Article

Water quality for agricultural use of the San Pedro River, Nayarit

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Abstract

The study area is of fluvian delta formation, with a predominance of cambisol and fluvisole soils. The main crops in the area are beans, corn, sorghum, tobacco and tomatillo. These are watered with water from the San Pedro River. Surface water, when it contains high concentrations of sodium or bicarbonate, can cause adverse effects in agriculture. With the objective of evaluating these effects, nine sampling sites were established in the riverbed and four samplings were carried out over a period of two years, in a rainy and dry season each year. The pH, EC, anions and major cations were determined, the hydrogeochemical type was established and the RAS, RAS^o, RASaj, PSI, CSR and the saturation index were calculated. In the section of the river from El Rosarito to El Mezcal, the water is bicarbonated sodium-calcium-magnesium and from Mexcaltitan to Boca de Camichin, it was chlorinated-sodium. The RAS in its different conceptualizations for the first section were from 0.38 to 1.58, the EC ranged between 131-367 µS cm^{-1} and the PSI<3%; while, for the last section, the RAS varied between 9.06-161.16, the EC between 2 350-4 3130 µS cm^{-1} and the PSI between 6.16-73.14%. The waters from the San Pedro de El Rosario to El Mezcal river turned out to be excellent to good quality. Chlorinated-sodium waters are not suitable for agricultural use.

Keywords: adjusted RAS, hydrogeochemistry, saturation index.

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Introduction

The San Pedro river basin, located in the states of Durango, Zacatecas and Nayarit, encompasses the Sierra Madre Occidental and the Pacific Coastal Plain physiographic provinces. The first is one of the great siliceous igneous provinces of the Cretaceous-Cenozoic, where the main types of rocks are andesitic, dacitic-rhyolitic, ignimbrite and alkaline basalts, which lie on a Pre-Cambrian, Paleozoic and Mesozoic basement; in its central zone, all the rocks are calcalcaline and their composition varies from diorite to granite, with granidioritic being the dominant one (Ferrari *et al*., 2005).

The Pacific Coastal Plain is a deltaic fluvial system formed by sediments from the San Pedro, Santiago and Acaponeta rivers and is related to marine transgressions during the late Pleistocene and Holocene (Curray *et al*., 1969). The rocks that make up this plain are extrusive igneous rocks from the Tertiary, alluvial and marshy deposits, made up of sand, gravel, silt and clay from the Quaternary (Ferrari *et al*., 2005). The main soils are cambisols and fluvisols (Bojorquez *et al*., 2006).

The Coastal Plain is of great importance because it has a high agricultural activity, in the study area 125 856 ha are cultivated and of which 85% are irrigated, and it is where the water from the San Pedro river is used for the Irrigation of beans (*Phaseolus vulgaris*), maize (*Zea mayz*), sorghum (*Sorghum bicolor* L. Moench), tobacco (*Nicotiana tabacum* L.) and tomatillo (*Physalis ixocarpa* Brot. ex Horn.). When this water is used for this purpose, it is important to consider the quality, since according to this is the management that must be given to prevent the problems that could cause.

The elements contained in natural waters come from the dissolution or weathering of rocks and soils, and are transported by surface currents and deposited in the soils of the lower parts, either naturally or through irrigation (Can-Chulim *et al*., 2008). From the ionic composition of the water, various criteria, index or associations are used, which allow classifying them, evaluating risks and determining their quality for agriculture.

Among these are the danger of salinization and that of sodification by means of the sodium adsorption ratio (RAS) and the percentage of exchangeable sodium (PSI), residual sodium carbonate (CSR) and others (Mandal *et al*., 2019). Most focus on the Na^+ content, on the concentration of Ca^{2+}, Mg^{2+} and on CO_3^{2-} and HCO_3^-. If the concentration of Na^+ is high, the danger of alkalization is high, this is magnified when there are high contents of CO_3^{2-} and HCO_3^-, due to the tendency of these ions to form precipitates with Ca^{2+} and Mg^{2+}, in addition to being in suspension the most soluble substances, including Na_2CO_3.

Yaron and Tomas (1968) demonstrated that high Na^+ content in irrigation water considerably increases the PSI and when this happens they decrease the physical, chemical and nutritional properties of the soil. In this study, a hydrogeochemical classification was made, the quality of the water for irrigation was evaluated using the RAS, PSI, CSR indices, and the carbonate precipitation process using the San Pedro River water saturation index in Nayarit; with the aim of evaluating the adverse effects that the use of this water can cause in agriculture.

Materials and methods

Description of the study area

The San Pedro River is born in the Michis mountain range, in Durango, at 3 000 masl and empties into the Pacific Ocean, its channel crosses the Sierra Madre Occidental and Pacific Coastal Plain physiographic provinces. Its basin has an area of 29 366.53 km^2 (INEGI, 2010). The study area is located in the Pacific Coastal Plain, San Pedro-Tuxpan sub-basin; which includes part of the municipalities of Rosamorada and Santiago Ixcuintla, completely Ruiz and Tuxpan, in Nayarit; it has an area of 3 018.71 km^2; the subhumid warm climate (Aw) predominates with an annual average temperature of 23.8 °C, a maximum of 26 °C and a minimum of 20 °C, with the highest temperatures from May to October and rainfall from June to October with an annual average of 1 555.8 mm. (DOF, 2015).

Sampling design

Nine sampling sites were established on the bed of the San Pedro river, located according to the physiography, the communication routes and the agricultural area of the basin. The sites were El Rosarito (ER), San Pedro Ixcatan (SPI), El Venado (EV), Ruiz (RZ), El Tamarindo (ET), Tuxpan (TUX), El Mezcal (EM), Mexcaltitan (MEX) and Boca de Camichin (BC) (Figure 1).

