A CONCEPTUAL MODEL FOR INCREASES OF SODIUM, SAR, ALKALINITY AND pH AT THE INDEPENDENCE AQUIFER IN GUANAJUATO

Modelo Conceptual del Incremento de Sodio, RAS, Alcalinidad y pH en el Acuífero de la Independencia, Guanajuato

M. Adrián Ortega-Guerrero1‡, Javier Z. Castellanos2, Ramón Aguilar G.2, Antonio Vázquez-Alarcón3, Eduardo Alanis R.1, Carlos Vargas C.1, and Francisco Urrutia E.1

SUMMARY

The Independence Basin, with an area of almost 700 000 hectares (1 729 676 acres), is completely dependent on sources of groundwater for agricultural, urban and industrial uses. Agriculture utilizes 85% of the water that is extracted from the granular aquifer of lacustrine origin that covers another aquifer of a fractured nature in the volcanic rock that dominates Mexico’s high plateau. The concentration of sodium, SAR, alkalinity and pH in the groundwater from the Independence aquifer has increased in the past two decades and is progressively damaging soil fertility. A total of 206 samples of groundwater were taken from the 2500 wells that extract water from both aquifers, in order to explain the origin and evolution of the quality parameters of irrigation water for agricultural use. The presence of dominant ions in the groundwater and their control in the quality parameters of irrigation water are consistent with the dissolving reactions of minerals present in the volcanic rocks that exist in the aquifers’ recharging zones. In particular, the presence and evolution of sodium, SAR, alkalinity and pH are associated with products from the reaction of the dissolving of the feldspathic mineral known as “albite” (sodium feldspar), which is also related to thermal waters in the fractured aquifer among ignimbrite rocks. This water, rich in sodium, may be migrating towards the granular aquifer through both the effects of density and the excessive extraction of water from the granular aquifer. It was established that the concentration of sodium presents moderate restrictions in approximately 18 000 hectares (44 477 acres) of irrigation by aspersion and 12 000 hectares (29 651 acres) of irrigation by gravity. These quantities may potentially increase in the future if adequate criteria are not established for managing the aquifer and for agricultural planning in the region.

Index words: Agricultural planning, granular and fractured aquifers, hydrogeochemistry, sodium increase.

RESUMEN

La Cuenca de la Independencia, con un área de casi 700 000 hectáreas, depende totalmente del agua subterránea para uso agrícola, urbano e industrial. La agricultura utiliza 85% del agua que se extrae del acuífero granular de origen lacustre, que cubre a otro acuífero de carácter fracturado en rocas volcánicas que dominan en el Altiplano Mexicano. En las dos últimas décadas, la concentración de sodio, RAS, alcalinidad y pH en el agua subterránea del acuífero de la Independencia se ha incrementado y está ocasionando daños progresivos en la fertilidad del suelo. Se tomaron 206 muestras de agua subterránea de un total de 2500 pozos que extraen agua de ambos acuíferos, para explicar el origen y la evolución de los parámetros de calidad del agua de riego para uso agrícola. La presencia de los iones dominantes en el agua subterránea y su control en los parámetros de calidad para riego son consistentes con las reacciones de disolución de minerales presentes en las rocas volcánicas que existen en las zonas de recarga del acuífero. En particular, la presencia y evolución de sodio, RAS, alcalinidad y pH se asocian a los productos de reacción de la disolución del mineral feldespático, llamado Albita, también relacionado con agua termal, en el acuífero fracturado en rocas ignimbálticas. Esta agua rica en sodio podría estar migrando hacia el acuífero granular, tanto por efecto de densidad, como por exceso en la extracción de agua en el acuífero granular. Se identificó que la

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1 Instituto de Geología, Universidad Nacional Autónoma de México. Apdo. Postal 70-296, 04510 México, D.F.  
‡ (maog@servidor.unam.mx)  
3 Departamento de Suelos, Universidad Autónoma Chapingo. Chapingo, Estado de México.

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sodicidad presenta restricciones moderadas para riego por aspersión en 18 000 ha y de 12 000 ha en riego por gravedad, aproximadamente. Estas cantidades potencialmente se incrementarán en el futuro de no establecerse criterios adecuados de manejo del acuífero y de planeación agrícola en la región.

Palabras clave: Planeación agrícola, acuífero granular y fracturado, hidrogeoquímica, sodificación.

