), cationes y aniones y oligoelementos; además se determinaron índices agrícolas: Índice de adsorción de sodio (SAR), Carbonato de sodio residual (CSR), Porcentaje de sodio soluble (PSS), Porcentaje de sodio (% Na), Relación de Kelly (RK), Relación de Absorción de Magnesio (RAM), Índice de Permeabilidad (IP), Salinidad Efectiva (SE), Salinidad Potencial (SP) y Potencial Osmótico (OP). En general, el PSS, %Na, RK, IP son bajas, sólo hay un punto anómalo (9) con valores altos en la parte oeste del área de estudio. Del mismo modo, SP, SE, Cl, Na y el RAS son bajos, excepto en el punto 16 y en contraste, CSR y pH son altos, excepto en este punto ubicado en el centro del área de estudio. Los resultados nos permiten inferir que el agua en ese acuífero no presenta problemas de sodicidad y de tóxicos. En 27 sitios se encontraron valores superiores a 250 µmhos/cm a 25 ° C, clasificados como de riesgo medio a alto de salinidad, es decir inadecuados para uso agrícola. El análisis del efecto combinado de la presencia de sodio (RAS) y salinidad (CE o SDT) muestra que 27 de los sitios analizados presentan restricciones de medias a muy altas para su uso en riego.

Palabras clave: salinidad, sodicidad, presión osmótica, relación de adsorción de sodio, conductividad eléctrica, riego, acuífero.

Record
Manuscript received: 22/03/2017
Accepted for publication: 21/07/2017

How to cite item
Santacruz, G., Ramos, J. A., Moran, J., Lopez, B., & Santacruz, E. E. (2017). Quality Indices of Groundwater for Agricultural Use in the Soconusco, Chiapas, Mexico. Earth Sciences Research Journal, 21(3), 117 - 127. doi:http://dx.doi.org/10.15446/esrj.v21n3.63455

ISSN 1794-6190 e-ISSN 2339-3459
http://dx.doi.org/10.15446/esrj.v21n3.63455

Introduction

As the surface water, groundwater is part of the hydrological cycle and, a significant portion of the world population depends on it. Even there are zones of the world where, for climatic or geological reasons, is the only source (Price, 2003). In the past 50 years the groundwater has played a key role in agricultural production (Giordano and Villholth, 2007), currently, 50% of potable water and 45% of the irrigated agricultural area of the planet depend on groundwater (Rifat et al., 2014). In arid and semi-arid areas of Latin America, aquifers are the source of a third of the total water usage (Miletto et al. 2006).

In arid and semi-arid zones of Mexico, groundwater is the main source of supply. In the tropics unconfined aquifers are important sources of water for agriculture and domestic use. Six million hectares area irrigated, of which one third is irrigated with groundwater (Marín, 2002; Asad and Garduño 2004; CONAGUA, 2013).

Knowledge of groundwater quality in time and space, it is important to differentiate its composition and function of this, devoting it to best use. This would have generated different techniques for water quality report, include the so-called Water Quality Index (WQI) grouping one or more physicochemical and bacteriological parameters (Guzman-Colis et al. 2011; Kankal et al. 2012) even supported by statistical techniques (Hülya and Hayal, 2007; Papaioannou et al. 2010; Hafizan et al. 2011; Mohd et al. 2011). To this, the pressures of agriculture and increasing living standards demanding better agricultural products (Wijnen et al. 2012) and therefore better quality of water used for agricultural activity are added.

The quality of irrigation water has repercussions on the production; it may affect plant growth and thus reduce levels of agricultural production (Yesilnacar and Gulluoglu, 2008; Deshpande and Aher, 2012). To evaluate the quality of water for agricultural use, there are considered some aspects such as salinity, effects of sodium on soil properties and toxicity of specific ions (Ayers and Wescot, 1985) that are included in various guidelines for interpreting quality. These guidelines have been outfitted in various indices as the Sodium Adsorption Ratio (Richards, 1954), Magnesium Adsorption Ratio (Rifat, 2014) Soluble Sodium Percentage (Todd and Mays, 1980) Residual Sodium Carbonate (Eaton, 1950), among others (Table 1).

Index	Equation	Reference
SAR	$\frac{Na^{+}}{\sqrt{\frac{Ca^{2+}+Mg^{2+}}{2}}}$	Richards, 1954
MAR	$\frac{Mg^{2+} \bullet 100}{Ca^{2+}+Mg^{2+}}$	Raghunath, 1987
PI	$\frac{(Na^{+}+\sqrt{HCO_3^{-}}) \bullet 100}{Ca^{2+}+Mg^{2+}+Na^{+}}$	Doneen, 1964
%Na	$\frac{Na^{+}+K^{+}}{Ca^{2+}+Mg^{2+}+Na^{+}+K^{+}} \bullet 100$	Wilcox, 1955
SSP	$\frac{Na^{+} \bullet 100}{Ca^{2+}+Mg^{2+}+Na^{+}}$	Todd and Mays, 1980
RSC	$(CO_3^{2-}+HCO_3^{-})-(Ca^{2+}+Mg^{2+})$	Eaton, 1950
KR	$\frac{Na^{+}}{Ca^{2+}+Mg^{2+}}$	Kelly, 1963

ES	If $Ca > (CO_3^{2-}+HCO_3^{1-}+SO_4^{2-})$, then
	ES=Σ cations* -$(CO_3^{2-}+HCO_3^{1-})$
	If $Ca > (CO_3^{2-}+HCO_3^{1-}+SO_4^{2-})$; but
	$Ca > (CO_3^{2-}+HCO_3^{1-})$, then
	ES=Σ cations* - Ca^{2+}
	If $Ca > (CO_3^{2-}+HCO_3^{1-})$ but
	$(Ca^{2+}+Mg^{2+}) > (CO_3^{2-}+HCO_3^{1-})$, then
	ES=Σ cations* - $(CO_3^{2-}+HCO_3^{1-})$
	If $(Ca^{2+}+Mg^{2+}) < (CO_3^{2-}+HCO_3^{1-})$, then
	ES=Σ cations* -$(Ca^{2+}+Mg^{2+})$
		Palacios and Aceves, 1970

PS	$Cl^{1-}+\frac{1}{2}SO_4^{2-}$	Palacios and Aceves, 1970
OP	$OP(atm) \approx CE(mS \bullet cm^{-1}) \times 0.36$	Wilcox, 1955
ESP	$-\frac{100(-0.0126+0.01475\,SAR)}{1+(-0.0126+0.01475\,SAR)}$	Richards, 1954

In Mexico the knowledge about the quality of groundwater for irrigation is scarce, it is considered as a requirement of lesser importance (Cardona et al., 2010). The Soconusco region in the state of Chiapas is in this condition (UNESCO, 2007 and 2010). There have been studies on the availability of water in the aquifer (Diaz, 2001; CONAGUA, 2009) and from them are considered relevant to study water quality in the Soconusco to reveal current conditions and that knowledge it can be referenced for farmers, agricultural planners and for future studies. The aim of this study was to analyze from the application of various indices, the spatial variation of the quality of groundwater for agricultural irrigation in the Soconusco region in the state of Chiapas, Mexico.

