# Chapter 5
# Hydrogeology and Hydrochemistry of the Serdán-Oriental Basin and the Lake Alchichica

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## 5.1 The Catchment Area: Surface and Groundwater

Lake Alchichica is in the Serdán-Oriental basin (SOB), the easternmost intermontane basin of the Mexican Plateau, and covers parts of the Puebla, Tlaxcala, and Veracruz states with an approximate area of 5250 km$^2$. High altitude mountain ranges delimit the central depression plateau (2300 m a.s.l); the most important are La Malinche (4461 m a.s.l.), the Citlaltépetl (5610 m a.s.l.), and the Cofre de Perote (4282 m a.s.l.) volcanoes (Riggs and Carrasco 2004; Gasca 1981).

The SOB is a Quaternary monogenetic volcanic field consisting of a variety of small volume volcanic edifices such as tuff rings, scoria cones, domes complexes such as Cerro Pinto, Cerro Pizarro, and Las Derrumbadas, and six maars (crater lakes) which are locally called *axalapascos* (derived from the náhuatl language, meaning "water in a pot of sand"). Most of them, namely Quechulac, La Preciosa,

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and Alchichica, formed by phreatic explosions, while Atexcac and Tecuitlapa originated from a phreatomagmatic explosion (Chako-Tchamabé et al. 2020; Carrasco et al. 2007; Gasca 1981).

The geological configuration of the SOB encompasses a regional basement of highly folded and faulted Cretaceous limestones and shales, covered by Miocene to Pleistocene andesitic rocks, which are successively overlaid by extensive pyroclastic deposits generated by both local phreatomagmatic volcanoes and large eruptions from neighboring volcanoes, and also by lacustrine deposits (Chako-Tchamabé et al. 2020). Carrasco-Nuñez and Chako-Tchamabé (Chap. 2, Geological evolution of the Alchichica crater) provide a detailed description of the regional geological evolution of the Alchichica crater.

SOB is an endorheic basin with no surface runoff outputs to other basins. The main streams within the basin are "Arroyo Xonecuila" and "Río Barranca La Malinche", running from the western part, within the state of Tlaxcala, and intermittently discharging into the playa-lake Totolcingo (Conagua 2015). The climatic and geological features in the basin explain the scarcity and intermittent character of surface runoff. Volcanic materials such as pyroclastic deposits and lava spills have relatively high hydraulic conductivities. On the other hand, the prevailing climate in the central part of the basin ranges from temperate arid to temperate semiarid with a mean precipitation value of 459 mm/year and mean evaporation of 1732 mm/year (see Chap. 4, Recent climate of the Serdán-Oriental basin), which entails a negative water balance. Consequently, a significant portion of the rainfall evaporates into the atmosphere, and the other portion infiltrates very rapidly underground (Gasca 1981).

There are two vast playa-lakes locate in the central and lowest parts of the basin: Tepeyahualco or El Salado (2312 m a.s.l.) to the north, and Totolcingo or El Carmen (2334 m a.s.l.) to the south (Alcocer et al. 2007), separated by the Cerro Pinto volcano. Nowadays, saline Tepeyahualco remains dry most of the year and partially fills up during the rainy season as a very shallow wetland, while freshwater Totolcingo, formerly a large single water body, nowadays fills up as two separate lakes during the rainy season, Laguna de Villavicencio to the west and Laguna Santiago de Ovando to the south, reducing their surface largely during the dry season (Alcocer et al., 2007; Silva-Aguilera and Escolero 2019).

Groundwater plays a vital role in the water balance and the lakes' water chemistry in the basin. The regional aquifer extends mainly in the lowest part of the basin and the mountainous border zones characterized by numerous fractures and dissolution cavities. Its composition is mostly pyroclastic and lava materials, which typically have high hydraulic conductivities. In the lower parts of the basin, medium to coarse grain non-consolidated alluvial deposits constitutes the upper layer. Laterally and inferiorly, the basement composed of Cretaceous limestones bound the aquifer (SOAPAP 1997; Riggs and Carrasco 2004).

In the playa-lakes area, the aquifer is semi-confined by clayey lacustrine deposits with very low hydraulic conductivity. The aquifer is unconfined in the rest of the basin, although it can be locally semi-confined by fine-grain alluvial materials. The aquifer thickness varies between approximately 300 m in the lower parts of the

basin to less than 20 m in the higher southern and southeastern areas (SOAPAP 1997). The water level fluctuates between 2 and 80 m (Can et al. 2011).

