

# The role of urban areas in aquifer vulnerability assessments: The Salamanca, Mexico, case

Ramiro Rodríguez C.

*Instituto de Geofísica, UNAM, México*

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## RESUMEN

La mayoría de los métodos de evaluación de vulnerabilidad acuífera consideran medios relativamente homogéneos. Una mancha urbana puede ser considerada como un medio inhomogéneo. Se analizan procedimientos para incorporar inhomogeneidades como áreas verdes en zonas urbanas, fallas, fracturas, cuerpos de agua superficiales (presas, lagos, cauces de ríos) en los métodos DRASTIC y AVI. Fugas de la tubería de agua potable y del drenaje son también analizadas. El Caso Salamanca en México donde se aplicaron los métodos DRASTIC y AVI es analizado.

**PALABRAS CLAVE:** Vulnerabilidad acuífera, DRASTIC, AVI, Salamanca.

## ABSTRACT

Most aquifer vulnerability assessment methods consider relatively homogeneous media. An urban area could be considered as an inhomogeneous media. Different procedures for incorporating such inhomogeneities in the DRASTIC and AVI methods are analyzed such as green areas in urban zones, faults, fractures, surface water bodies (dams, lakes, riverbeds). Leakage from pipelines and sewage is discussed. The Salamanca Case in central Mexico, where the DRASTIC and AVI methods were applied, is analyzed.

**KEY WORDS:** Aquifer vulnerability, DRASTIC, AVI, Salamanca.

## INTRODUCTION

Most methods of aquifer vulnerability assessment consider homogeneous and isotropic media and/or geologic, meteorological and hydrodynamic characteristics of relative easy representation and extrapolation. The stratigraphy is always considered parallel to the surface and the different geological layers are assumed to have a homogeneous composition. At regional level the simplification of the geological environment allows to know the vulnerability of the aquifer systems, but at a local level or "small" scales, 1:10,000, the space variations of the parameters can limit the usefulness of the methods. An associate problem is that the aquifer vulnerability evaluations are difficult to validate. Alternative validation based on the hypothesis that if active sources of contamination exist on vulnerable lands, the solutes can leak and be present in the groundwater flow, have been proposed by Ramos (2003), Ramos and Rodríguez (2003) and Báez (2001).

The localized quantifications, in general in the localizations of the wells or exploratory perforations, are interpolated, in most cases, using geostatistical methods or techniques such as Kriging. The method AVI (Aquifer Vulnerability Index) proposed by Van Stempvoort *et al.* (1995) is more localized than the DRASTIC index (Aller *et al.*, 1985)

or the improved proposal of DRASTIC designed basically for the European environment, SINTACS (Civita and De Maio, 1997). In these last two methods the selection of ranges for the geologic composition of the aquifer and of the vadose area depends on the user's experience.

The evaluation of the net recharge depends on the quantity and quality of available data of precipitation, P, and temperature, T. This information is generated by climatologic stations distributed irregularly in the studied territory and whose operation is intermittent most of the times. The evapotranspiration is calculated from P and T by means of empiric relationships without considering the vegetation type in forest and/or agricultural lands.

## AQUIFER VULNERABILITY OF COMPLEX MEDIA

An aquifer system whose hydrostratigraphy does not present a regular geometry, and whose permeability is not laterally homogeneous, will be considered as a complex environment, from the point of view of the methods of aquifer vulnerability assessment.

The hydraulic conductivity,  $k$ , is the reference parameter for the aquifer vulnerability. Fractures, faults, changes

of facieses, of grain size, are the main factors that induce changes in  $k$ .

In large sedimentary valleys the selection of the composition of the vadose zone and of the aquifer does not represent serious problems. The presence of paleochannels, for instance, with different hydraulic conductivity should be considered. They can act as perched aquifers or like media of greater permeability.

In sedimentary media, with large clay and clayey packages that can create aquitards, pumping can cause differential compaction of the clayey layers. The intensity of the extraction and the geometry of the clayey layers cause subsidence that originates fractures in the land. Sometimes the dimension and linearity of these propitiate their identification as normal faults. If differential collapse affects compact lenses of sandy clay or gravel clay or cemented strata of gravels or sands, their rupture increases conductivity. Locally the displacement can also diminish the conductivity.