Materials and Methods

Localization and characterization of the study area

The aquifer of Soconusco is in the region of Soconusco, Chiapas. This area consists of sixteen municipalities, covering an area of 5,475.5 km^2 (Fig. 1). Agricultural activities are predominantly export-oriented crops such banana (Musa paradisiaca), mango (Mangifera indica L.), coffee (Coffea var.) and corn (Zea mays), soybean (Glycine max) and beans (Phaseolus vulgaris).

The climate is hot and humid type with temperatures ranging from 25-34 °C in spring and summer, while for the rest of the year temperatures are average values of 18-22 °C. It presents a rainfall ranging between 1,500 mm and 4,000 mm, with a regional average of 2,450 mm (JICA, 1999) due to the topographic variability. It is a region of great ecological diversity, with different strata termohídricos (Flottemesch and Schriker, 1993) and the presence of different types of soils (Deinlein, 1993), which have their origin in volcanic ash.

HYDROGEOLOGICAL FRAMEWORK

The basis of the stratigraphic column that emerges in the Chiapas region is of Proterozoic age and is composed mainly of granitoids and orthogneises (Weber et al., 2006).

Covering discordant to the basal rocks, the rocks of the upper Paleozoic are represented by the detrital series belonging to the Paso Hondo and Grupera formations (López-Ramos, 1980), also by metamorphic rocks, including serpentinites, schists, gneisses and quartzites (Salas, 1975), which were intruded by granodiorites, diorites and granites, rocks of the Batolito of Chiapas.

Covering discordant to the sequence to the Paleozoic units are detrital-calcareous sediments (conglomerates, sandstones, limes and clays) that date from the Triassic and Jurassic, these are the Formations Todos Santos, Grupo Sierra Madre and Angostura (Morán-Zenteno, 1994).

Volcanic rocks cover all previous rocks and are composed of volcanic rocks whose composition ranges from acidic to basic from the Chiapaneco Volcanic Arc in the Cenozoic (Mora-Chaparro, et al., 2007).

Finally, the rocks of the Pliocene-Holocene are constituted by deposits of silts, sands, clays and pyroclastic deposits derived from the volcanic activities of the Chichonal and Tacaná; As well as by alluvial materials and residual soils.

The aquifer “Soconusco” is located in the physiographic province known as the Highlands of Chiapas, it is mainly distributed in the coastal plain, which is bounded on the south by the Pacific Ocean and west by the Sierra of Chiapas or the granite massif of Chiapas (Diaz, 2001; Macias et al., 2010).

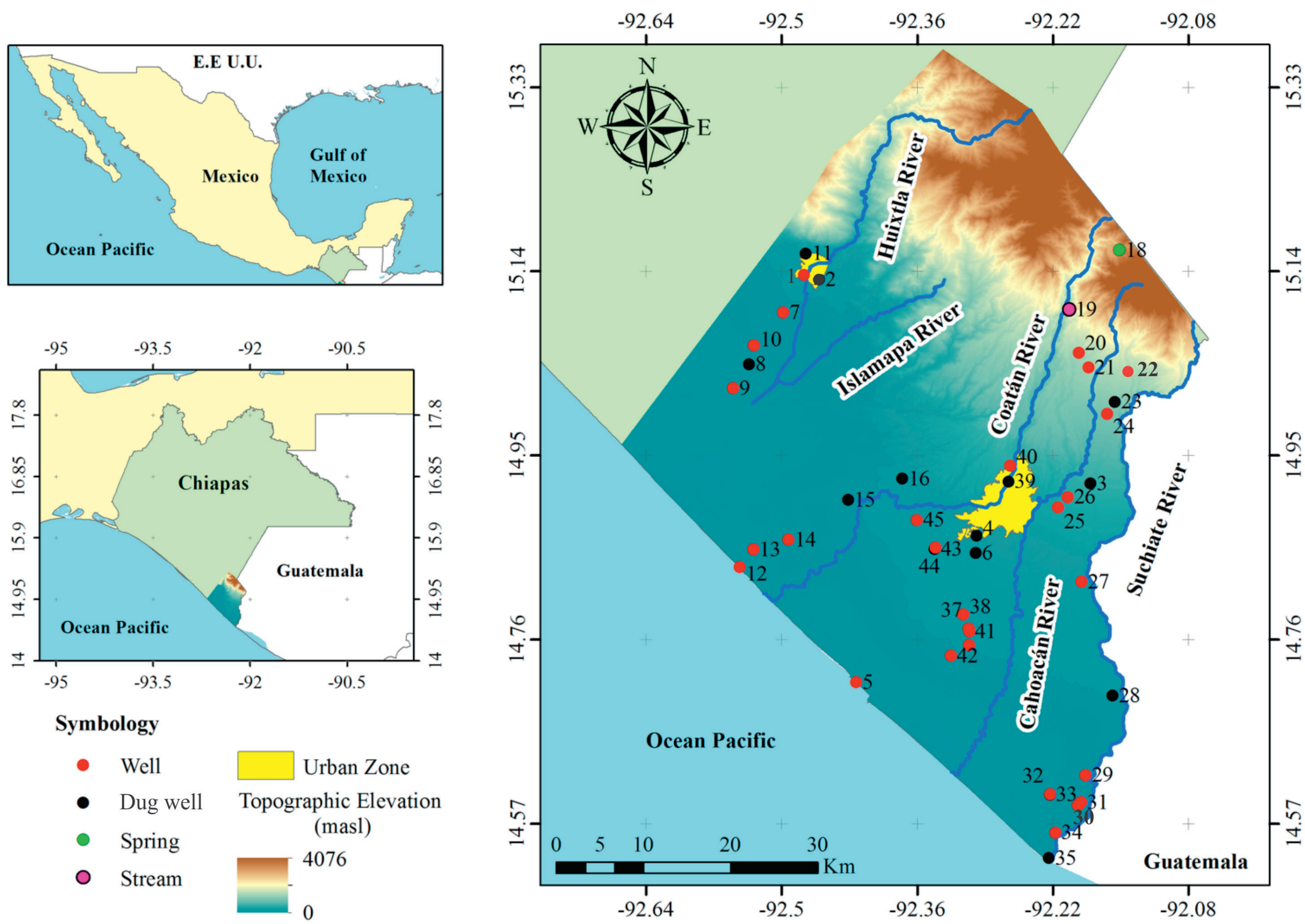

Figure 1. Location of the Soconusco aquifer and sampling points.