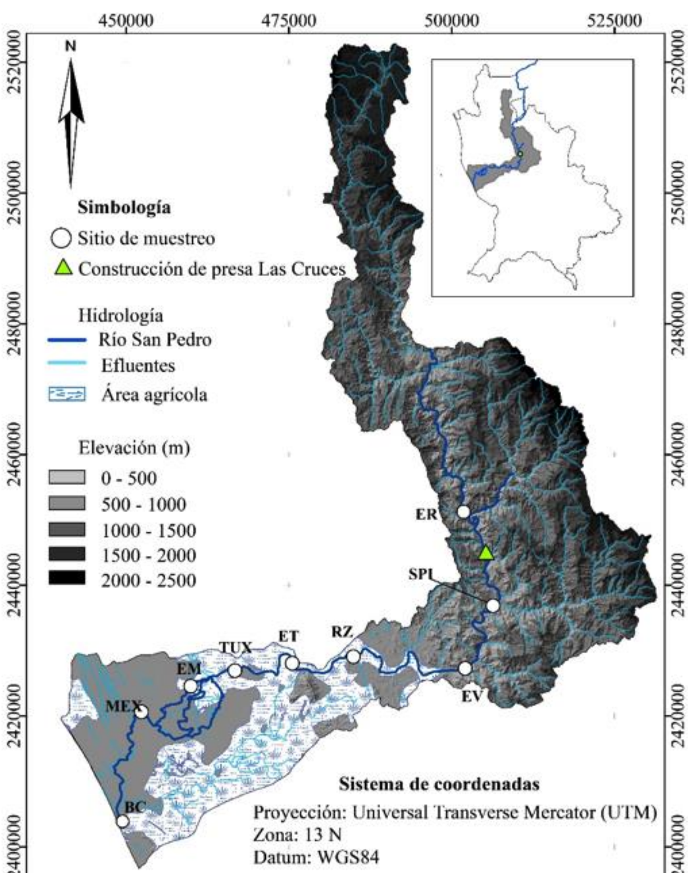

Figure 1. Sampling sites in the San Pedro riverbed in Nayarit.

Four samplings were carried out in the months of October 2016, April 2017, December 2017 and May 2018. Each site was georeferenced using a GPS with UTM coordinate system. Due to the formation processes that affect the basin, from Rosarito to Mezcal they are considered the first section and are waters from the natural channel of the San Pedro river. The Mexcaltitan and Boca de Camichin sites, being a transition zone between inland waters and marine intrusion waters, were considered the second section. Two samples were taken at each site, with 1 L polyethylene containers.

Chemical analysis

They were determined in triplicate, based on the APHA methods (2012): pH with a Thermo Scientific Orion Star A211 potentiometer; EC using an Oakton CON 700 conductivity meter; Ca^{2+} and Mg by titration with EDTA; Na^{+} and K^{+} by the photometric flame emission method with a Cole-Parmer Photometer; CO_3^{2-} and HCO_3^{-} by titration with sulfuric acid; SO_4^{2-} by turbidimetry; and Cl^{-} by titration with silver nitrate according to the NMX-AA-073-SCFI-2001 standard.

Analysis of data

Hydrogeochemical analysis. To establish the hydrogeochemical facies, their evolution and the causes that influence the ionic composition of the waters along the San Pedro river basin, the Piper diagram was used (Güler *et al*., 2002).

Quality parameters

Physical-chemical regime or pH. For agricultural use the desirable pH is between 5.5 and 6.5 (Steiner, 1968). Although according to water quality guidelines, a pH range between 6.5 and 8.5 is normal (Krishna *et al*., 2017).

Electric conductivity. The waters were classified based on electrical conductivity (EC) according to Richards (1990), who establishes that to prevent soil salinization by the application of irrigation the water is classified as: low salinity water C1:<250 µS cm^{-1}), medium salinity water (C2: 250-750 µS cm^{-1}), high salinity water (C3:750-2250 µS cm^{-1}), very high salinity water (C4: 2 250-5 000 µS cm^{-1}) and water of exceptionally high salinity (C5:>5 000 µS cm^{-1}).

Sodium content. This evaluation was performed using the sodium adsorption ratio (RAS). This index foresees the risk of sodification and, consequently, the possible effects that waters can have on the physical properties of soils due to the effects of Na^{+} when precipitating calcite ($CaCO_3$). The RAS values were determined in their different conceptualizations: original RAS (RAS_{or}), corrected RAS (RAS°) and adjusted RAS (RAS_{aj}). Using the equations.

$$(RAS_{or}) = \frac{[Na^{+}]}{\sqrt{\frac{[Ca^{2+}]+[Mg^{2+}]}{2}}} ; \quad (RAS°) = \frac{[Na^{+}]}{\sqrt{\frac{[Ca_x^{2+}]+[Mg^{2+}]}{2}}} ; \quad (RAS_{aj}) = \frac{[Na^{+}]}{\sqrt{\frac{[Ca^{2+}]+[Mg^{2+}]}{2}}} [1+(8.4-pH_c)]$$

Where: Na^{+}, Ca^{2+} and Mg^{2+} are expressed in $mmol_c\ L^{-1}$. Ca_x^{2+} represents the content of Ca in irrigation water in $mmol_c\ L^{-1}$, corrected for the salinity of the water (EC), for the content of bicarbonate ions in relation to its own content of calcium (HCO_3^-/Ca^{2+}) and for the partial pressure of carbon dioxide (CO_2) exerted on the first millimeters of the soil (p= 0.0007 atm) (Suárez, 1981).

pH_c is the theoretical pH in equilibrium with calcite, and 8.4 is approximately the pH of a non-sodium soil in equilibrium with calcite. $pH_c=(pK_2'-pK_c')+pCa+pAlk$. pCa which is the negative logarithm of the molar concentration of [Ca^{2+}]; pAlk is negative logarithm of the equivalent concentration of [$CO_3^{2-}+HCO_3^-$]; pK'_2 and pK'_c are the negative logarithm of the second dissociation constant of H_2CO_3 $K_2'=\frac{[H^+][CO_3^{2-}]}{HCO_3^-}=4.7\text{x}10^{-11}$ and the solubility product of $CaCO_3$ $K_c'=[Ca^{2+}][CO_3^{2-}]=5\text{ x}10^{-9}$, both corrected by the ionic force they exert the components of water (Bower *et al*., 1965).