INTRODUCTION

In the state of Guanajuato, the principal source of water for agricultural use is of subterranean origin. The development of a more high-tech, sustainable agriculture depends on the availability of this resource in sufficient quantities and with acceptable quality. Evidence exists, however, that indicates that the volume of water available from subterranean sources is diminishing significantly with the passage of time (Chávez, 1998; Guerrero, 1998) and that the quality of groundwater in the state is progressively deteriorating (Castellanos, et al., 2001). Both of these factors threaten the agricultural, economic and social development of the state. Castellanos, et al. (2001) came to the conclusion that between 1982 and 1998 the concentration of sodium, the Sodium Adsorption Ratio (SAR) and the pH of groundwater of the state of Guanajuato all increased significantly. For this reason, evaluations of the flow systems of groundwater and of the hydrogeochemistry associated with them will be essential if we are to gain an understanding of the origin and mechanisms of the degradation of groundwater used in irrigation, and of its spatial and temporal evolution. The principal objective of this study is to propose a hydrogeochemical model that -in an initial phase of research- satisfactorily explains the processes that condition the natural chemical composition of groundwater, as well as those that are modifying it in an adverse way, based on the analysis of one specific hydrogeological unit. This hydrogeochemical model was developed on the basis of the identification of the principal variables that affect water quality from the agricultural perspective, which are a) the concentration of dissolved solids or salts, b) the relative presence of sodium (SAR), and c) total alkalinity and the concentration of other specific ions, complemented by hydrogeological information. The final application of this study, and of other research projects now underway, is the implementation of policies and programs that are adequate for managing this aquifer as well as appropriate agricultural practices in the state of Guanajuato.

Description of the Area of Study

The basin selected for this study is part of what has been hydrologically defined as the “Independence Basin” (Ortega-Guerrero, 2000), formerly known as the “Laja River High Basin” (SARH, 1981). The Independence Basin is located in the upper centernorth area of the state of Guanajuato (Figure 1), in the proximities of the continental watershed of the Lerma River Basin (to which it belongs) and the Pánuco River Basin. It covers an area of 6840 km² (684 000 ha), calculated on the basis of a digital model of elevation. This basin includes parts of the municipalities of San José Iturbide, Dr. Mora, San Luis de la Paz, Dolores Hidalgo, San Diego de la Unión, San Felipe, and San Miguel de Allende; all of which have a very large part of their territory within the basin, though small areas of the municipalities of Guanajuato, León and Ocampo are also located there.

All of the municipalities located within the basin depend exclusively on its subterranean flows for their supplies of potable water and water for domestic, agricultural and industrial use. Among these sectors, agriculture is the principal consumer, as it uses almost 85% of the volume of water extracted (CNA, 1996). At present, there are some 2500 wells in the basin, despite the existence of three “Strict Degrees of Interdiction” (“Decretos de Veda Rígida”), dated 1958, 1964, and 1976, respectively. The total depth of the wells varies from 100 to 300 m, while the static depth level is between 50 and 200 m. The level of water in these wells is dropping at a rate that varies from 2 to 5 m yr⁻¹, which makes it necessary to drill to ever-greater depths with the consequent increases in maintenance costs and energy consumption (CNA, 1996). This situation is similar to that which prevails in the rest of the state of Guanajuato (Chávez, 1998).

In the interior of the Independence Basin there are two aquifers. One of them is located in a granular medium of lacustrine origin, while the other is found among fractured rocks of acidic composition called ignimbrites and rhyolites (Ortega-Guerrero, 2000). The aquifer in the fractured rocks extends towards the mountainous zones on the margins of the basin and is located below the granular aquifer in the zones of irrigated agriculture, that are generally found in the flat areas of the basin. Given that many of the
irrigation wells take water from both aquifers, it was not possible to evaluate the properties and characteristics of each one independently.

**METHODS AND MATERIALS**

A total of 206 sample sites were selected in such a way that they are representative of the basin under study. To assure representativeness, the water samples were taken from the wells at least two hours after the pumps had begun to operate. The parameters measured in the field for each sample were pH, temperature, electrical conductivity, and alkalinity. The first three of these were measured using a Conductronic apparatus, Model PC18, calibrated in the field with the 5, 7, and 10 buffers, while for electrical conductivity a solution of potassium chloride at a known concentration was used. For the determination of total alkalinity, a 200 mL aliquot was filtered through a 0.45 micron Millipore screen of cellulose nitrate. The method for quantifying total alkalinity in the field consisted in using an acid-base titration with yellow methyl as the indicator.