The granites and granodiorites are widely distributed in the Sierra of Chiapas, mainly in the northern part of the aquifer (recharge area). These rocks are one of the major sources for the formation of alluvial deposits and function as impermeable barriers to groundwater flow (Diaz, 2001, Macias et al., 2010). Volcanic rocks of basic and intermediate composition are composed of andesites and basalts, their permeability is relatively low, as it is compact enough rocks. However, the coastal plain has been formed by the accumulation of permeable sediments flowing down from the mountains in fluvial environments; and, by the processes of coastal marine type. This group of geological formations consists mainly of unconsolidated materials as clastic, sand, gravel, boulders and thin, such as clay and silt sediments, these sediments are those that constitute the aquifer (Diaz, 2001; Macias et al., 2010).

Hydrological balance

The hydrogeological balance of 2002 (CONAGUA, 2002) indicate that the volume of natural recharge is 885.9 million m3/year and 52.2 million m3/year of induced recharge, the actual evaporation is 325.4 million m^3/year natural discharge (springs) is 442.2 mm^3/year. The groundwater discharge to the sea is 27.7 million m^3/year and extraction wells is 1.62 Mm^3/year. With these figures, the CONAGUA (2002) considers the aquifer Soconusco in balance. In the 2009 update availability (CONAGUA, 2009) consider an average annual recharge of 938.2 Mm^3/year. It is noteworthy that high rainfall in the region in combination with the presence of permeable materials in the plains allows high infiltration and soil washing.

Sampling and activities laboratory measurements

In February 2013 sampling was performed on 45 samples from springs, dug wells and wells, the samples were taken during the dry season to determine major cations and anions (Fig. 1). All samples were collected in bottles of high density polyethylene, washed and rinsed seven times with deionized water. The containers for collection of samples for the determination of cations and trace elements were washed with 10% hydrochloric acid. For each collected sample, was measured in situ, pH, EC, temperature, redox potential, dissolved oxygen, and alkalinity. Immediately after collection, the samples for cations and trace elements were acidified with pure nitric acid to pH <2. All samples were stored at a temperature below 4 °C. The major ions and trace elements were analyzed in the laboratory of the Centre for Geosciences, National Autonomous University of Mexico. Atomic Emission Spectroscopy was used with Inductively Coupled Plasma (ICP-OES) to determine the concentrations of cations higher calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}) and potassium (K^{+}) and higher sulphate anions ($SO4^{2-}$) and chloride (Cl-) were analyzed using liquid chromatography. Alkalinity and bicarbonate (HCO_3^-) were determined by titration on the site. The ionic balance error (electro neutrality) in each of the 45 samples was considered less than 5%.

DRINKING WATER QUALITY ANALYSIS

To determine the quality of the groundwater for drinking purposes, WQI is computed according to the following relationship (Conesa, 1993):

Where *Ci* is percent value function assigned to the parameters, *Pi* weight assigned to each parameter and k constant taken from the values for the organoleptic characteristic (Table 2). k value in groundwater is normally 1, except in polluted water, which uses the values in Table 2.

Weight	Characteristic of water
1.0	For clear waters without apparent contamination
0.75	For waters with slight color, a scums and unnatural turbidity
0.50	For water with appearance of pollution and a strong odor
0.25	For dark waters that present fermentation and with a strong odor

CLASSIFICATION OF WATER IN CONNECTION WITH AGRICULTURAL USE

The classification of water for irrigation was made considering the conditions of acidity and alkalinity (pH), as well as sodicity rates as sodium adsorption ratio (SAR), the Residual Sodium Carbonate (RSC) is considered, the percentage Sodium Soluble (SSP), Sodium Percentage (% Na), the ratio Kelly (RK) and permeability index (PI) (Eaton, 1950; Todd and Mays, 1980). To evaluate and rank the water relative to saline conditions was considered to electrical conductivity (EC), Salinity Effective (SE), Salinity Potential (SP) and osmotic potential (OP) which is closely related to the EC and Total Dissolved Solids (TDS) (Palacios and Aceves, 1970; Aguilera and Martinez. 1996; Porta et al., 2010) the combination of these last three values allow classifying irrigation water. Likewise, the water is classified considering the combined effects of salinity and sodium contents employment diagram Salinity Laboratory of the Department of Agriculture of the United States and Wilcox Diagram. All indices were determined in a spreadsheet, by applying standard equations.

RESULTS AND DISCUSSION

The quality of data were analyzed based on their electroneutrality condition. The 45 groundwater samples perform that criterion.

In the study área, aproximately 60% groundwater samples show distribution of mixed cations, 26 % are Na+K type, 8% are Ca and 6% are Mg Type wáter on Piper Trilinear Diagram. Among the major anions, 88% are plotted within the HCO_3 type, 6% are mixed type, 4% are SO_4 type and while only one simple has the influence of Cl type. The majority of the studied samples, are plotted in the Ca-HCO_3 type of water (60%), 18% are Na-Ca-HCO_3 type, 12% are Na-HCO_3 type, 6% are Ca-Mg-Cl type and 4% are Na-Cl type water on Piper Diagram (Fig. 2a).

The (Gibbs, 1970) diagram was originally constructed for surface water analysis; However, it is possible to recognize some processes that occur to groundwater. The three main mechanisms that control surface water chemistry can be defined as the domain of atmospheric precipitation (rainfall), rock dominance, and control of the evaporation-crystallization process (Gibbs, 1970). This diagram is constructed with the chemical data (anions and cations) of the groundwater samples.

The graph of TDS vs. Na/(Ca + Na) of The Gibs diagram (1970) indicates the dominance of dilution by mixing, rock alteration in the study area and in another group the evaporation process predominates (Fig. 2b).

The quality of water for human consumption indicates that 64% of the analyzed samples have very good quality, 20% have medium quality and 7% have poor or excellent quality and only 2% have very poor quality (Fig. 2c).

Terms of acidity and alkalinity

The quality of water used for irrigation significantly influences the productivity of crops, depending on the presence of dissolved salts in it and their concentrations. Salts change the osmotic processes, and the presence of toxic substances (such as boron) can affect the metabolic processes in plants. The maximum and minimum pH values are 9.2 (point 19) and 6.1 (point 21), respectively. Three (points 18, 19 and 36) of the 45 samples, have pH values above 8.5 and all are above 6 (Fig. 3a).