Aquifer recharge occurs by surface runoff that infiltrates into the subsurface in the lowest parts of the mountain slopes during the rainy season (Cruickshank 1992). Crucial recharge areas are where the pluvial precipitation rate is high, the coarse-grained alluvial materials predominate, and fractured rocks are present. All these characteristics coincide in the La Malinche volcano to the south and the Citlaltepetl – Cofre de Perote mountain range to the east. A minor recharge area is the perennial or seasonal thawing process at the highest peaks (SOAPAP 1997).

Local discharge expressions are the springs at the base of the highest mountains and the plateau. The most important are Vicencio, Ojo de Agua, Lara Grajales, and El Carmen (Reyes 1979). Most of them exhibit yield and drainage depletion or diversion for irrigation purposes (Alcocer et al. 1998). El Carmen, located in the northwest zone of the basin, is the only spring that provided a significant yield in 1997, discharging a mean value of 40 L/s with ample seasonal and annual variations (SOAPAP 1997). Springs suggest local discharges with short residence times in the flow system. Additionally, there were some springs in the southeast zone of Lake Alchichica (García 2010). However, none of them remain nowadays, suggesting an abatement of the phreatic level (Silva-Aguilera and Escolero 2019). The mountain areas' springs discharge minor water volumes, which may imply that most of the infiltrated water percolates deep into the fractured volcanic layers and flows under gravitational control joining the regional aquifer (SOAPAP 1997).

Given the basin's endorheic nature, the main water outputs occur through evaporation from the water bodies' surface (Alcocer et al. 2004). In areas with a shallow phreatic level, direct evaporation from the soil is common, as in the Totolcingo region, where the phreatic level is less than 1 m from the surface. Evapotranspiration occurs where vegetation roots reach shallow phreatic levels, such as in the Huamantla valley; however, it is not significant on a regional scale because the vegetation cover is scarce in the basin (SOAPAP 1997).

Escolero (2018) recently defined this regional groundwater flow system (RGFS) and named it the "Tepeyahualco" RGFS. Groundwater in this system flows from the recharge zones in the basin's borders and converges to the center in the lowest parts (Fig. 5.1). There are local discharges in the six lakes (Alchichica, Atexcac, Quechulac, La Preciosa, Aljojuca, and Tecuitlapa). The global discharge base levels are the playa-lakes Totolcingo and Tepeyahualco (Escolero 2018).

Stratigraphy and geology suggest that the RGFS extends beyond the surface basin. Karstic rocks that underlie or laterally bound the volcanic fill in some basin areas could drag the aquifer to lower levels located in adjacent basins. However, it is unknown whether these formations have the necessary structural continuity (SOAPAP 1997). A numerical model approach suggests a flow component discharging to lower elevation basins through a "port" located between Cofre de Perote and Los Humeros Caldera to the north of the basin (Cruickshank 1992). However, further research is needed in this regard.

Since the early eighties, numerous wells have been drilled for groundwater exploitation purposes in different basin areas, mainly near Lakes Alchichica, La
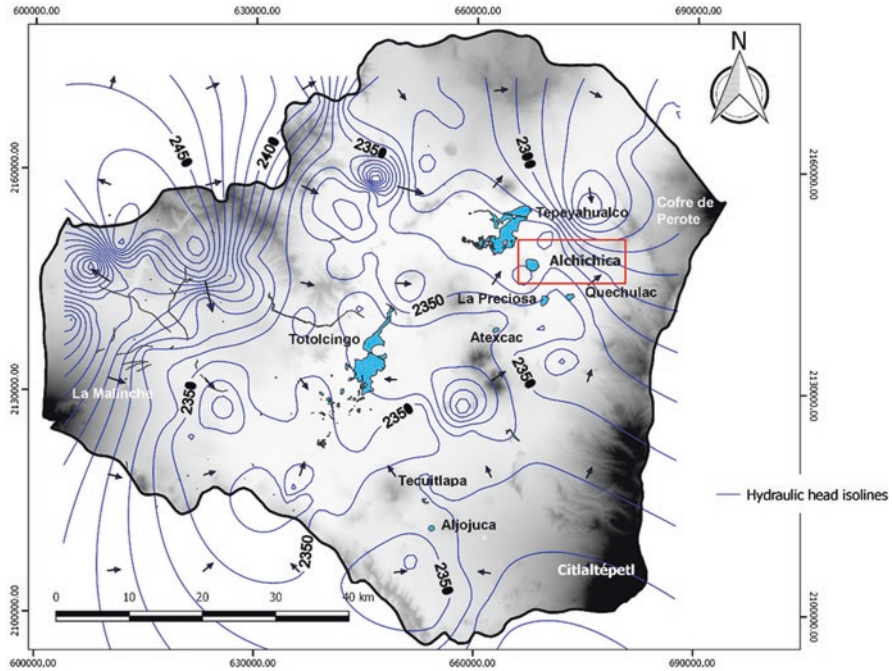
**Fig. 5.1** Location of the lakes in the SOB. Hydraulic heads' isolines (m a.s.l) built with SOAPAP (1997) data and the general groundwater flow directions are shown