Once these field measurements had been carried out, we proceeded to fill 125 mL sample bottles that had been previously treated with acid and distilled water. Two samples were taken from each well: one for determining anions, the other for determining cations. High-purity nitric acid was added to the samples to be tested for cations in order to stabilize them and avoid the precipitation of metals. The pH value was reduced to two units. Once the bottles were completely filled, and in order to avoid the presence of air bubbles, they were covered, sealed with Parafilm, and stored in ice for the rest of the sampling day. Later, they were kept in refrigeration until the time came to analyze them.

The chemical analyses were carried out using the plasma and inductively coupled mass spectrometry (ICP-MS) techniques, as well as ion chromatography (IC). The elements analyzed were calcium, magnesium, sodium, potassium, chlorides, bicarbonates and sulfates (APHA, AWWA, WPCF, 1989).

**RESULTS AND DISCUSSION**

**Characteristics of Groundwater Measured in the Field**

The temperatures of the groundwater in the 206 wells selected (Figure 2) were between the extreme values of 14 °C and 47 °C (57 to 117 °F), while the dominant temperature was between 25 °C and 30 °C (77 to 86 °F). Ten wells were identified with water temperatures above 36 °C (97 °F), six of which were located in the San José Iturbide-Dr. Mora region, one between San Luis de la Paz and San Diego de la Unión, one in the area of Atotonilco (southwest of San Miguel de Allende), and two others in San Felipe. The average temperature of the groundwater was 27.1 °C (80.8 °F).

Studies carried out in the 1970s demonstrated the existence of a granular aquifer with normal
temperatures (or relatively cold temperatures) and of a fractured aquifer (in rhyolitic rocks) with hot or thermal waters (SARH, 1979) that stretches into the states of Aguascalientes and San Luis Potosí. In all cases, the granular aquifer is above the fractured one, which is consistent with the producers’ observations. The origin of this thermal effect is associated with the radioactive disintegration of certain minerals present in the volcanic rocks of acidic composition (rhyolites) (SARH, 1979), although other processes may be associated with this thermal phenomenon, such as -among the principal ones- the influence of the geothermic gradient and the depth of the circulation of groundwater (Toth, 1999), the presence of geological faults (Press and Silver, 1978), and the heating of water through contact with hot rocks in young volcanic zones (Ellis and Mahon, 1977). The occurrence of all of these processes is feasible in the zone of study due to its geological evolution (Ortega-Guerrero, 2000), which leads to the thermal water from the fractured aquifer manifesting itself with greater influence as the column of water from the granular aquifer is reduced; that is, according to the degree to which the granular aquifer continues to be exploited excessively. The origin of this thermal effect in the groundwater in Mexico’s high plateau, the form and the dynamics of its incorporation into the granular aquifer and the control it exerts over the solubility of the minerals present in the volcanic rocks are still being studied by various institutions.

The pH of the water used for irrigation has important implications for the availability and management of nutrients. The distribution of pH in the groundwater is shown in Figure 3, where it varied from 5 to 8.5, with a dominant range of 7 to 7.5 in the central part of the basin. On the edges of the basin, meanwhile, figures both above and below this range can be observed indistinctly. The average pH value is 7.33.

The relationship between temperature (T) and pH reflects a slight increment in the latter as the temperature of the groundwater increases, as shown by the regression model in Table 1. It is important to emphasize that the coefficient of correlation ($R^2$) is naturally low for this type of relationship, due to the mixing of cold water and thermal water that occurs because the wells cut through both aquifers and because we are dealing with an incipient process associated with a complex thermodynamic and geochemical system in which many variables operate. The dominant chemical reactions that may control pH will be discussed below.

The electrical conductivity (Figure 4) presents variations in a range from $100 \times 10^{-3}$ to $1400 \times 10^{-3}$ dS m$^{-1}$, which indicates a moderate concentration of total salts in solution. In general, water with an electrical conductivity of between $400 \times 10^{-3}$ and $600 \times 10^{-3}$ dS m$^{-1}$ predominate, as only two zones were observed in which the values were above $1000 \times 10^{-3}$ dS m$^{-1}$: San Luis de la Paz-San Diego de la Unión and the vicinity of the Sierra of Guanajuato. According to Ayers and Wescot (1985), in general there are no restrictions on the use of groundwater for irrigation due to electrical conductivity.