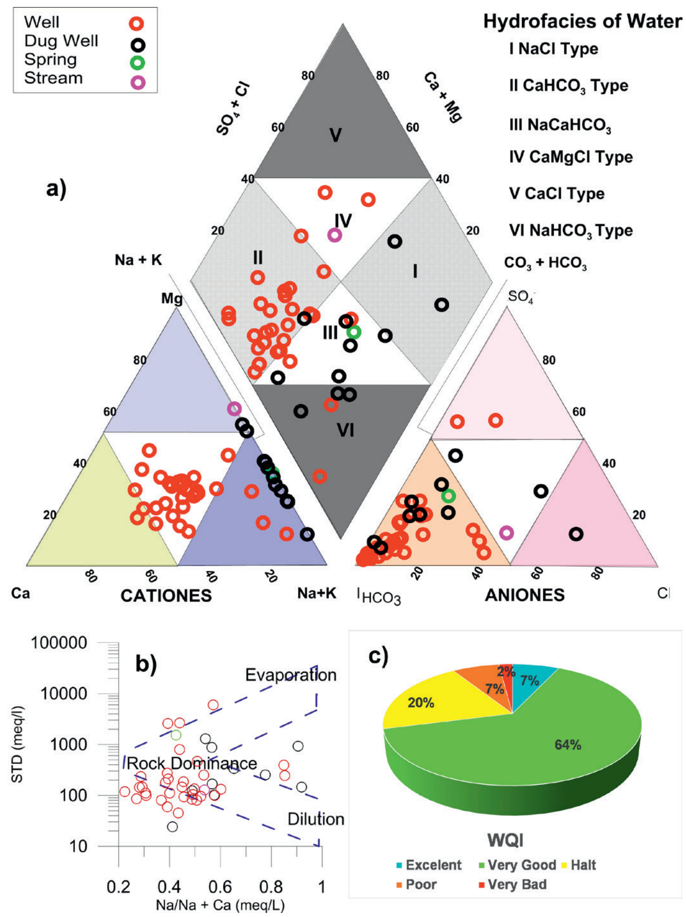

Figure 2. a) Piper diagram of the groundwaters of the study área, b) Gibbs diagram showing the mechanisms controlling the chemistry of groundwater of major cations c) Graph showing the distribution of the water quality of Soconusco aquifer.

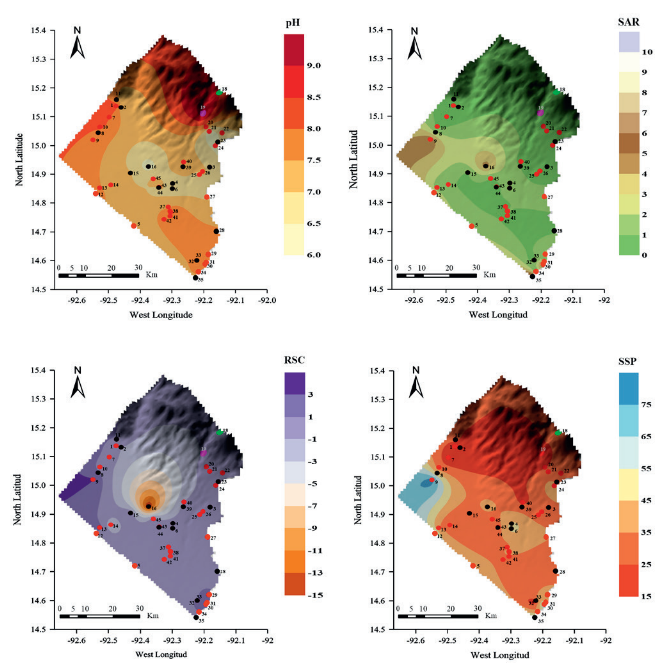

Figure 3. Spatial Distribution of Indices a) pH, b) Sodium Adsorption Ratio (SAR), c) Residual Sodium Carbonate (RSC) and d) Soluble Sodium Percentage (SSP).

Values above pH 8.5 and below 6 are indicative of an abnormal water quality are a signal of the presence of an ion toxic to crops. Water with pH values within this range creates conditions of assimilation of different nutrients such as phosphorus and some micronutrients (Ayers and Wescot, 1985).

Terms of sodicity

The presence of sodium in water at concentrations considerable permeability can affect the rate of infiltration and soil tillage (Romero, 2009), so that a high proportion of sodium relative to the calcium concentration causes a decrease in infiltration its dispersing effect on soil aggregates (Grattan and Oster, 2003 Ruda 2005). The data for assessing the quality of water relative to sodium are the SAR, the RSC, the SSP, the% Na, the RK and the PI. There is more possibility of sodification if the proportion of sodium is high with respect to the presence of calcium and magnesium (Peinado-Guevara et al., 2011).

The maximum and minimum values are 10.77 SAR (point 35) and 0.27 (point 22) respectively (Fig. 3b). This index shows that there is no danger of sodicity in water drawn from the aquifer Soconusco, only use No. 35 presents values above 10, which is the lower limit for classifying water as well. (Fig. 3b).

The presence of carbonates and bicarbonates have effects on the quality of water for irrigation, when their presence is greater than the concentration of calcium plus magnesium exists the possibility of forming carbonates of sodium, causing deflocculation soil (Palacios and Aceves, 1970; Aguilera and Martinez, 1996), the agricultural land irrigated with such water may become infertile (Rifat et al., 2014). The RSC indicates the danger of sodium carbonate, when the cations have already reacted with carbonates and bicarbonates of calcium and magnesium, to predict the trend of these cations to precipitate in the soil when irrigated with highly carbonated water (Peinado-Guevara et al., 2011). Four samples (items 9, 13, 29, 30) have RSC values, higher than 1.25 meq/L (Fig. 3c), the rest shows values below this limit and are considered safe for use in agricultural irrigation. The maximum and minimum values, are 3.55 RSC (point 30) and -15.38 (point 16), respectively.

Displacement of calcium and magnesium in the cation exchange process initiated when the sodium content in solution is greater than 50% of the cations (Palacios and Aceves, 1970, Aguilera and Martinez, 1996), high percentages of sodium in water (greater than 50%) used in irrigation, prevents the growth of crops and reduce soil permeability (Rifat et al., 2014), SSP values below 50 indicate good water quality and above this value indicate that the water is not suitable for irrigation (Fig. 3d). The maximum value found in this sample was 80.02 (item 9) and the minimum was 15.2 (point 33), four harvesting (items 9, 12, 30, 35) present above the limit of 50 values (Fig. 3d).

Groundwater can be grouped according to their sodium content in percent (% Na), these are considered excellent for use in agricultural irrigation, and have lower values when 20%, good values 20-40%, with permissible values 40-60%, 60-80% doubtful and unsuitable when presenting values above 80% (Wilcox, 1955). The maximum and minimum values found in the aquifer under study are 80.8% and 18.4%. Three points (2, 7 and 33) have classified as excellent water; 24 exploitations have classified as good quality water; 14 have classified as admissible water; two points present a classification of water considered doubtful and as suitable for use in agriculture (Fig. 4a).

The presence of sodium with respect to the calcium plus magnesium concentration is measured by the rate or the Kelly index , values greater than 1 indicate excess sodium in water, and values less than 1 indicate that water is suitable for use in agricultural irrigation (Aher and Deshpande, 2011; Deshpande and Aher, 2011, 2012). The maximum and minimum values for the aquifer Soconusco were 4.01 and 0.18, respectively; four points (9, 12, 30 and 35) have values greater than 1 (Fig. 4b).