Preciosa, and Quechulac to the east, and San Salvador El Seco to the north (Alcocer 2004). Eighty percent of the groundwater extracted is for irrigation, increasing as agriculture activities develop (Can et al. 2011).

Along the flow path, groundwater interacts chemically with geological materials. Therefore, groundwater ionic composition and concentrations in the SOB relate to the aquifer's predominant volcanic materials. Regional hydrogeochemical characterizations conducted in the SOB found a sodic-bicarbonate composition and an average, depth-dependent, low ionic concentration (Can et al. 2011; SOAPAP 1997).

The phreatic (shallow) water has a relatively high ionic concentration for freshwater, with a mean value of 865 mg/L. The predominant cations are sodium and magnesium, with a mean concentration of 7.2 meq/L and 6.4 meq/L, respectively, while the predominant anion is bicarbonate with a mean value of 6.9 meq/L. These concentrations result from recharge water interaction with the various filling materials composing the aquifer's upper layers. Shallow wells located in the saline lakes' surroundings (Alchichica, Tepeyahualco, and Totolcingo) exploit phreatic waters with higher ionic concentrations because they are in constant ionic exchange with the materials of the lacustrine stratum, where continuous evapo-concentration occurs (Can et al., 2011; SOAPAP, 1997).

Besides the chemical differences with depth, and according to the main groundwater flow pattern, there is a horizontal trend of increasing salinity and ionic

concentrations from the recharge zones to the discharge zones in the playa-lakes at the center of the SOB (SOAPAP 1997; Silva-Aguilera 2019).

## 5.2 Hydrogeology and Hydrogeochemistry of Groundwater in the Vicinity of Lake Alchichica

There is a topographic gradient of 1 m in Lake Alchichica's surface with a SE-NW orientation. This fact, supported by groundwater flow nets constructed with piezometric data (Alcalá 2004; García 2010; Meneses 2002; Silva-Aguilera 2019), suggests that groundwater inflows and outflows follow the same direction.

The flownets indicate at least two inflow zones: the first to the southeast and the second to the east. Also, there is at least one outflow zone to the north. Silva-Aguilera (2019) measured groundwater samples' physical and chemical characteristics obtained from piezometers representing the shallow aquifer's hydrogeochemical characteristics discharging into Lake Alchichica (Table 5.1). The mean values indicate fresh (Total Dissolved Solids, TDS < 3 g/L) and slightly alkaline water. The relative abundance of anions and cations is as follow $HCO_3^- > SO_4^{2-} > Cl^-$, and $Na^+ > Ca^{2+} = Mg^{2+} > K^+$, respectively.

The chemical characteristics associate with the geological materials of the basin. Lake Alchichica basin comprises a sequence of two stratigraphic units formed predominantly by pyroclastic deposits of basaltic andesitic composition (Chako-Tchamabé et al. 2020). The predominance of bicarbonate suggests the relatively recent water infiltration since this cation is associated with $CO_2$ coming either from the atmosphere or the soil. However, another source of this anion may be the