**Table 1. Regression model of pH and temperature (T), sodium and temperature, and total alkalinity versus electrical conductivity (EC).**

<table>
<thead>
<tr>
<th>Model</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH = 0.04T + 6.36</td>
<td>0.13</td>
</tr>
<tr>
<td>Sodium = 0.1T – 1.06</td>
<td>0.16</td>
</tr>
<tr>
<td>Alkalinity=0.007EC+0.92</td>
<td>0.66</td>
</tr>
</tbody>
</table>

$R^2$ is the coefficient of correlation.
Quality Parameters of the Groundwater Used in Agricultural Irrigation

The sodium in irrigation water propitiates the dispersion of colloids or clays, once they come into contact with the soil and displace the divalent cations Ca$^{2+}$ and Mg$^{2+}$, and exerts a negative effect on the soil structure by reducing the ease with which it conducts water and oxygen along its profile (Aceves, 1979). This in turn has a negative effect on soil fertility, because in addition to affecting aeration it increases pH and reduces the availability of Fe and Zn (Castellanos, et al., 2001). The concentrations of sodium in the groundwater from the Independence Basin range from 1 me L$^{-1}$ to 11 me L$^{-1}$. In general, concentrations are below 4 me L$^{-1}$; however, there is a large region in which the concentrations reach values as high as 6 me L$^{-1}$-between San Luis de la Paz and San Diego de la Unión- and as high as 5 me L$^{-1}$—to the east of San Miguel de Allende. Table 1 shows the relationship between sodium and the temperature of groundwater, obtained from a linear regression model.

The origin of the sodium in groundwater is explained by the presence of igneous rocks called ignimbrites in the recharging zones. The mineralogical makeup of these rocks includes sodium feldspars such as albite, whose chemical composition is NaAlSi$_3$O$_8$. According to Jones, et al. (1977), the dissolving reaction of feldspar is as follows:

$$\text{NaAlSi$_3$O$_8$(s) + H}_2\text{CO}_3 + 9/2\text{H}_2\text{O = Na}^+ + \text{HCO}_3^- + 2\text{H}_4\text{SiO}_4 + \frac{1}{2}\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4(s)}$$

In this reaction, the mineral albite is dissolved through the action of the lixiviation of carbonic acid (H$_2$CO$_3$), giving rise to products in solution such as sodium (Na$^+$), bicarbonate (HCO$_3^-$), silica in solution as silicic acid (H$_4$SiO$_4$), and the clay-like mineral kaolinite or kaolin [Al$_2$Si$_2$O$_5$(OH)$_4$]. As can be observed, this reaction has a direct effect on the concentration of sodium, alkalinity and pH. Sodicity is expressed as the Sodium Adsorption Ratio (SAR):

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

which represents the relative presence of Na$^+$ with respect to the cations Ca$^{2+}$ and Mg$^{2+}$ and is adimensional (Aceves, 1979). The SAR at the Independence Aquifer varies from 1 to 40 (Figure 5). Concentrations above 9 are found west of San Luis de la Paz, where values as high as 40 were registered. This zone presents severe restrictions on the use of groundwater for agricultural use (Ayers and Wescot, 1985). There are various zones with moderate restrictions (sodicity values above 3) on the use of groundwater, the largest of which corresponds to the region of approximately 800 km$^2$ between San Luis de la Paz and San Diego de la Unión. The second most important area is located in the region of San José Iturbide and Dr. Mora, while the others appear as isolated zones in the interior of the basin, such as Laguna Seca, the eastern area of San Miguel de Allende, the northern part of Dolores Hidalgo and the southeast portion of San Felipe. According to Ayers and Wescot (1985), the ideal water is that which has an SAR below 3, so that in the rest of the agricultural region there are no restrictions on the use of groundwater for irrigation.

There is evidence that the sodicity in the groundwater from the Independence Aquifer has increased in the past 18 years (Castellanos, et al., 2001); a situation that is recognized by the growers in the region who confront an ever-greater deterioration
in the fertility of their soils. It is estimated that at present in the interior of the basin approximately 15% of the agricultural surface area (18 000 ha or 444 77 acres) presents moderate restrictions on the use of water for aspersion irrigation and 10% (12 000 ha or 29 652 acres) for gravity irrigation (considering Ayers and Wescot’s, 1985, criteria). The possibility exists that this situation may worsen due to tendencies in the exploitation of groundwater in the Independence Basin, which may well be similar in the rest of the state of Guanajuato.