Soil permeability is affected by the presence of sodium, calcium, magnesium, and bicarbonate in irrigation water when it is applied continually. Considering this index water is classified as Class I and Class II if it has more than or equal to 75% PI, this water is considered good quality for use in irrigation. In Class III, the water presents values lower than PI 25% (Joshi et al., 2009; Ishaku et al. 2011; Obiefuna and Sheriff, 2011). In this study the maximum and minimum values of PI were 161.5% and 46.5% (Fig. 4c), respectively, so we can conclude that the Soconusco aquifer is of good quality for irrigation.

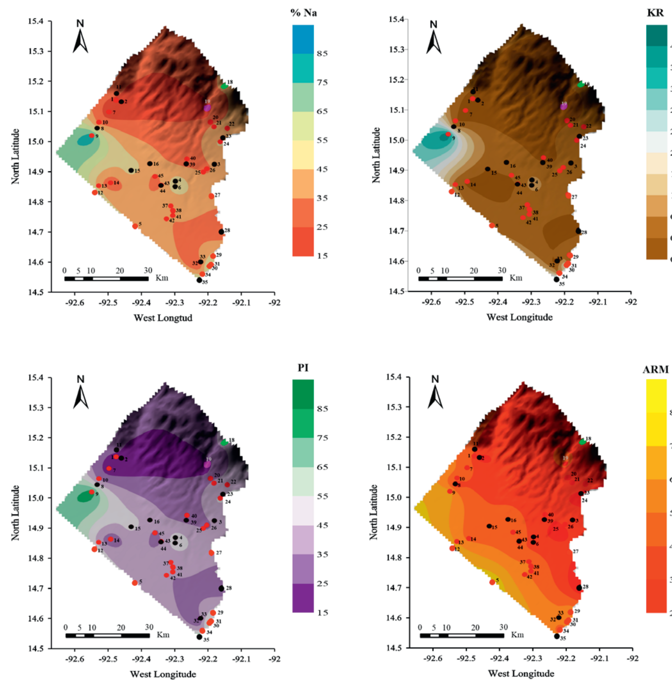

Figure 4. Spatial distribution of the indices a) % Na, b) Kelly ratio (KR), c) Permeability indices (PI) and d) Magnesium Adsorption Ratio (MAR).

In most of the water, calcium and magnesium remain in equilibrium, the presence of magnesium in concentrations affecting agricultural production sensitive to the chemical component (Nagaraju et al., 2006) cultures. In general groundwater containing low concentrations of magnesiumcan be higher if the water is in contact with dolomite containing high concentrations of it, its content in the water is a relevant indicator for the classification of water for use in irrigation The index allows to evaluate Magnesium Adsorption Ratio (MAR), that provides percentage values greater than 50%, causes harmful effects on soil (Obiefuna and Sheriff, 2011; Nag and Ghosh, 2013; Rifaf et al., 2014) values. The maximum and minimum values found in this study were 79.5% (point 5) and 20.2% (point 29), respectively. Only 10 of the 45 sites sampled 50% have higher values, which are located very close to the coastline (Fig. 4d).

Salt conditions

High concentrations of salts in irrigation water can cause an increased presence of salts in the root zone and accumulation in the soil profile, causing reduction in growth, development and production of agricultural crops (Grattan and Oster, 2003; Romero 2009). The presence of salts affects the OP and reduces crop yields (Palacios and Aceves, 1970; Aguilera and Martinez, 1996). EC measures the presence of salts in the water; it is directly proportional to the concentration of salts in solution (Palacios and Aceves 1970; Aguilera and Martinez, 1996; Porta et al., 2010). Other criteria to evaluate the conditions of salinity in the water are the SE and SP (Aguilera and Martinez 1996; Porta et al., 2010) and the OP that is closely related to the EC and with the TDS, the conjunction of the latter three values allows to classify irrigation water (Palacios and Aceves, 1970, Aguilera and Martinez, 1996, Porta et al., 2010).

Salinity is considered the most important criterion for classifying irrigation water (Ghasseme et al., 1995), salinity in soils causes reduced productivity (Essien and ubit, 2013). Electrical conductivity is a measure of the risk of salinity, the excess of it reduces the osmotic activity and interferes with the uptake of water and nutrients from the soil to the plant, so while the higher the EC less water will be available to plants (Nagaraju et al. 2006; Joshi et al. 2009, Ishaku et al., 2011, Obiefuna and Sheriff, 2011; Nag and Ghosh, 2013). EC values under 250 µmhos/cm at 25 °C in the irrigation water are considered excellent (C1) of 250-750 are classified as good (C2) of 750-2000 (C3) are admissible in 2000 3000 (C4) is considered to be doubtful use, so the water above 3000 µmhos/cm at 25 °C values (C5) are considered inadequate, since soil salinity tends to increase in proportion to the concentration of salts in the water that is irrigated (Hamdy et al., 1993, Sharma and Rao 1998; Perez-Sirvent et al., 2003), the concentration of salts in the soil can be two to six times corresponding to conductivity of irrigation water (Hamdy et al., 1993; Perez-Sirvent et al., 2003).

In this study, the maximum and minimum values of CE (Fig. 5a) were 3995 µmhos/cm at 25 °C and 49 µmhos/cm at 25 °C. 19 of 45 sampling points have lower values than 250 µmhos/cm at 25 °C, 18 points have values between 250-750, three point has classified as admissible water; the rest of the sampling points, 5 of 45 had higher values at 2000 µmhos/cm at 25 °C, ie, they are unsuitable for use in agriculture (Fig. 5a) waters. In an area near the aquifer under study Olea (2013) found values ranging from 152 EC µmhos/cm, in wells near the city of Huixtla, to 31,700 values µmhos/cm wells or very close to the shoreline wells.

EC values found in the Soconusco aquifer, suggest that are mild problems of salinity, although the SE and SP indicate that the water from this aquifer is generally of good quality. Considering the above, it was deemed appropriate to classify the water according to OP and the presence of TDS. OP values below 0.1 atm are indicators of some saline water with excellent quality, values between 0.1-0.3 are indicators of saline water with good quality, values of 0.3-0.7 indicates saline water with allowable quality water, point between 0.7-1.1 very saline water with growing problems and values greater than 1.10 atm OP indicators are very saline water with significant problems. The results of this index for the Soconusco aquifer show that 4 points has excellent water quality, 26 points have saline water of good quality; 9 are classified allowable salt water quality and other points (6 of 45) are classified as very saline water with major problems.