## URBAN ZONES

Urban areas of great extension, very common in developing countries, present interesting characteristics from the point of view of the evaluation of vulnerability. It is considered that the whole urban area covers the soil (that implies a non permeable soil and absence of recharge), although these settlements have wide non covered areas as non building terrains, parks and other green areas. In these urban environments it is common that the systems of distribution of drinkable water, pipelines and the sewage, have leakages. In most Mexican cities the estimated leakage volume is 25 to 35%. These volumes are reincorporated to the local aquifers and they represent an important percentage of the local recharge.

Large population concentrations grow around industrial corridors. The handling, storage and final disposition of raw material and of liquid and solids wastes bears risks of environmental affectation to soils and aquifers. If industrial areas, facilities and ducts, are located on vulnerable lands, they could act as potential sources of contamination. Many times the electric power supply is achieved by means of thermoelectric plants, with the consequent increment of water consumption.

In a great number of cases the waste waters are conducted by means of non protected channels toward receiving bodies, rivers or lagoons of oxidation. Although the sedimentation of the organic load creates impervious riverbeds, big flows can remove it and if the channels or riverbeds are located on permeable rocks they can act as recharge areas for the local aquifers and consequently as sources of contamination. These waters are used in agriculture although

some national environmental standards forbid or restrict that type of use.

In general, the new urban settlements located over volcanic and calcareous terrains have no sewage disposal. Holes and fractures are used for disposal of waste waters, increasing the aquifer vulnerability and the risks of pollution. In some urbanizations located on hard rocks, local authorities opted for wells of absorption instead of pipelines for sewage. The cost is smaller. By this practice a practically invulnerable site becomes vulnerable.

The requirements of building materials are supplied by quarries (clay, gravel, sand) in the vicinity of the growing urban settlements. The clay, gravel and sand extractions generate big hollows that make more vulnerable the local aquifer system. Those sites are used later as trash dumps. The closing of these places follows not always the respective environmental standards.

When the groundwater constitutes the main source of urban supply, the watertable can evolve negatively in relatively short periods of time. This down draw can be greater if the urban area is surrounded by agricultural lands whose extraction can be much bigger than the urban one. DRASTIC as SINTACS and AVI methods consider the depth of the static level, if it is increased in meters by year, the characteristics of the vadose zone are modified and therefore the vulnerability zoning. The non stationarity is a characteristic of the vulnerability assessment; its dynamic must be considered (Rodríguez, 2003).

## ALTERNATIVE PROCEDURES

The incorporation of inhomogeneities in the vulnerability evaluations requires its correct identification and its assimilation in the method to apply. Their geopositionation facilitates its handling.

The bodies of water, particularly the riverbeds affect the assessment outlines of aquifer vulnerability. To determine if lakes and dams recharge the aquifer it is convenient to carry out isotopic analysis (oxygen 18 and deuterium). The analysis of the riverbeds or channels (sediment accumulation and consequently the decrease of the conductivity of these) allows to understand if the water that circulates for them can or not facilitate the solute percolation toward the local aquifers. This consideration is particularly outstanding in those countries of Latin America that use the riverbeds like receptors of urban and industrial untreated wastewaters mainly if the river recharges the aquifer. The riverbeds also act as hydraulic barriers.

The channels of the streams can be incorporate by means

of permeability measurements in both riverbanks of the riverbed. The depth of the watertable can be known through shallow wells or piezometers or to be inferred interpolating among the base flow and some near well. The riverbeds are generally located in weakness zones of the geological formations. The permeability *in situ* determination of the shallow formations also facilitates the selection of ranges for the vadose zone in DRASTIC and in SINTACS.