To determine the ionic strength of the waters of the San Pedro river, the equation $I=\frac{1}{2}\sum CiZi^2$, was used, where Ci is the molar concentration of each ion in solution and Zi is its valence. To perform the calculation of $(pK_2'-pK_c')$ the Debye and Hückel equation was used with a certain ionic strength (I) as follows: $pK_2'-pK_c'=\left\{2.0269+\left[0.5092\left(\frac{4(I)^{\frac{1}{2}}}{1+2(I)^{\frac{1}{2}}}+\frac{(I)^{\frac{1}{2}}}{1+1.45(I)^{\frac{1}{2}}}\right)\right]\right\}$. The number 2.0269 is the difference between $pK_2'-pK_c'$, the latter term expresses the Debye and Hückel correction for a specific ionic strength of a given type of water (Bower *et al*., 1965).

The RAS in its different conceptualizations are classified into four classes: low sodium water (S1), medium sodium water (S2), high sodium water (S3) and very high sodium water (S4).

Interchangeable sodium percentage (PSI). According to Sposito and Mattigod (1977), if it is assumed that Ca^{2+} and Mg^{2+} are chemically the same, in what refers to the exchange of cations, and that the exchangeable cations in the soil are only Na^+, Ca^{2+} and Mg^{2+}, the equation stated as.

$$PSI=\frac{K_G RAS100}{1+K_G RAS}$$

The values of RAS_{or}, RAS° and RAS_{aj} were taken from the water of the San Pedro river and the PSI in the soils was calculated, this, under conditions of equilibrium between the irrigation water and the soil. To obtain the PSI_{min} and PSI_{max}, values, the K_G ion selectivity constants were those used by Velazquez-Machuca *et a*l. (2002) K_{Gmin} = 0.0072444 and K_{Gmax} = 0.0168999 that correspond to the soils with sandy-clayey-silty and clayey texture, respectively.

Residual sodium carbonate (CSR). When irrigation water has high concentrations of HCO_3^- and which is also higher than the concentration of Ca^{2+} plus Mg^{2+}, there is a possibility that sodium carbonate (Na_2CO_3) will form. Due to its high solubility, Na_2CO_3 can remain in solution, even after Ca^{2+} and Mg^{2+} carbonates have precipitated as the soil solution becomes more concentrated (Castellon-Gomez *et al*., 2015). The CSR index was calculated using the equation. $CSR=(CO_3^{2-}+HCO_3^-)-(Ca^{2+}+Mg^{2+})$.

Where: Ca^{2+}, Mg^{2+}, CO_3^{2-} and HCO_3^- are expressed in mmolc L^{-1}. Values <1.25 are classified as good quality, between 1.25 and 2.5 as conditioned and >2.5 is not recommended (Nishanthiny *et al*., 2010). Negative values indicate that there are no problem and positive values indicate that Ca^{2+} and Mg^{2+} precipitate, and the higher the index, the greater the magnitude of the precipitation.

Saturation index. When irrigation waters have appreciable concentrations of bicarbonates, a fraction of this constituent precipitates into the soil as $CaCO_3$, according to the equation: $Ca^{2+}+2HCO_3^- \rightarrow CaCO_3\downarrow + H_2O + CO_2\uparrow$. Precipitation reduces the salinity of the soil but increases the proportion of Na^+ in the solution, and consequently influences the exchange complex. The saturation index (IS) was used to know the tendency of HCO_3^- ions in irrigation waters to precipitate in the soil. IS is defined as the current pH of water (pH_a) minus the theoretical pH that water would have if it were in equilibrium with calcite (pH_c) (Langelier, 1936). Saturation index $(IS)=pH_a-pH_c$. Positive values indicate that the bicarbonate from the irrigation water will precipitate in $CaCO_3$ when it comes into contact with the soil and negative values indicate that the irrigation water will dissociate calcite from the soil.

Results and discussion

Hydrogeochemical classification. Using the Piper diagram (Figure 2), MEX and BC are classified as chlorinated-sodium (Cl-Na) and are characterized by the intrusion of seawater, since they are in a transition zone between continental and ocean waters. In the ER to EM sites, the hydrogeochemical type was sodium-calcium-magnesium-bicarbonate (Na-Ca-Mg-HCO_3). According to Madrigal-Solis *et al*. (2017), bicarbonated waters generally correspond to recent water, which has had a short time of permanence and interaction with rocks, this absence of changes was related to the altitudinal gradient that does not allow long periods of contact with geological material.