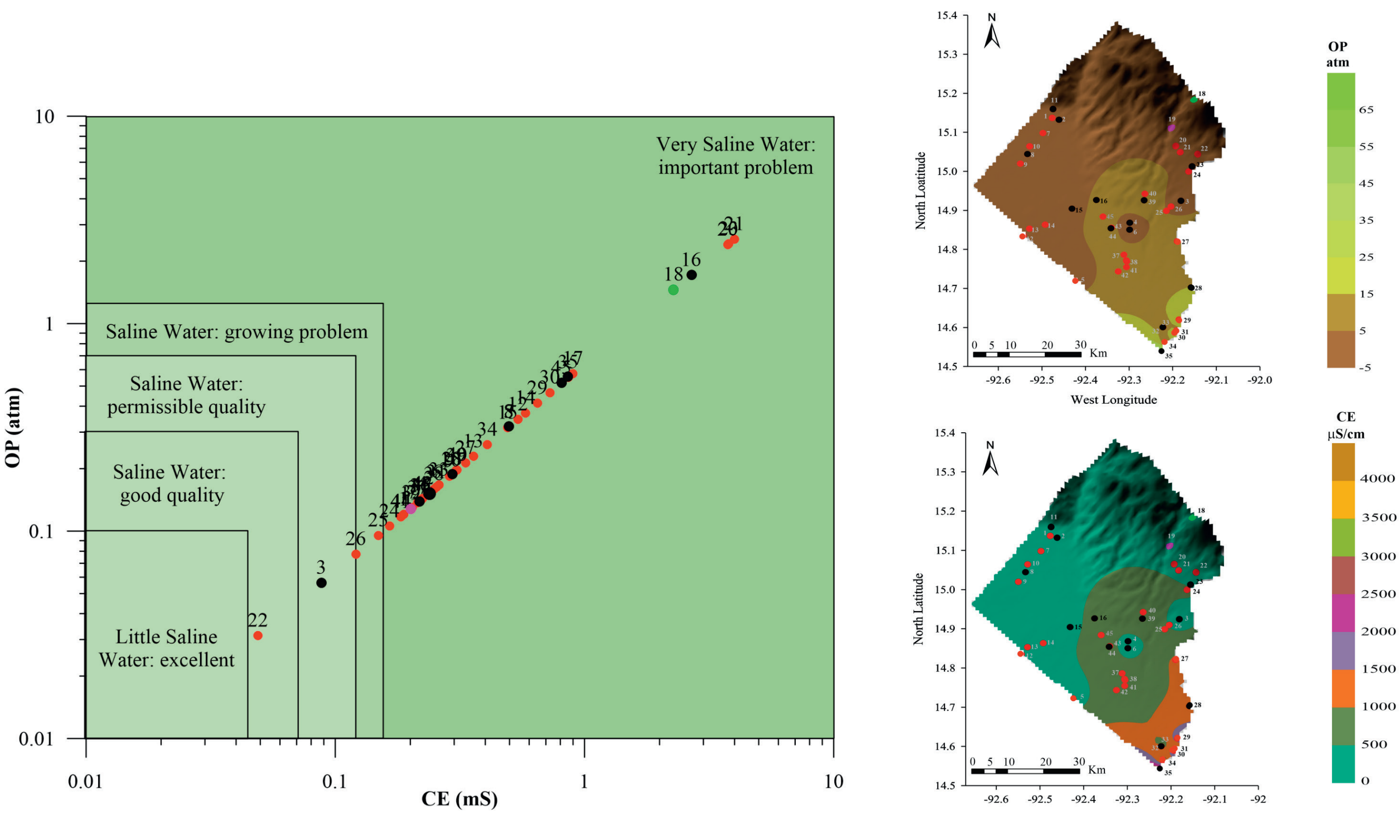

Figure 5. Spatial distribution of the indices a) Osmotic Potential (OP) vs Electrical Conductivity (EC), b) Osmotic potential (OP) and c) Electrical conductivity (EC).

Concerning TDS, if these values are between 0-1000 mg/L it is considered non-salt fresh water if they are between 1000-3000 mg/L slightly saline, of 3000-10000 is considered moderately saline, values TDS above 10000 mg/L are indicative of highly saline waters. The minimum and maximum values of TDS for this study are 87 mg/L and 50,760 mg/L. About the 45 samples taken from the Soconusco aquifer, 40 are classified as non-salt fresh water, 4 are classified as slightly saline, 1 is classified as moderately saline. It is important to remember that the presence of dissolved water in excessive amounts ions cause physical and chemical effects on the soil and plants (Ahamed et al., 2013), reduces the ability of plant roots to extract water from the ground. There is a direct relationship between the presence of salts, measured from the EC, and the OP. Thus, as noted above, most of the samples water from wells in the Soconusco aquifer are between non-salt fresh water to considered non-salt fresh water (Fig. 5c).

The more realistically estimated danger of salinization, since it considers that the soluble salts of irrigation water are incorporated to soil, taking into account the precipitation of less soluble salts such as calcium and magnesium carbonates; as well as calcium sulphate (Rodriguez et al., 2008, Mancilla, 2012, Barrios, 2014). Similarly, the SP to estimate the risk that can generate the salts when the moisture content in soil is low, it is considered as one of the best estimates of the effect of salts on plants (Rodriguez et al., 2008), considers the precipitation of less soluble salts such as chlorides and sulfates (Nagaraju et al., 2006; Mancilla, 2012; Barrios, 2014), leading to increases in osmotic pressure and reduced crop production.

The maximum and minimum values of ES obtained in this study were 30.04 meq/L (point 16) and 0.15 meq/L (point 20), respectively. Of the 45 water samples taken in the Soconusco aquifer, 37 ES presented values lower than 3, which is the upper limit for classification as good quality water. Six exploitation (items 9, 12, 14, 17, 29 and 30) have water classified as conditional (with ES values above 3 but less than 15) and two harvests (points 16 and 35) are classified as not recommended water ES with values greater than 15. With respect to the PS results indicate that the maximum value was 27.9 (Item 16) and the minimum was 0.06 (point 34), the same limits used in the ES are applied to classify water in respect to the PS; according to the above 42 of the 45 samples fall in the classification of good quality water; two (points 14 and 35) have conditioned water and one (point 16) is classified as not recommended (Figs. 6a, 6b and 6c).

Classification water considering the% Na, the SAR and the EC

The combination of SAR and EC values for each of the sampling points were plotted in the diagram developed by the Laboratory of the US Salinity (Fig. 7a), the chart allows classification of irrigation water. About the 45 samples collected in the in Soconusco aquifer, 19 points are classified as C1S1 water, ie, low risk of salinity and low risk of sodification. Eighteen of the 45 samples are classified as C2S1 (medium risk and low risk of salinity sodification). Two samples (points 17 and 45) fall into the classification C3S1 and which are at high risk of salinity and low risk of sodification. Four samples (points 18, 20, 21 and 23) are classified as C4S1, which should be only used on soils with good water permeability. The use of water from the Soconusco aquifer is conditioned by the salinity levels rather than those of sodification. But also points 16 and 35 begin to show signs of high and very high risk of sodification.