**Table 5.1** Mean values of major ions and physicochemical parameters of groundwater sampled from piezometers located in the inferred inflow to the lake zone (Silva-Aguilera 2019). (TDS = total dissolved solids)

| Parameter | Value |
| --- | --- |
| Electrical conductivity (mS/cm) | 1.8 |
| TDS (g/L) | 0.9 |
| Total alkalinity (mg/L CaCO$_3$) | 658 |
| pH | 7.2 - 7.7 |
| CO$_3^{2-}$ (mg/L) | 0 |
| HCO$_3^-$ (mg/L) | 592 |
| SO$_4^{2-}$ (mg/L) | 160 |
| Cl$^-$ (mg/L) | 153 |
| Na$^+$ (mg/L) | 141 |
| K$^+$ (mg/L) | 10 |
| Mg$^{2+}$ (mg/L) | 87 |
| Ca$^{2+}$ (mg/L) | 87 |

Cretaceous carbonate rocks outcropping in some portions of the basin, especially in the central and northeast areas (SOAPAP 1997). The relatively high content of $SO_4^{2-}$ may be explained by the dissolution of evaporites (e.g., gypsum and anhydrite) that could be present within the Cretaceous carbonate's formations. The volcanic rocks' albite minerals confer a sodic character to SOB's groundwaters (Ortega et al. 2002; Can et al. 2011). The lithological magnesium sources are the ferromagnesian minerals from the basic igneous rocks (SOAPAP 1997). Some portions of the aforementioned Cretaceous carbonates may be dolomitized, representing another potential magnesium source (Boggs 1995; Custodio and Llamas 1976). Calcium may come either from the dissolution of calcic feldspar, a constituent of igneous rocks, or the Cretaceous carbonate rocks. However, to know the particular sources and processes taking place in the SOB's groundwaters, a hydrogeochemical modeling approach is needed.

The close relationship between the groundwater flow system and Lake Alchichica has implications in its chemical composition (as discussed in the next section) and its water balance. The latter reminds the relevance of considering the connectivity existing between groundwater and surface water. Water inputs in Lake Alchichica are pluvial precipitation and groundwater inflow, while outputs are evaporation from the lake's surface and groundwater outflows. Consequently, both water level and stored water volume depend on the water balance (Alcalá 2004; García 2010; Silva-Aguilera 2019). Estimations of the lake's mean annual water balance (Fig. 5.2) point out that water that evaporates each year is around 1.2 times higher than the water entering by precipitation and groundwater inflow (Alcalá 2004), highlighting the importance of preserving groundwater inflows.

Since Lake Alchichica formation, sometime in the Late Pleistocene to the Holocene (Chako-Tchamabé et al. 2020), the water balance has changed as a function of climate variability in the region (Silva-Aguilera 2019). Kaźmierczak et al. (2011) found mineralogical and isotopic evidence in the microbialites suggesting
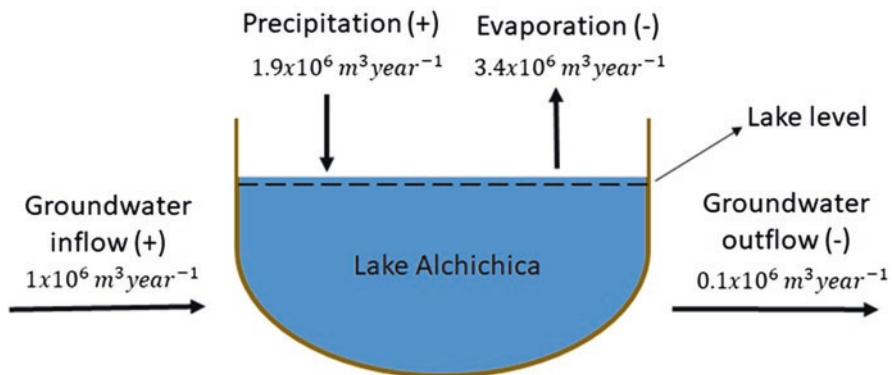


**Fig. 5.2** Water balance conceptual model showing Lake Alchichica's water inputs and outputs. (Modified from Silva-Aguilera 2019, based on Alcalá 2004 data)

fluctuations of the lake's water level modulated by dry and wet climatic conditions in the last 3000 years.