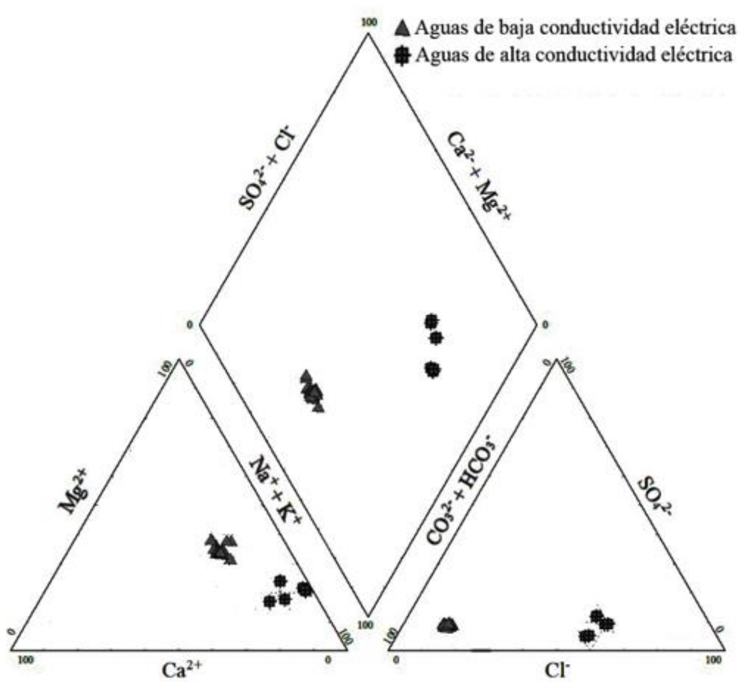

Figure 2. Hydrogeochemical classification of the San Pedro river water in Nayarit.

The ionic composition obeys the following order: $Na^+ + K^+ > Mg^{2+} > Ca^{2+}$; for anions it was $HCO_3^- + CO_3^{2-} > Cl^- > SO_4^{2-}$, while in MEX and BC it was $Cl^- > HCO_3^- + CO_3^{2-} > SO_4^{2-}$ (Table 1). Low ionic concentrations are due to the silicate material being insoluble. The alkaline behavior is caused by the ignimbrite rocks and alkaline basalts of the Sierra Madre Occidental. Based on Vidal-Solano *et al*. (2005), during post-subduction magmatism, ignimbrites in their composition have high iron and alkali contents up to Na_2O+K_2O= 8-10%, which explains the sodium behavior of water; also, according to Aranda-Gómez *et al*. (2005), the SMO basaltic rocks are rich in MgO and SiO_2. Therefore, Mg^{2+} is one of the cations with the highest content.

Physical-chemical regime (pH). For the ER-EM section, in the rainy season, waters were obtained from neutral to moderately alkaline pH, with values from 7.3 to 8. During the dry season, the pH was from moderately alkaline to strongly alkaline, with values from 7.7 to 8.9, where the highest results were obtained in the fourth sampling. For the MEX and BC sampling sites, the pH turned out to be neutral to mildly alkaline, in MEX the pH_{min} and pH_{max} were 7.3 and 7.8, and in BC 7.3 and 7.7 (Table 1).

Table 1. Ionic composition of the water of the San Pedro river in Nayarit.

ID	pH	EC (μS cm^{-1})	Class	Ca^{2+}	Mg^2	Na^+	K^+	Σ	CO_3^{2-}	HCO_3^-	Cl^-	SO_4^{2-}	Σ	Error (%)
				($mmol_c$ L^{-1})										
Sampling 1 October 2016, rainy season														
ER	8	157	C1	0.32	0.5	0.65	0.06	1.53	0	1.18	0.19	0.12	1.49	1.32
SPI	7.7	141	C1	0.29	0.45	0.59	0.05	1.38	0	1.07	0.17	0.11	1.35	1.09
EV	7.8	131	C1	0.27	0.42	0.55	0.04	1.28	0	0.97	0.18	0.1	1.25	1.19
RZ	7.8	139	C1	0.29	0.45	0.58	0.04	1.36	0	1.02	0.19	0.11	1.32	1.49
ET	7.6	147	C1	0.3	0.47	0.62	0.05	1.44	0	1.1	0.18	0.12	1.4	1.41
TUX	7.4	158	C1	0.33	0.51	0.66	0.05	1.55	0	1.15	0.22	0.13	1.5	1.64
EM	7.4	184	C1	0.38	0.59	0.77	0.06	1.8	0	1.34	0.26	0.15	1.75	1.41
MEX	7.4	2530	C4	2.45	4.4	16.77	1.12	24.74	0	7.73	13.53	2.84	24.1	1.31
BC	7.3	23605	C5	5.57	49.8	172.6	2.88	230.8	0	87.36	126.2	11.26	224.8	1.31
Sampling 2 April 2017, drought season														
ER	8.4	297	C2	0.6	0.95	1.24	0.11	2.9	0.12	2.12	0.36	0.23	2.83	1.22
SPI	8.5	276	C2	0.58	0.96	1.06	0.1	2.7	0.15	1.93	0.31	0.23	2.62	1.5
EV	8.5	266	C2	0.56	0.88	1.06	0.1	2.6	0.14	1.85	0.34	0.21	2.54	1.17
RZ	8.5	237	C2	0.52	0.8	0.91	0.09	2.32	0.12	1.65	0.28	0.2	2.25	1.53
ET	8.4	254	C2	0.56	0.82	1.01	0.09	2.48	0.14	1.74	0.32	0.2	2.4	1.64
TUX	8	314	C2	0.66	1.16	1.13	0.12	3.07	0	2.32	0.4	0.26	2.98	1.49
EM	8	367	C2	0.78	1.35	1.32	0.14	3.59	0	2.69	0.5	0.3	3.49	1.41
MEX	7.6	4010	C4	3.87	6.95	26.62	1.77	39.21	0	12.3	21.38	4.49	38.17	1.34
BC	7.4	35367	C5	7.36	70.7	263.5	4.32	345.8	0	131	188.9	16.89	336.9	1.31

