Arsenic and lead pollution of the Salamanca aquifer, Mexico: origin, mobilization and restoration alternatives

RAMIRO RODRÍGUEZ, AURORA ARMIENTA
Geophysics Institute, UNAM, Cd. Universitaria, 04510 Mexico City, Mexico
e-mail: rrdz@tonatiuh.igeofcu.unam.mx

JOEL BERLIN
Ecology Direction, Salamanca Municipality, UTA, Salamanca Glo, Mexico

J. ANGEL MEJIA
COTAS, Parque Ecológico, Salamanca Glo, Mexico

Abstract Arsenic and lead concentrations, around and over Mexican standards for drinking water, were detected in the Salamanca aquifer system. Groundwater is the only water supply source for the more than 140,000 Salamanca inhabitants. A refinery, a thermoelectric plant and agrochemical industries are established in the urban area. Three aquifer units integrate the aquifer system: a shallow one, a semi-confined intermediate one and a deep formation. The highest As and Pb values correspond to the non-exploited shallow formation. The deep aquifer contains As but not Pb. A monitoring programme is being carried out in wells, shallow dug wells and piezometers. Aquifer vulnerability mapping, using the AVI and DRASTIC methods, revealed the influence of a subsidence fault on the solute transport. Variations in the concentrations are related to the abstraction regime, the fault extension and also to the irregular distribution of clay and sand layers.

Key words: aquifer pollution; arsenic; hydrocarbons; lead; Mexico; restoration; subsidence faults

THE SALAMANCA CASE

Salamanca, in Guanajuato State, central Mexico, is an important industrial centre (Fig. 1). A Pemex (Mexican oil company) refinery, a thermoelectric plant and pesticide manufacturing industries are located in the urban area. Agriculture is also an important activity. Groundwater is the only water supply source for the more than 140,000 inhabitants. In the basin there are more than 1900 wells; 1600 of them are active. 85% of the abstraction is used for agriculture.

An active subsidence fault associated with the intense abstraction regime crosses the urban area and the refinery lands. It has been recorded since 1982. The accumulated displacement is about 60 cm in the urban area and 1.5 m in "J. Rosas", a rural community located 7 km from Salamanca (Garduño et al., 2001). The fault provoked a pipeline breakage and a hydrocarbon spill. Free phase was detected in one urban well. The urban wells have 40 m of close casing preventing flows from the shallow
aquifer. The fault is acting as a preferential channel for surface pollutants. There is hydraulic connection between the shallow and the intermediate formations (Fig. 2). The Lerma River crosses the urban area. The river receives untreated wastewaters. It acts as a hydraulic barrier that separates the urban area into two regions, north and south. The industrial area is located in the northern part.

Three units compose the local aquifer system: a shallow non exploited one, defined by granular material with a predominance of clay and clay-sand layers (Fig. 2); an intermediate one, the exploited unit, which includes granular materials; and a deep formation formed mainly of fractured volcanic rocks. The shallow water table is located at 18–19 m depth, whereas the piezometric level of the intermediate unit is found at 30–35 m. The thermoelectric plant only exploits the deep formation. Its piezometric level is located at a depth of 65–70 m.

The aquifer description above corresponds to the northern part. In the southern part there is no shallow unit. Volcanic rocks, basalts and tuffs form the main aquifer formation, which can be associated with the intermediate aquifer to the northern part (Rosales, 2001). The deep permeable unit is not well defined.

ARSENIC AND LEAD DISTRIBUTION

There are no historical records of water quality. The high groundwater temperature in deep wells drilled in the early 1970s supports the hypothesis of quality problems since that period, implying the presence of fluorine and perhaps arsenic. Arsenic and lead concentrations over the national and international standards for drinking water were detected in the shallow and the exploited aquifer (Rodríguez et al., 2000). The first reports, in the late 1990s, corresponded to the northern aquifer system. To the
south there is no industry but three urban waste dumps are located over volcanic rocks. An urban well located near of one of these sites also contains Pb and As. The environmental authorities did not control these sites. Industrial wastes could also be deposited.

The origin of the As and Pb is not clear. As could be associated with the hydrocarbon spill, with leakages from industrial wastes (mainly agrochemicals), or with As bearing rocks, or could be a combination of some of the three potential sources. Pb could originate from hydrocarbon dissolved phases. However, since 1990 lead has not been incorporated into Mexican gasoline. The spill was reported in 1992. The Guanajuato mining area (silver, gold and lead) is not far away from Salamanca.