During the last decades, the lake's water level reduction has been remarkably evidenced for the region's inhabitants (Alcocer and Escobar 2007). The most apparent indication is that microbialites originally formed underwater (see Chap. 22, Microbialites: diversity hotspots in the Mexican Plateau) are currently exposed approximately 2 m above the water level. The water level records covering the period from 1959 to 1992 reveal a total decrease of 2.57 m, with an estimated rate of 7.6 cm year$^{-1}$ (Silva-Aguilera 2019). Alcalá (2004) estimated that water level decreased 2.35 m from 1992 to 2004, which translates into a higher rate of 20 cm/year. It means a reduction of almost 5 meters in 45 years. From 2004 to the present, there are no records, but there is visual evidence of continued microbialites exposure, suggesting the water level keeps dropping (Silva-Aguilera 2019; Silva-Aguilera and Escolero 2019).

The water level decline is related to climate variability and groundwater exploitation (Alcocer et al. 2004). As mentioned, water output by evaporation from the lake's surface has been significantly higher than water inputs by precipitation and groundwater flows during the last decades, explaining the water level decrease. However, the increase in the water level decline rate from 1992 on could be associated with the intensive groundwater exploitation for irrigation in the region.

## 5.3 Past and Present Hydrochemical Characteristics

The chemical identity of inland waters comes from the concentration and ratios of major ions (mainly $CO_3^{2-}$, $HCO_3^-$, $SO_4^{2-}$, $Cl^-$, $Ca^{2+}$, $Mg^{2+}$, $Na^+$, and $K^+$) and depends on local or regional conditions for each water body. The reference frame for such conditions is the watershed or sub-basin, and they can be divided into (a) the geological substrate type, which contributes with dissolved salts to surface water bodies and connected aquifers; (b) the prevailing climate, mainly related to the precipitation/evapotranspiration balance, which reflects on dilution-concentration phenomena and even on the eventual precipitation of dissolved salts from the water; and (c) the increasing anthropic activities that directly or indirectly alters the inland aquatic resources upon which it so closely depends.

Lake Alchichica is a model example of these local influences on the main chemical identity of its waters. The northern sub-basin, Llanos de San Juan, has the driest climate in the area, with mean annual evaporation rates much higher than the precipitation ones, especially in and around Lake Alchichica (see Chap. 4, Recent climate of the Serdán-Oriental basin). This situation would point to a greater salinity than the current one for the lake, around 8.5-9.0 g/L. The saline condition results from the freshwater aquifer inflow that partially compensates for the precipitation deficit (Silva-Aguilera and Escolero 2019). The lake is also indirectly affected by water abstraction for irrigation, especially in the adjacent area where the groundwater that feeds Alchichica circulates. This situation contributes negatively to the water

balance of the lake. It threatens to reduce the water volume in the lake (as clearly shown by the increasing amount of microbialite ring exposed on the shoreline) and the primary chemical identity to which the peculiar biota of Lake Alchichica has adapted.

This section presents data of the major ionic composition for Lake Alchichica water and some variables linked to salinity and alkaline reserve, such as electrical conductivity (at 25 °C), overall ionic concentration and total alkalinity (Tables 5.2 and 5.3). Among a few others, the referred publications have been selected as they present comparable data for the lake's open waters.

The comparative descriptors related to salinity and ionic composition and concentration are shown in Tables 5.3, 5.4, and 5.5, and Figs. 5.2 and 5.3.

Table 5.3 shows a slight trend of increasing electrical conductivity, ionic concentration and total alkalinity over time. For pH, there are no records in the oldest publication (Taylor, 1943), while for most of the subsequent data, the values show homogeneity in the water column. This is so because in saline waters with a high alkaline reserve, such as those of Lake Alchichica, pH shows a conservative behavior, which is also not affected by this oligotrophic lake's low biological activity (see Chap. 7, Physico-chemical characteristics). All pH values ranged around 9.0.

The aquifer's groundwater entering Lake Alchichica (Table 5.1) is highly mineralized but still freshwater with an ionic composition dominated by calcium. Upon contact with the lake's open water, it changes drastically (Tables 5.3 and 5.4). The mixing of both water sources changes the carbonate-bicarbonate equilibrium (pH < 8. 0 in the surrounding aquifer becomes around 9.0 within the lake). As a consequence, the newly formed carbonates profusely precipitate along with calcium.

At the lake basin's littoral zone, where springs from the aquifer supply water to the lake, the chemical interaction gave rise to a notorious feature of Lake Alchichica: the stromatolite (microbialites) ring. Some autotrophic microorganisms associated with the microbialites contribute actively to such precipitation (see Chap. 22, Microbialites: diversity hotspots in the Mexican Plateau).