In general, the concentration of calcium in the groundwater of the Independence Aquifer varies between figures close to 0.5 me L^-1 and 5 me L^-1, with the sole exception being one site near the Sierra of Guanajuato in the municipality of Dolores Hidalgo. Generally speaking, higher values for the presence of calcium - from 2.5 me L^-1 to 5 me L^-1 - are found in the mountainous zones, while lower values (below 2.5 me L^-1), predominate in the agricultural zones within the area of influence of the granular aquifer. The origin of calcium is associated with the dissolution of minerals that contain this element, such as those known as anorthite, hornblende and the presence of varieties of limestone (calcium carbonate), while the reduction of concentrations of this element in the interior of the granular aquifer may be due to processes of cationic exchange along the flow of groundwater.

The concentration of magnesium in the Independence Aquifer varied between 0.5 me L^-1 and 3 me L^-1. Concentrations above 1.5 me L^-1 were found towards the Sierra of Guanajuato, San Diego de la Unión, San Luis de la Paz, and San Miguel de Allende. In general, the concentration of magnesium is higher towards the edges of the basin and tends to decrease towards the plains, where values equal to or less than 0.4 me L^-1 predominate. Although the concentration of magnesium is always lower than that of calcium, its tendency is similar.

In the interior of the Independence Basin, chloride is found in concentrations that range from 0.1 me L^-1 to 1.6 me L^-1. The highest concentrations were found in the limits of the basin and values decreased progressively towards the interior, where concentrations from 0.1 me L^-1 to 0.4 me L^-1 predominate. It is in the vicinity of San Luis de la Paz that the highest values for chloride in groundwater were detected. Once again, according to the criteria of Ayers and Wescot (1985), chloride places no restriction on agricultural use in the region.

Alkalinity is caused by bicarbonates, carbonates and hydroxides in the water and for this reason is associated with pH. The concentration of total alkalinity (referred to as CaCO_3) in the groundwater varied from 1 to 11 me L^-1, while the highest values - between 8 and 11 me L^-1 - were found between the communities of San Diego de la Unión and San Luis de la Paz (Figure 6). In the rest of the aquifer, concentrations below 6 me L^-1 predominate. The areas with the highest concentrations of bicarbonates correspond to i) zones with higher electrical conductivity, indicating the contribution of this parameter to the concentration of salts in groundwater (Table 1), and ii) zones with high concentrations of sodium. This would confirm that the dissolution of feldspar sodium is the dominant mechanism in the increase of salinity, sodicity, alkalinity and pH in groundwater. The thresholds for the concentration of sodium and bicarbonate that negatively affect crops depend on the form of irrigation. In the case of irrigation by aspersion, this threshold is reduced due to the effect of the foliar absorption of these toxic ions (Ayers and Wescot, 1985).

The concentration of sulfates in the groundwater from the Independence Basin varied from 0.5 me L^-1 to 3.5 me L^-1. The highest concentration was found in a mining region near San Luis de la Paz. Outside of this area, the concentration of sulfates in groundwater represents no restriction on agricultural use in the region, according to the criteria of Ayers and Wescot (1985).

Figure 7 shows the percent classification of the total concentration of anions and cations present in groundwater, also known as “Piper’s Diagram”. The dominant ion among the anions analyzed was

![Figure 6. Distribution of total alkalinity (me L^-1).](image-url)
bicarbonate, which dominates the concentration of the sulfates and chlorides by more than 70%. With respect to the cations, it can be seen that most of the samples are of the calcic type, although a progressive tendency towards the dominion of sodium can be defined. The percentage of magnesium is reduced considerably in the samples that contain sodium, in contrast to those that contain calcium. For this reason, the predominant family in the groundwater is calcic-bicarbonate, with an incipient influence of water rich in sodium, associated with the fractured aquifer below the granular aquifer in the zones of agricultural irrigation.