ID	pH	EC (µS cm^{-1})	Class	Ca^{2+}	Mg^{2}	Na^{+}	K^{+}	Σ	CO_3^{2-}	HCO_3^{-}	Cl^{-}	SO_4^{2-}	Σ	Error (%)
				(mmol$_c$ L^{-1})										
Sampling 3 December 2017, Rainy season														
ER	7.5	210	C1	0.44	0.68	0.84	0.09	2.05	0	1.55	0.27	0.18	2	1.23
SPI	7.7	190	C1	0.39	0.61	0.78	0.08	1.86	0	1.41	0.24	0.16	1.81	1.36
EV	7.6	180	C1	0.39	0.59	0.71	0.07	1.76	0	1.34	0.22	0.14	1.7	1.73
RZ	7.8	190	C1	0.36	0.58	0.85	0.07	1.86	0	1.42	0.23	0.15	1.8	1.64
ET	7.5	200	C1	0.41	0.64	0.83	0.08	1.96	0	1.5	0.24	0.15	1.89	1.82
TUX	7.4	210	C1	0.44	0.69	0.82	0.1	2.05	0	1.58	0.25	0.16	1.99	1.49
EM	7.3	210	C1	0.42	0.7	0.83	0.11	2.06	0	1.58	0.28	0.15	2.01	1.47
MEX	7.3	3440	C4	4.98	5.67	21.43	1.56	33.64	0	10.18	19.62	2.92	32.72	1.39
BC	7.5	43130	C5	8.90	86.25	321.3	5.28	421.7	0	159.6	230.5	20.6	410.8	1.32
Sampling 4 May 2018, drought season														
ER	8.5	290	C2	0.56	0.98	1.17	0.13	2.84	0.12	2.03	0.37	0.25	2.77	1.25
SPI	8.6	270	C2	0.42	0.98	1.11	0.13	2.64	0.12	1.87	0.35	0.23	2.57	1.34
EV	8.7	260	C2	0.55	0.84	1.04	0.11	2.54	0.18	1.73	0.33	0.22	2.46	1.6
RZ	8.6	230	C1	0.46	0.75	0.94	0.1	2.25	0.16	1.53	0.3	0.2	2.19	1.35
ET	8.9	250	C2	0.42	0.91	1	0.11	2.44	0.18	1.7	0.29	0.2	2.37	1.46
TUX	7.7	290	C2	0.61	0.94	1.17	0.12	2.84	0	2.15	0.37	0.25	2.77	1.25
EM	7.8	290	C2	0.59	0.95	1.18	0.12	2.84	0	2.14	0.37	0.25	2.76	1.43
MEX	7.8	16330	C5	12.98	37.61	98.69	9.41	158.7	0	46.45	93.2	13.87	153.5	1.66
BC	7.7	43820	C5	9.08	87.98	321.9	5.39	424.4	0	157.1	235.2	21.01	413.3	1.32

ID= identification (sampling site); ER= El Rosarito; SPI= San Pedro Ixcatan; EV= El Venado; RZ= Ruiz; ET= El Tamarindo; TUX= Tuxpan; EM= El Mezcal; MEX= Mexcaltitan; BC= Boca de Camichin.

Most of the salts derive from a strong base like Na^+, K^+, Ca^{2+} and Mg^{2+} and a weak acid like CO_3^{2-} and HCO_3^-, according to Raviolo and Farre (2017) the hydrolysis of these produces basic aqueous solutions, while the NaCl and $MgSO_4$ derived from a strong base with a strong acid produce neutral solutions. The presence of Na_2CO_3 provides the water with high alkalinity (Sen, 2015), for this reason the pH of the San Pedro river is above neutrality (pH> 7). Normal pH values in irrigation water range from 6.5 to 8.5, the waters of the San Pedro River in a dry period reached values up to 8.9, according to Hong *et al*. (2013) these will have implications on the availability and management of nutrients. If they are used for fertigation, it will be necessary to lower the pH between 5.5 and 6.5.

Electric conductivity. The EC_{min} and EC_{max} in the ER-MS section were 131 and 367 µS cm^{-1}, in MEX it was 2 530 and 16 330 µS cm^{-1}, and in BC 23 605 and 43 820 µS cm^{-1}. At the end of the rainy season, the waters of the ER-EM section were classified as C1; however, in the dry period, only RZ remained classified as C1, the other sites were classified as C2. MEX was classified in samples 1, 2 and 3 as C4, in sample 4 as all the samples from BC were classified as C5 (Table 1).

Waters classified as C1 can be used for most crops, in almost any type of soil with very little probability that salinity will develop. Waters called C2 can be used as long as there is a moderate degree of washing, in almost all cases no special salinity control practices are needed. The water of the San Pedro river depending on its EC can be used for irrigation from ER to EM. For EC> 3 000 µS cm^{-1} the degree of restriction is severe (Castellón-Gómez *et al*., 2015), this situation occurs for MEX and BC, therefore it is not recommended for irrigation.

Sodium content. The values of RAS_{or}, RAS° and RAS_{aj} were less than 1.6 in the samples of the ER-EM section, and were classified as S1, both in the rainy season and in the dry season. They can be used for irrigation in most soils with little probability of reaching dangerous levels of exchangeable sodium. With the RAS_{or} MEX it was classified as S3 in samples 1, 2 and 3, while in sample 4, as well as in all BC samples, it was classified as S4. With RAS_{aj}, MEX and BC were S4 in the four samplings (Table 2). S3 and S4 waters are unsuitable for agricultural use, according to Richards (1990); Mandal *et al*. (2019) can produce toxic levels of exchangeable sodium in soils and cause infiltration problems, particle dispersion and structure loss.

Table 2. RAS_{or}, RAS°, RAS_{aj}, PSI, CSR and IS of the water of the San Pedro river in Nayarit.