A slight change in the composition proportions is observed, mainly towards increasing magnesium and chlorides, which is not evident for the other ions. To further explore this trend, both ions were plotted (Fig. 5.4).

Comparing the six cases -even considering some fluctuation that could relate to different methodologies for data collection, preservation, and/or analysis-, a trend

**Table 5.2** Sampling data from information sources. (One sampling date, except for [1]every 3 months, and [2]every month,? unknown month; sampling details in each reference)

| Sampling year | Month | Sampling site | References |
|---|---|---|---|
| **1941** | ? | Near shore | Taylor (1943) |
| **1988-89** | 5 to 5[1] | Water column | Vilaclara et al. (1993) |
| **2001** | 5 | Water column | Armienta et al. (2008) |
| **2007** | 6 | Water column | Kazmierczak et al. (2011) |
| **2011** | 6 | Water column | Sigala et al. (2017) |
| **2019** | 1 to 12[2] | Water column | Armienta and Vilaclara unpublished |

**Table 5.3** Electrical conductivity standardized at 25 °C ($K_{25}$), sum of ionic concentrations as total dissolved solids (TDS), and total alkalinity (T. Alk.) for Lake Alchichica [* inferred data from a 0.66 (TDS/$K_{25}$) factor; ** TDS data from direct gravimetric analysis.? unknown]. References for years and sampling sites in Table 5.2

| Sampling | $K_{25}$ | TDS (ionic sum) | T. Alk. |
|---|---|---|---|
| Year | mS/cm | g/L | mg/L as $CaCO_3$ |
| 1941 | 12.55* | 8.19 | 1915 |
| 1988-89 | 12.88* | 8.50** | 2087 |
| 2001 | 12.87 | 8.49* | 2114 |
| 2007 | 13.35 | 8.76** | ? |
| 2011 | 13.52* | 9.95 | 2199 |
| 2019 | 13.53 | 10.08 | 2236 |

**Table 5.4** Concentration (mg/L) of main anions and cations in Alchichica through recent times (1941-2019). (*Original data expressed as the sum of both types of anions in meq/L,? unknown). References for years and sampling sites in Table 5.2

| Sampling Year | $CO_3^{2-}$ | $HCO_3^-$ | $SO_4^{2-}$ | $Cl^-$ | $Mg^{2+}$ | $Ca^{2+}$ | $Na^+ + K^+$ |
|---|---|---|---|---|---|---|---|
| 1941 | 1068 | 1068 | 970 | 2595 | 349 | 10 | 2570 |
| 1988-89 | 462 | 802 | 1026 | 3022 | 331 | 12 | 2222 |
| 2001 | 900 | 900 | 996 | 3115 | 431 | 11 | 2620 |
| 2007 | ? | ? | 804 | 3095 | 433 | 15 | 2518 |
| 2011 | 965 | 720 | 1065 | 3860 | 458 | 20 | 2861 |
| 2019 | 876 | 943 | 969 | 3947 | 485 | 8 | 2852 |

towards a sustained rise in chlorides and magnesium ions stands out. The increase in chlorides is consistent with a light salinity upturn, although such a relationship is less clear for magnesium. The explanation could lie in the type of volcanic rocks at the Alchichica crater and its surroundings (Chako-Tchamabé et al. 2020). Basalt pyroxenes contribute magnesium (Hounslow 1995), calcium feldspars, and possibly dolomitized limestones supply both calcium and magnesium upon contact with the aquifer feeding Alchichica. A similar increase is observed in salinity and alkalinity (Table 5.3). Changes between 1941 and 2019 (in mg/L, computed by the following equation: [(final value–initial value)/initial value]*100) are ≥17% for the ionic sum and total alkalinity and as high as >35% for chlorides and magnesium. These variations suggest a change in the chemical identity set by the composition of the major ions, i.e., an incipient transformation in Lake Alchichica's water's chemical signature.