A piezometric depression was observed in the shallow unit around the fault trace. It was provoked by the abstraction regime of the intermediate formation. Induced flows from the shallow unit are recharging the exploited aquifer, polluting it. The refinery wells are locally controlling the piezometric behaviour of the northern part.

Hydraulic conductivity was measured in representative outcrops and along the fault trace (Rodriguez et al., 2001). Very high values were determined along the fault. Sand and sand-gravel layers and an irregular paleochannel network control shallow groundwater flow paths (Rosales, 2001).

AVI (Van Stempvoort et al., 1995) and DRASTIC (Aller et al., 1985) aquifer vulnerability mapping was carried out in the urban area (Rodriguez et al., 1999, 2001). The highest vulnerabilities are correlated with the fault. Along the fault, the free phase reached a thickness of 2 m in late 2000. Early in 2001, a depth of some centimetres was still detectable. Hydrocarbons could reduce the iron oxy-hydroxides inducing As mobility. The As concentration in drinking water is the result of the combination of polluted and unpolluted water. Some neighbourhoods consumed only polluted water (As and Pb) increasing health risks. Benzene and transformation products were also reported (Rodriguez et al., 2000).
The distribution of As and Pb obtained in both aquifer units (shallow and intermediate) do not follow similar patterns. A correlation between As and Pb concentrations was not observed. Relatively high concentrations of Pb were detected in some piezometers (Table 1). At those points, low As contents were found. As but not Pb was detected in some of the deep wells.

Well numbers 4 and 24 maintain As concentrations greater than the national standard. Both of them are located less than 500 m from the refinery.

Table 1 Pb and As concentrations in piezometers, and As evolution in well 24.

<table>
<thead>
<tr>
<th>Piezometers:</th>
<th>Pb (mg l⁻¹)</th>
<th>As (mg l⁻¹)</th>
<th>Well 24: Date</th>
<th>As</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM-20</td>
<td>0.093</td>
<td>0.014</td>
<td>19 August 1997</td>
<td>0.055</td>
</tr>
<tr>
<td>PM-21</td>
<td>0.101</td>
<td>0.022</td>
<td>3 November 1998</td>
<td>0.073</td>
</tr>
<tr>
<td>PM-23</td>
<td>0.085</td>
<td>0.016</td>
<td>23 February 1999</td>
<td>0.065</td>
</tr>
<tr>
<td>PM-25</td>
<td>0.295</td>
<td>0.019</td>
<td>26 December 1999</td>
<td>0.068</td>
</tr>
<tr>
<td>PM-26</td>
<td>0.103</td>
<td>0.021</td>
<td>25 April 2000</td>
<td>0.059</td>
</tr>
</tbody>
</table>

THE RESTORATION PROGRAMME

A preliminary restoration programme included: the installation of more than 45 observation wells of 30 to 50 m depth; free phase recovery and a new battery of urban wells, after closing of the most polluted wells. Wells 4 and 24 were closed late in 2000. The new wells will be located to the south, out of the urban area. Pemex will cover the cost of both activities. The groundwater-monitoring programme will continue to analyse the spatial and temporal evolution of the pollutant.

Controlled abstraction in the shallow aquifer could induce free phase flows to the induced piezometric depressions. The role of the fault in hydrocarbon mobility is being analysed. An air sparging and vapour extraction system is being considered for hydrocarbon residual removal.

The population located around the most polluted wells, 4, 11 and 24, was drinking water directly from those wells. The local population usually have underground water storage tanks. A recommendation was to consume bottled water. An epidemiological study is also being considered.

DISCUSSION

The wide distribution of lead and arsenic supports the hypothesis of a natural origin. However, there is not enough mineralogical or even geological evidence to confirm this. The As content in the thermal (deep) wells can be considered as additional proof of its natural origin. The higher contents of lead in the shallow aquifer than in the intermediate formation indicate its anthropogenic origin. A Pb speciation study is being carried out.

Arsenic mobility could be induced by the presence of hydrocarbons. It could also be related to industrial wastes. Arsenic was used in pesticide manufacture. There is
evidence of irregular dump sites across the whole area. Some of the old landfills did not have strict environmental controls.

Water table oscillations provoked by abstraction variations influence the LNAPL's distribution. The fault and paleochannels present high values of hydraulic conductivity, in comparison with the clay and clayey shallow layers, and are acting as preferential channels for contaminated groundwater.

The simultaneous presence of arsenic, lead, benzene, transformation products, and even radon, represents a health risk that must be avoided (Rodriguez et al., 2000).

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REFERENCES