The presence of dominant ions in the groundwater and their control in the quality parameters for irrigation are consistent with the reaction of the dissolution of minerals present in the volcanic rocks present in the aquifer's recharging zones. The dissolution of the mineral known as albite (in which the products of the reaction are Na⁺ and HCO₃⁻) is of particular interest because the amount of these products in the groundwater increases in proportion to this reaction. Limits on the production of both ions are controlled by the saturation of the solution with respect to the mineral kaolin, which is the solid product of the reaction. It is also evident that temperature must play an important role in the kinetics of this reaction (Anderson, 1996) and in the conditions in which it occurs; that is, the kinetics of the dissolution of albite will be different in the fractured aquifer than in the granular one. In the first
case, the contact with groundwater takes place on the surface of the fractured rocks, where it can reach an equilibrium with the secondary minerals (Drever, 1988). In the second case, in contrast, under the lacustrine conditions in which the granular aquifer was formed (Ortega-Guerrero, 2000), the phenomenon of the exchange of solutes between sediments (particles of clay, sand, and gravel) and the interstitial water or water from the pores, as well as biological productivity and the distribution of oxygen (Drever, 1988) are feasible.

The natural concentration of different ions responds to the thermodynamic equilibrium established through many tens, hundreds, or thousands of years in the aquifer. The natural chemical composition was modified progressively by the form and intensity with which the exploitation of the aquifer has been carried out over the past 50 years. The use of pesticides and fertilizers and their influence on water quality is an additional aspect that should be evaluated for this aquifer. All of these modifications of the chemical properties of the groundwater will progressively condition agricultural planning in the region, which is why a dynamic strategy that takes into account such changes is required.

For this reason, it is necessary to understand the geological and hydrological controls that affect the chemical quality of water and its evolution over time. At the same time, the chemical evolution of groundwater depends on the order of contact with different materials that make up the aquifer and their movement along the direction of flow, as well as on the local pH conditions and the pressure of carbon dioxide in the recharging zone of the hydrological basin (Maxey and Mifflin, 1966; Domenico, 1972; Palmer and Cherry, 1984; Toth, 1999). In the specific case of the Independence Basin, we are dealing with a zone located at the junction of three physiographic provinces: (a) the Eastern Sierra Madre; (b) the Mexican High Plateau (Altiplanicie); and, (c) the Transmexican Neo-volcanic Strip (Faja Neovolcánica Transmexicana). For this reason, there exist different lithologic and mineralogical influences on the behavior of groundwater, in addition to tectonic and volcanic processes. The presence of different igneous rocks of acidic composition (ignimbrites) gives rise to the predominance of minerals rich in silica and silica-aluminates of sodium, potassium and calcium (feldspars) that explains the presence of these cations and the predominance of bicarbonates. The presence of sodium is also explained by the hydrolysis of feldspar sodium.

The migration of thermal water present in the fractured aquifer, rich in sodium, is apparently advancing progressively towards the granular aquifer, due to the irrational exploitation that is characteristic of the Independence Basin. If current policies in terms of the management of this aquifer and its intensive use in agriculture continue, it can be anticipated that there will be an increase in the problems of soil fertility in the near future in this Basin. For this reason, it is necessary to understand in greater detail the origin and mechanisms of the migration of sodium in the aquifer and how it affects crops. These processes are now the subjects of ongoing research.

**CONCLUSIONS**

- The quality of groundwater for agricultural irrigation in the Independence Basin is the result of the geological evolution of the region and the interaction of the water itself with the rocks and minerals along its direction of flow. The increase in sodicity, SAR, alkalinity and pH in the water of the aquifer at the Independence Basin is associated with the dissolution of sodium feldspar, known as albite; a mineral that forms part of the fractured aquifer. This aquifer borders laterally on the granular aquifer as well as in the subsoil, where the region’s agricultural activities are mainly carried out. The concentrations of sodium in the granular aquifer were maintained at low levels in natural conditions through the effects of the exchange of calcium and magnesium. The irrational exploitation of the aquifer, however, upsets this hydraulic and hydrogeochemical equilibrium. The fractured aquifer contains thermal water that mixes with the water from the granular aquifer as a consequence of the conditions of well construction. For this reason, there exists a temperature increase that may potentially be accompanied by a greater concentration of sodium, as the wells penetrate more and more deeply and come ever closer to the fractured aquifer; or, perhaps, due to the reduction of the column of water in the granular aquifer that would permit the elevation of the thermal water. This water, rich in sodium, is progressively advancing towards the granular aquifer, where the irrigated agricultural zones are situated and where ever greater damage is occurring to the fertility of the soil due, principally, to the combined effects of the increased concentrations of sodium and the higher SAR. It is important that
these processes be evaluated in greater detail and be taken into account in agricultural planning in the basin because, to date, 15% of the total irrigated area presents moderate restrictions on irrigation by aspersion and another 10% presents restrictions on irrigation by gravity. It is to be expected that these percentages will increase over time.

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