ID	RAS	Class	PSI	RAS°	Class	PSI	RASaj	Class	PSI	CSR	Classification	IS	Classification
						Sampling 1, rainy season							
ER	1.02	S1	1.21	0.82	S1	0.98	0.55	S1	0.67	0.36	B	-0.83	Dilute
SPI	0.97	S1	1.16	0.76	S1	0.91	0.46	S1	0.56	0.33	B	-1.21	Dilute
EV	0.94	S1	1.12	0.71	S1	0.85	0.38	S1	0.46	0.28	B	-1.15	Dilute
RZ	0.95	S1	1.14	0.74	S1	0.88	0.44	S1	0.53	0.28	B	-1.17	Dilute
ET	1	S1	1.19	0.79	S1	0.94	0.49	S1	0.59	0.33	B	-1.36	Dilute
TUX	1.02	S1	1.21	0.82	S1	0.98	0.57	S1	0.68	0.31	B	-1.4	Dilute
EM	1.11	S1	1.31	0.92	S1	1.11	0.74	S1	0.88	0.37	B	-1.33	Dilute
MEX	9.06	S3	9.72	10.14	S3	10.73	18.32	S4	17.68	0.88	B	-0.01	Dilute
BC	32.8	S4	27.43	-	-	-	101.54	S4	52.78	31.99	NR	0.96	Precipitates
						Sampling 2, drought season							
ER	1.41	S1	1.67	1.32	S1	1.57	1.49	S1	1.77	0.69	B	0.05	Precipitates
SPI	1.21	S1	1.44	1.12	S1	1.33	1.23	S1	1.46	0.54	B	0.08	Precipitates
EV	1.25	S1	1.49	1.14	S1	1.36	1.23	S1	1.46	0.55	B	0.08	Precipitates
RZ	1.12	S1	1.33	1	S1	1.19	1.02	S1	1.21	0.45	B	-0.02	Dilute
ET	1.22	S1	1.44	1.1	S1	1.31	1.17	S1	1.39	0.5	B	-0.08	Dilute
TUX	1.18	S1	1.41	1.14	S1	1.35	1.32	S1	1.57	0.5	B	-0.25	Dilute
EM	1.28	S1	1.52	1.26	S1	1.5	1.58	S1	1.87	0.56	B	-0.14	Dilute
MEX	11.44	S3	11.93	13.24	S3	13.52	27.02	S4	23.86	1.48	C	0.56	Precipitates
BC	42.17	S4	32.5	-	-	-	140.2	S4	60.35	52.98	NR	1.33	Precipitates

ID	RAS	Class	PSI	RAS°	Class	PSI	RASaj	Class	PSI	CSR	Classification	IS	Classification
Sampling 3, rainy season													
ER	1.12	S1	1.34	0.98	S1	1.16	0.88	S1	1.06	0.43	B	-1.11	Dilute
SPI	1.1	S1	1.31	0.94	S1	1.12	0.78	S1	0.93	0.41	B	-0.96	Dilute
EV	1.01	S1	1.21	0.85	S1	1.02	0.7	S1	0.84	0.36	B	-1.11	Dilute
RZ	1.24	S1	1.47	1.05	S1	1.25	0.83	S1	0.99	0.48	B	-0.93	Dilute
ET	1.15	S1	1.36	0.99	S1	1.18	0.86	S1	1.03	0.45	B	-1.11	Dilute
TUX	1.09	S1	1.3	0.95	S1	1.14	0.87	S1	1.03	0.45	B	-1.2	Dilute
EM	1.11	S1	1.32	0.97	S1	1.16	0.86	S1	1.03	0.46	B	-1.37	Dilute
MEX	9.29	S3	9.93	11.75	S3	12.2	22.36	S4	20.68	-0.47	B	0.35	Precipitates
BC	46.59	S4	34.64	-	-	-	161.16	S4	63.5	64.5	NR	1.56	Precipitates
Sampling 4, drought season													
ER	1.33	S1	1.58	1.24	S1	1.47	1.35	S1	1.6	0.61	B	0.11	Precipitates
SPI	1.33	S1	1.57	1.22	S1	1.44	1.14	S1	1.36	0.59	B	0.02	Precipitates
EV	1.25	S1	1.48	1.12	S1	1.34	1.21	S1	1.44	0.52	B	0.22	Precipitates
RZ	1.21	S1	1.44	1.05	S1	1.26	1.01	S1	1.21	0.48	B	0.05	Precipitates
ET	1.23	S1	1.46	1.1	S1	1.31	1.03	S1	1.23	0.55	B	0.33	Precipitates
TUX	1.33	S1	1.58	1.25	S1	1.48	1.41	S1	1.67	0.6	B	-0.65	Dilute
EM	1.34	S1	1.59	1.26	S1	1.49	1.4	S1	1.66	0.6	B	-0.56	Dilute
MEX	19.62	S4	18.67	-	-	-	63.65	S4	41.69	-4.14	B	1.68	Precipitates
BC	46.21	S4	34.46	-	-	-	159.87	S4	63.32	60.08	NR	1.8	Precipitates

ID= identification (sampling site); ER= El Rosarito; SPI= San Pedro Ixcatan; EV= El Venado; RZ= Ruiz; ET= El Tamarindo; TUX= Tuxpan; EM= El Mezcal; MEX= Mexcaltitan; BC= Boca de Camichin. B= good, C= conditioned; NR= not recommendable.

Ionic strength was calculated to determine the implicit pHc in RASaj. The formula to determine the activity coefficient of any ion in a solution is that of Debye-Hückel: $-\log\gamma_i = 0.51 Z_i^2 I^{1/2}$, with the ionic strength (I) being the only variable $I = \frac{1}{2}\sum CiZi^2$. According to the correlation between EC and I, the latter can be determined from the EC of any solution in its functional relationship I= αf(EC), where α is a constant that depends on the ionic composition of the solutions saline, and EC is the experimental electrical conductivity.

Figure 3 shows the experimental relationship I= αf(EC) of the waters of the San Pedro river (a) for the ER-EM section with low electrical conductivity and, (b) for the MEX-BC section, waters with high electric conductivity. The value of α for the waters with low EC was α= 0.0129 and for those with high EC it was α= 0.011. These constants can be used for waters with low and high EC, however, the I is unique for a given composition, the value of which depends on the concentration of each ionic component and its respective valence.