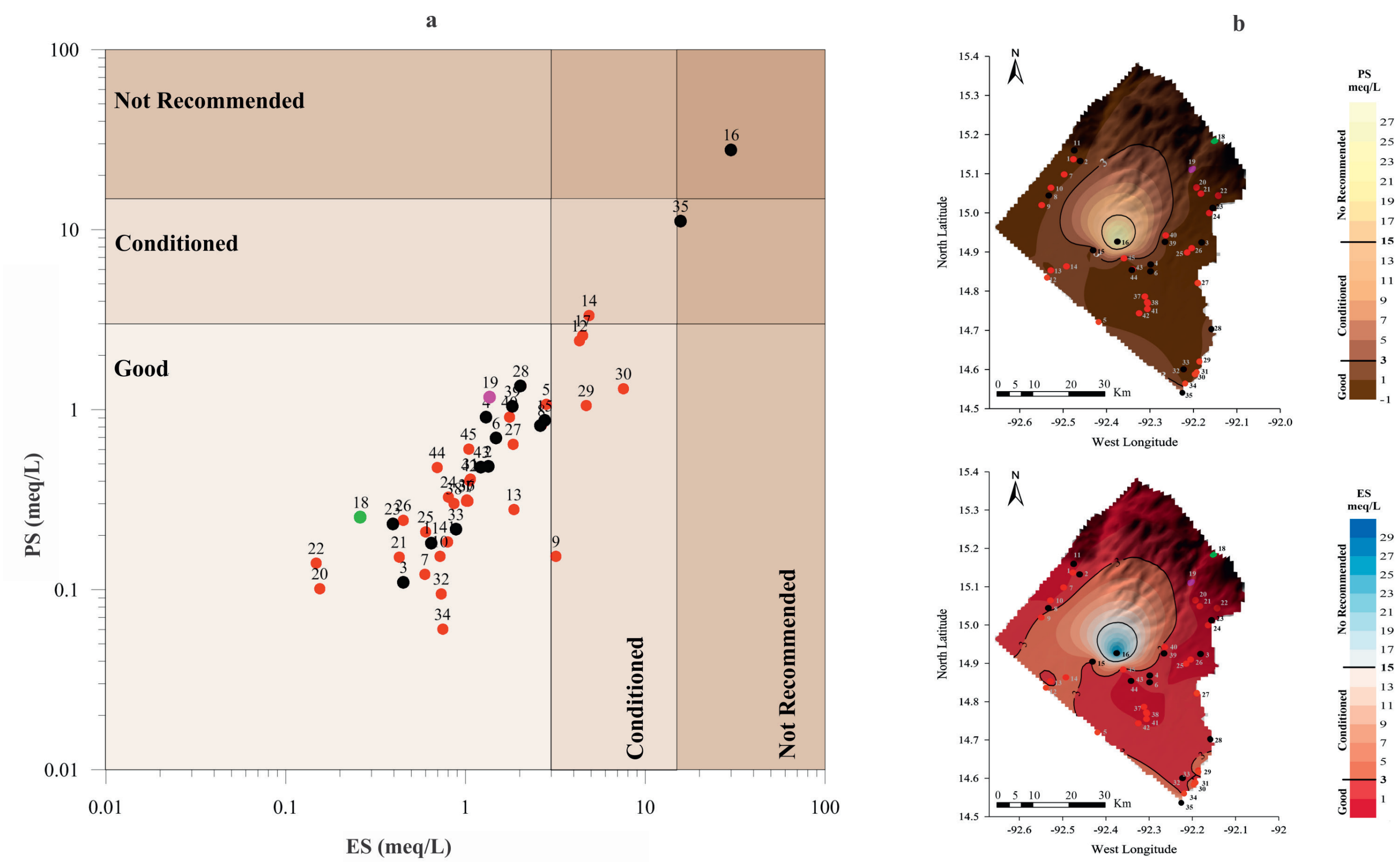

Figure 6. Spatial distribution of the indices a) Effective salinity (ES) vs potential salinity (PS), b) Potential salinity (PS) and c) Effective salinity (ES).

The % Na is plotted together with the EC in the diagram Wilcox and it classifies water for use in irrigation (Fig. 7b). 36 of the samples collected fall into the classification of good to excellent, 2 are considered permissible to good, both fall into the category of admissible doubtful equal number of samples (points 18 and 16) are classified as doubtful inadequate, notably, 3 of the 45 samples taken from the Soconusco aquifer are classified as inadequate (Fig. 7b). It is worth remembering that there is no precedent studies on water quality to serve as reference.

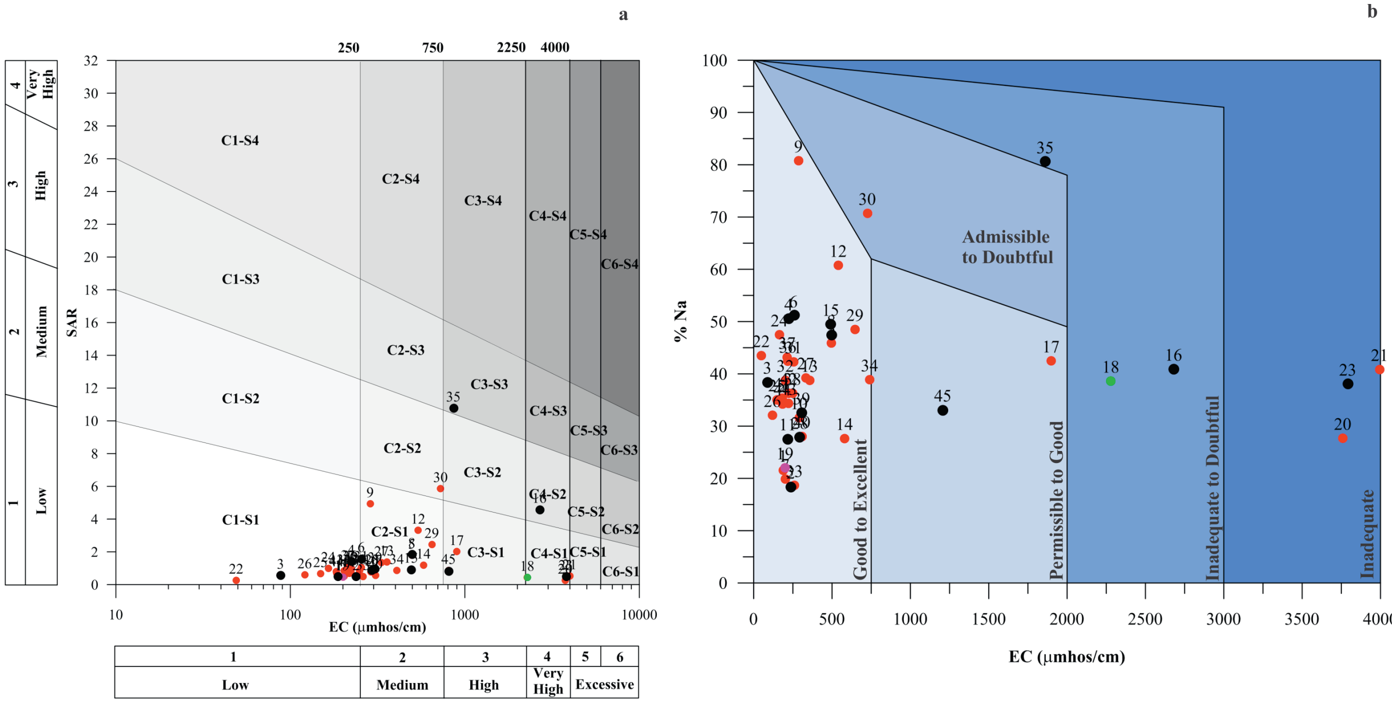

Figure 7. Water classification according to a) Wilcox y) Electrical Conductivity (EC) vs Percent Sodium (% Na), for the Soconusco aquifer.