Given the past fluctuations and recent trends that seemingly point to an increase in some salinity descriptors, could this signify the beginning of a critical change for the biota? Suppose this trend accelerates at human scales (already seen for other maar lakes in Mexico, e.g., Escolero and Alcocer 2004). In that case, an increase in salinization linked to global warming and the local aquifer's exploitation may eventually threaten the unique Alchichica's biota (see Chap. 20, Diversification and Endemisms). Such a scenario would be significantly adverse for the

**Table 5.5** Concentration (meq/L) of main anions and cations in Alchichica through recent times. References for years and sampling sites in Table 5.2

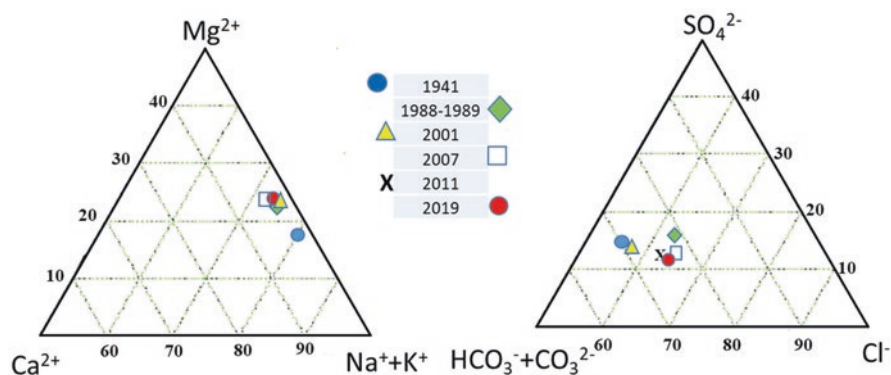| Sampling Year | $CO_3^{2-} + HCO_3^-$ | $SO_4^{2-}$ | $Cl^-$ | $Cl^- + SO_4^{2-}$ | $Na^+ + K^+$ | $Mg^{2+}$ | $Ca^{2+}$ | $Ca^{2+} + Mg^{2+}$ |
|---|---|---|---|---|---|---|---|---|
| **1941** | 38.3 | 20.2 | 73.2 | 93.4 | 119.0 | 28.7 | 0.5 | 29.2 |
| **1988-89** | 28.5 | 21.4 | 85.2 | 106.6 | 92.8 | 27.2 | 0.6 | 27.8 |
| **2001** | 44.7 | 20.7 | 87.9 | 108.6 | 109.8 | 35.5 | 0.5 | 36.0 |
| **2007** | 30.9 | 16.7 | 87.3 | 104.0 | 105.8 | 35.6 | 0.7 | 36.3 |
| **2011** | 44.0 | 22.2 | 108.9 | 131.0 | 120.1 | 37.6 | 1.0 | 38.6 |
| **2019** | 44.7 | 20.2 | 111.3 | 131.5 | 119.9 | 39.9 | 0.4 | 40.3 |



**Fig. 5.3** Modified Piper diagrams for cation and anion proportions in % of meq/L. References for years and sampling sites in Table 5.2
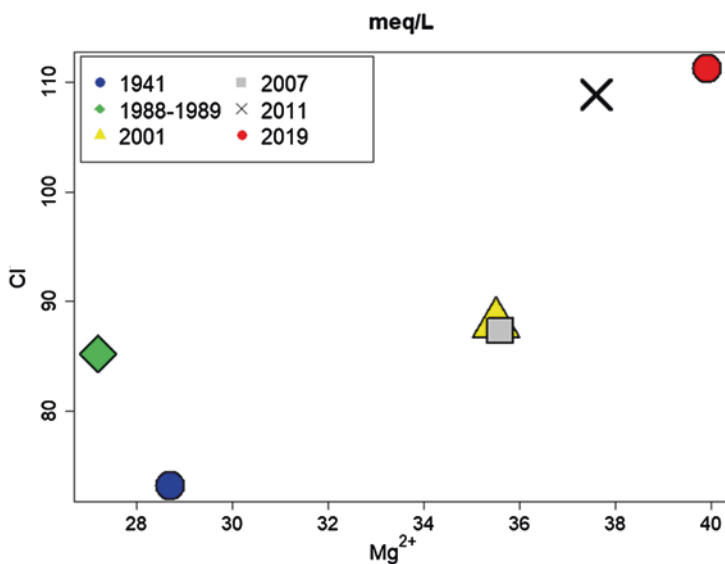


**Fig. 5.4** Chloride *versus* magnesium plot (meq/L). References for years and sampling sites in Table 5.2

microendemisms, which exclusively live in the lake. They are very well adapted to the current conditions of Lake Alchichica. However, they could get extinguished if the hydrochemistry were to change substantially in the short term (see Chap. 21, Conservation actions).

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