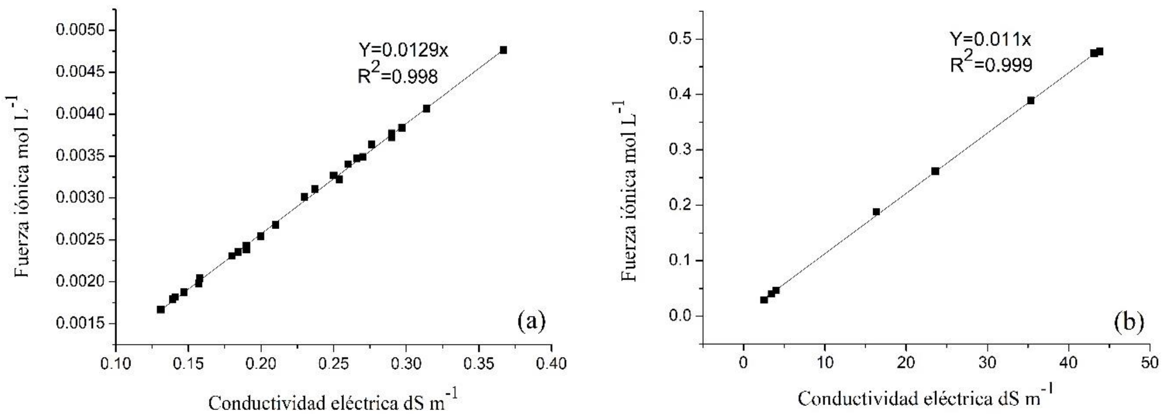

Figure 3. Functional relationship of ionic strength with the electrical conductivity of the water of the San Pedro river, Nayarit. a) ER-EM; and b) MEX-BC.

Leffelaar *et al*. (1983) in 50 extracts at saturation of various soil profiles, obtained a coefficient of α= 0.0144 and López-García *et al*. (2016) in wastewater obtained an α= 0.0116. These activity coefficients turned out to be like those determined in the water of the San Pedro river, therefore, with the EC it is sufficient to obtain an ionic force with a high degree of approximation.

Exchangeable sodium percentage. According to the Gapon selectivity constants used and the different RAS conceptualizations, the PSI_{min} and PSI_{max} of the waters of the San Pedro river were obtained. For the ER-EM section with low EC, the maximum values of PSI, which can be reached by the river waters when applied to the soil, were below 3%. Mexcaltitan with the different RAS their PSI was from 13.3 to 51.8% and BC from 35.7 to 73.1%. Table 2 shows the PSI averages for each sampling site. The predominant salts of the San Pedro river water are sodium, calcium and magnesium bicarbonates, followed by NaCl, and when evaporation processes exist, sodium carbonate appears.

According to López-García *et al*. (2016), due to the high solubility of sodium salts, these are dissolved even under evaporation conditions, and the CO_3^{2-}-HCO_3^- system could be converted to $CaMg(CO_3)_2$, which increases the concentration of sodium in the solutions and in turn the PSI. Elbashier *et al*. (2016) mentioned that the PSI of the ground and the RAS are approximately the same. Figure 4 shows the PSI-RAS relationship for the different RAS formulations of the waters of the San Pedro river. It is observed that the variations of the PSI in the soils depend on the K_G values, if the relationship $K_G=\frac{RSI}{RAS}$, is analyzed, the ratio of exchangeable sodium $RSI=\frac{SI}{(CIC-SI)}$, is a function of sodium exchangeable (SI) and cationic exchange capacity (CIC), and the latter, in turn, depends on the content of clays, or on the texture of the soil.

Therefore, when increasing the RAS, the magnitude of the PSI increase will be a function of the texture, as shown in Figure 4, where the PSI_{max} corresponds to a clay soil, while the PSI_{min} to a sand-clay soil-slimy.

The PSI values that can be reached by the waters of the San Pedro river in the ER-EM section do not present a risk for application to the soil; however, Castellanos *et al*. (2000), mention that some soils can present permeability problems from 5% exchangeable sodium, especially if they are clayey. The agricultural area of the San Pedro river basin is characterized by having cambisol and fluvisol soils of coarse to medium texture (Bojorquez *et al*., 2006) therefore, the PSI will be less than the calculated PSI_{max}. In practice, the actual PSI values in soil commonly turn out to be higher than those calculated by means of formulas, this is because the soil solution almost always has a higher sodium concentration than the irrigation water.