The previous analysis pointed out that the problems associated with the aquifer sodicity Soconusco are not considered and are presented in specific areas; However, the problems associated with salinity may increase, although they have not seen yet and there are no studies that indicate problems of soil salinization in the study region, which is due in great measure to the heavy rainfall, the soil conditions, climate and, above all, hydrogeochemical Soconusco.

Presence of toxic ions (chloride and sodium) for plants

Some ions, depending on the concentration in which they are in the water, can be toxic to crops, usually they accumulate in leaves. Often toxic chlorine ions, sodium and boron (Ayers and Wescot 1985. If the chloride concentration exceeds crop tolerance may result from the burning of leaves to tissue death, when the content of this element is less than 4 meq/L, the water is classified as good, if it is between 4-10 meq/L is classified as conditional, and if you have concentrations above 10 meq/L are classified as not recommended water. The maximum value found in this study was 21.5 meq/L (point 16) and the minimum was 0.03 meq/L, with a coefficient of variation of 11.22. Of the 45 samples, 43 presented below 4 meq/L (Fig. 8a) values, indicating that the Soconusco aquifer presents no problems according to this chemical element and is classified as good ie may be used for irrigation.

Sodium often causes similar damage causing chlorides and nutritional imbalances in plants. Values less than 3 meq/L of Na are indicative of low toxicity hazard to plants of this; values 3-9 meq/L indicate medium risk and values of more than 9 meq/L are high risk indicators for sodium. The maximum and minimum values obtained in this sample were 16.6 meq/L and 0.07 meq/L, respectively, with a coefficient of variation of 5.6. In 38 of the 45 samples collected, sodium values obtained are less than 3 meq/L, ie it is endangered by water with low sodium. Five samples (points 9, 12, 17, 29 and 30) have values between 3 and 9 meq/L, indicating water at average risk. Two samples (points 16 and 35) have more than 9 meq/L values at high risk for sodium (Fig. 8b).

CONCLUSIONS

- Geochemistry of groundwater of Soconusco display the order of ionic abundance is $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ and $HCO_3^- > SO_4^{2-} > Cl^-$ trend.
- The type of water that predominate in the study area is Ca-HCO_3 type.
- The main hydrochemical processes occurring in groundwater are dilution by mixing, water-rock interaction and only some samples show evaporation effects.

- WQI indicate that more than half samples are not suitable for drinking purposes (60% is very good quality).
- The groundwater of the Soconusco aquifer has no problems of sodicity for agricultural use.
- The soil, climatic and physiographic conditions, as well as rainfall of around 1,500 to 4,000 mm/year in the region, favor the recharge of the aquifer and the adequate mechanisms for the natural drainage of the aquifer, avoiding the salinity of groundwater.
- The combination of PS/ES, classifies most of the water as good for agricultural use, only some samples fall as conditioned and two samples as not recommended for this use.
- The combination of % Na/EC, classifies the groundwater of the Soconusco aquifer, as excellent, only some as admissible to doubtful and very few are classified as doubtful to inadequate.

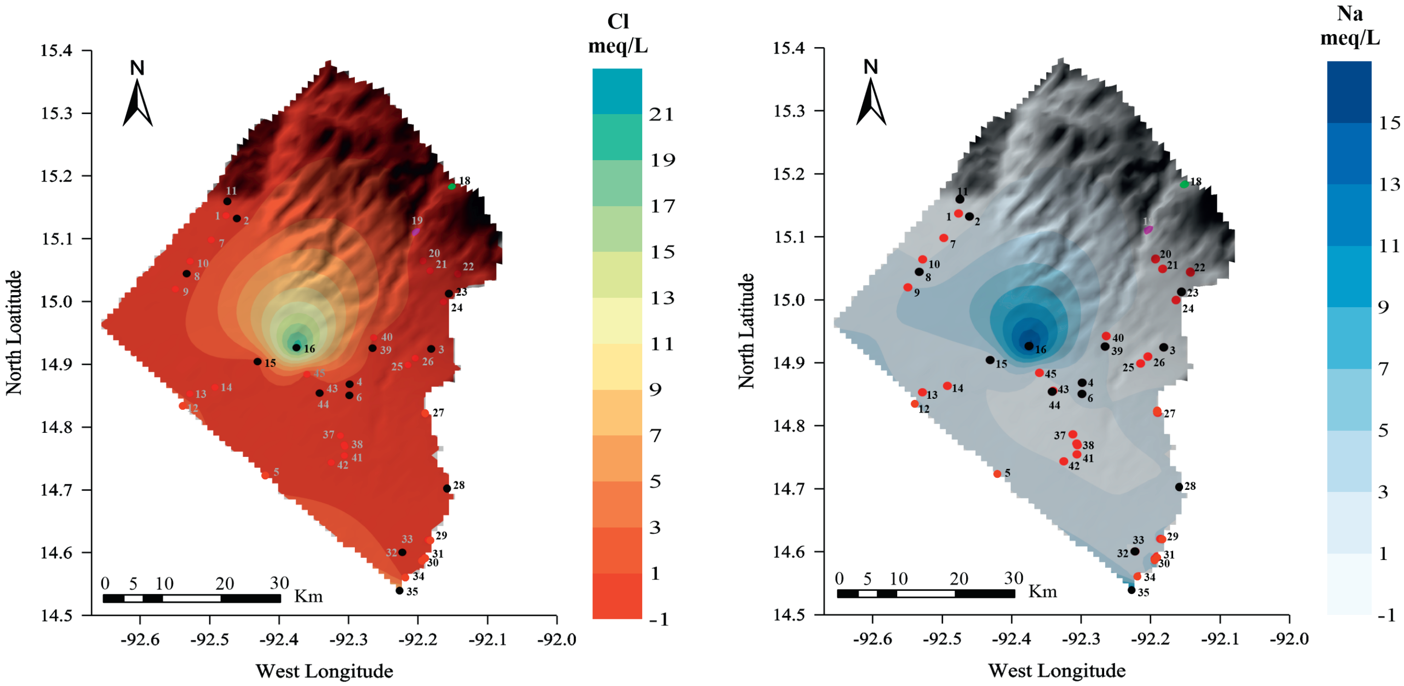

Figure 8. Spatial distribution of toxic ions a) ion Cl and b) Na, for the Soconusco aquifer.

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