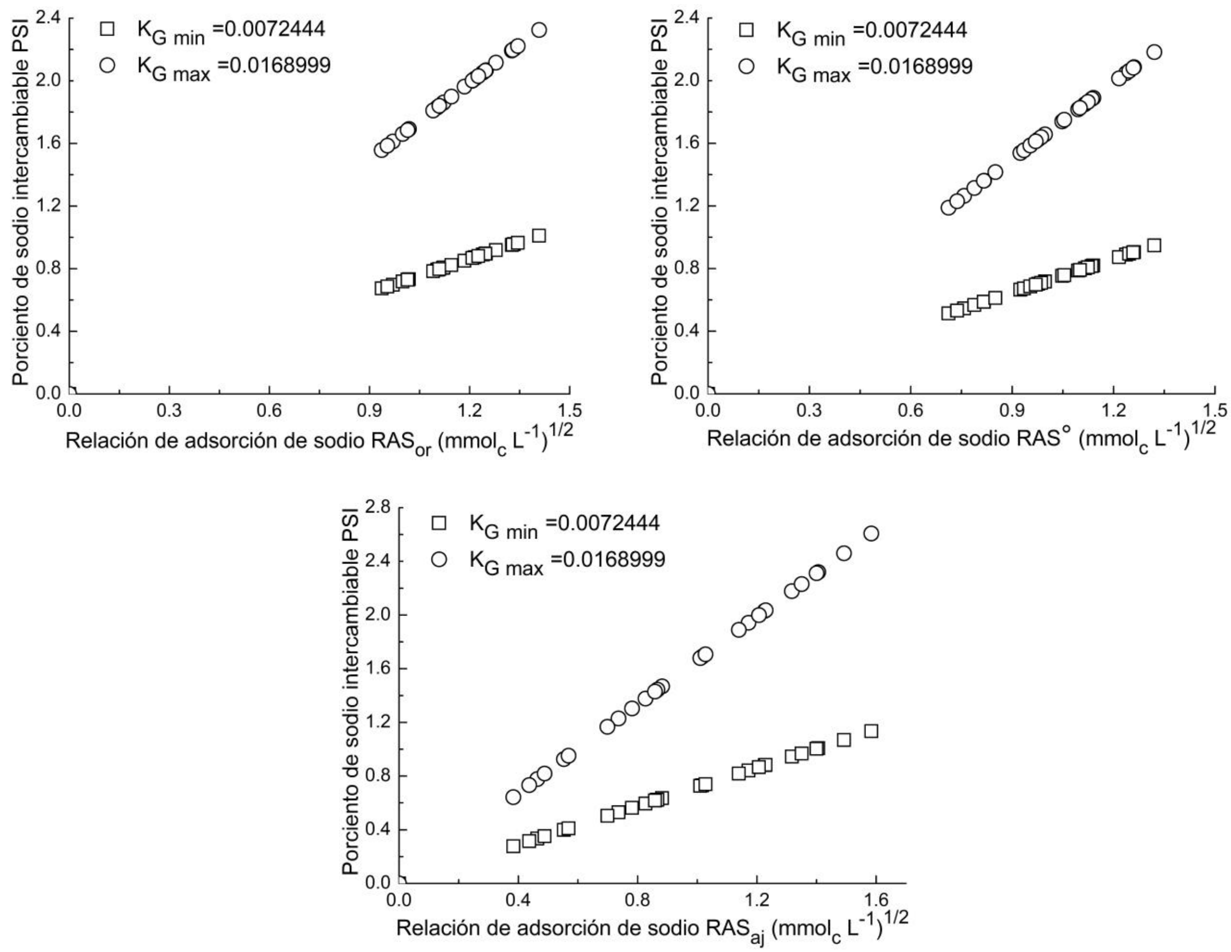

Figure 4. PSI-RAS relationship of the water of the San Pedro river in Nayarit.

Residual sodium carbonate. The CSR indicates that the ER to EM and MEX sites in samples 1, 3 and 4 were classified as good quality water (<1.25). In sample 2, MEX is classified as conditional; BC in the four samplings was classified as not recommended (Table 2). Positive values indicate that there is a higher content of CO_3^{2-} and HCO_3^- than Ca^{2+} and Mg^{2+}; however, this difference was not significant to restrict the use of these waters for irrigation. In the dry period, higher values were obtained than in the rainy season, this is because the flow rates are reduced and the concentrations of Ca^{2+} and Mg^{2+}, due to their lower solubility than the Na^+ salts, precipitate in the form of carbonates. Dhembare (2012) mentions that when negative values are obtained, they are due to the fact that Ca^{2+} and Mg^{2+} do not precipitate and remain in solution. Castellón-Gómez *et al*. (2015) mention that waters with high CSR values are not risky if used in fertigation, since CO_3^{2-} and HCO_3^- can be destroyed by adding acids.

Saturation index (IS). Negative values were obtained in the rainy season for ER to EM sites, indicating that the waters of the San Pedro river when applied in irrigation will dissolve $CaCO_3$ in the soil. In the dry period, in the second sampling, in the ER, SPI and EV sites, the water showed a tendency to precipitate $CaCO_3$ in the soil, this also happened in sampling 4 from ER to ET, the other sites obtained negative values. In the waters of MEX and BC, positive values were obtained, with the exception of MEX in sample 1 (Table 2).

The predominance of bicarbonates in the waters of the San Pedro river suggests a certain danger to be used for irrigation. According to Hannam *et al*. (2019), waters with high concentrations of HCO_3^-, tend to precipitate calcium in the form of carbonates, as the soil solution is concentrated. Based on the solubility of the CO_3^{2-} and HCO_3^- salts, which can be formed with the majority cations in water, $CaCO_3$ will be the first to precipitate, followed by $MgCO_3$, processes that generally occur at pH> 8.2, by what when applying the irrigation with waters with this pH there will be precipitates. The *IS* indicates that in the rainy season the waters of the San Pedro river will dissolve calcite from the soil, however, in the evaporation process, the CO_3^{2-} and HCO_3^- will tend to precipitate, such as in the dry period. López-García *et al*. (2016), mention that the precipitation of calcite causes Ca^{2+} to stop participating in the exchange complex, and Na^+ to participate more. The presence of Na^+ in the cation exchange complex has a decisive influence on the physicochemical properties of the soil, since a high content of this ion in water considerably increases the PSI and, in turn, the pH.

Conclusions

The water from the San Pedro river in Nayarit from the section El Rosarito (ER) to El Mezcal (EM) was of the sodium-calcium-magnesium-bicarbonate type and presented higher alkalinity (pH> 7); they are of low electrical conductivity due to the short residence time, the insolubility of the silicate minerals of the Sierra Madre Occidental and the absence of significant sources of contamination; they are of good quality for crop irrigation. In the MEX-BC section it was chlorinated-sodium due to the mixture with the marine intrusion water and they are not suitable for agricultural use.

The CSR and the saturation index indicate that these waters tend to precipitate $CaCO_3$ when the evaporation process occurs and in the dry season. The agricultural soils of the area are formed by alluvial sediments from the San Pedro River, therefore, over a geological-historical time span, the pedogeochemical profiles of the soils are constantly enriched with microscopic calcite.

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