To incorporate fractures and inclusive faults in the methods of vulnerability assessment is necessary to know the hydraulic conductivity of the formation affected by fractures and/or faults and of the formation without affectation. The difference can be of a couple of orders of magnitude (Rosales, 2002). The use of constant head permeameters, for *in situ* determinations, requires an excellent geologic mapping of outcrops for the selection of representative points of the medium (Xiang, 1994). The number of measurements will depend of the fracture density, the variations in grain size and/or the porosity of the considered formation.

In the urbanized areas it is convenient to take a census of the non covered areas and if it is possible to carry out an edaphologic and urban geology mapping. The lower vulnerability class and range is assigned to the covered terrains. A still not solved problem is the incorporation of the recharge. In the green areas it is assumed that the recharge volumes correspond to the locally calculated by means of some relationship type Turc or Thornthwaite starting from annual data of temperature and precipitation (Civita, 1994). The leakages can be incorporated by estimating the annual volume (potable water and sewage) reported by the authority entrusted of water supply, divided by the surface of the urban area. The number of points in those the estimated recharge will be incorporated, will be in function of the scale of the study area and of the surface and distribution of green areas.

If the study area comprises agricultural lands, in the calculation of the net recharge must be incorporated the so-named irrigation return to the available rainfall recharge. The estimated additional recharge for irrigation return in Mexico is 20 % for cultivations with irrigation for aspersión (Rodríguez *et al.*, 1999).

### THE SALAMANCA CASE

In the urban area of Salamanca, Guanajuato state, central Mexico a refinery, a thermoelectric plant and organic compounds factories, some of them producing agrochemicals, are located. In the area they are located more than 1900 wells, 1600 actives, from which so alone 33 of them managed by the municipality for urban supply. The dependence of ground water is total; there are not alternative supply

sources. The intense extraction regime is causing subsidence in the area. The differential compactation of the land has given place to the fault that practically divides the urban area in two. The estimated subsidence velocity is of 6 cm / year.

An aquifer vulnerability assessment was carried out in the Salamanca urban area. The DRASTIC and AVI index methods were applied (Rodríguez *et al.*, 2001). In the elaboration of both maps the fault trace, the Lerma riverbed and the green areas were considered. The rule of these three factors was analyzed (Borja, 2003). A more representative aquifer vulnerability maps were obtained. The aquifer vulnerability map becomes a pollution risk map with the incorporation of potential sources of contamination. A pollution sources census was done. The sites were geopositioned. A catalog of 25 different types of sources was elaborated (active and inactive industrial lands, chemical contingencies, active and closed trash dumps and landfills, and cemeteries, among other).

To incorporate the fault were carried out more than 70 permeability measurements along the trace of the fault. A fringe of 50 meters of affectation to both margins of the fault, with presence of fractures in the soil and buildings was reported (Garduño *et al.*, 2000). The superficial layers, clay, sandy and gravel clay, presents hydraulic conductivities that varies from  $2.5 \cdot 10^{-7}$  to  $6.0 \cdot 10^{-8}$  m/sec, while in the area of the fault these varies from  $8.0 \cdot 10^{-3}$  to  $6.0 \cdot 10^{-5}$  m/sec. Permeability measurements were made in the riverbed of the Lerma river and in more than 20 green areas of the urban area. They were selected green areas that never were building to get non altered soils. Salamanca has a relatively big density of green areas, about 12 % of the total area.

The fault crosses diagonally the city breaking pipelines of the system of drinkable water and the sewage. The estimate volume of leakages of the pipelines is 30% while for the sewage is of 25%. The incorporation of these additional volumes alters locally the class for net recharge in DRASTIC, passing from 3 to 4. The calculated recharge was 49 to 79 mm per year, while the volumes of the leakages varied from 38 to 61mm per year, almost of the same order of the precipitation recharge. The total recharge used for DRASTIC was 87 to 140 mm. The class in DRASTIC changed from 3 to 6, affecting the vulnerability assessment. The net recharge was calculated using 10 years of precipitation and temperature data coming from four meteorological stations located around Salamanca. The Turc expression was used to obtain the real evaporation (Rodríguez *et al.*, 2001).

The DRASTIC map (Figure 1) is not necessarily correlated point to point with the AVI map (Figure 2), since while the first one incorporates seven parameters, the sec-

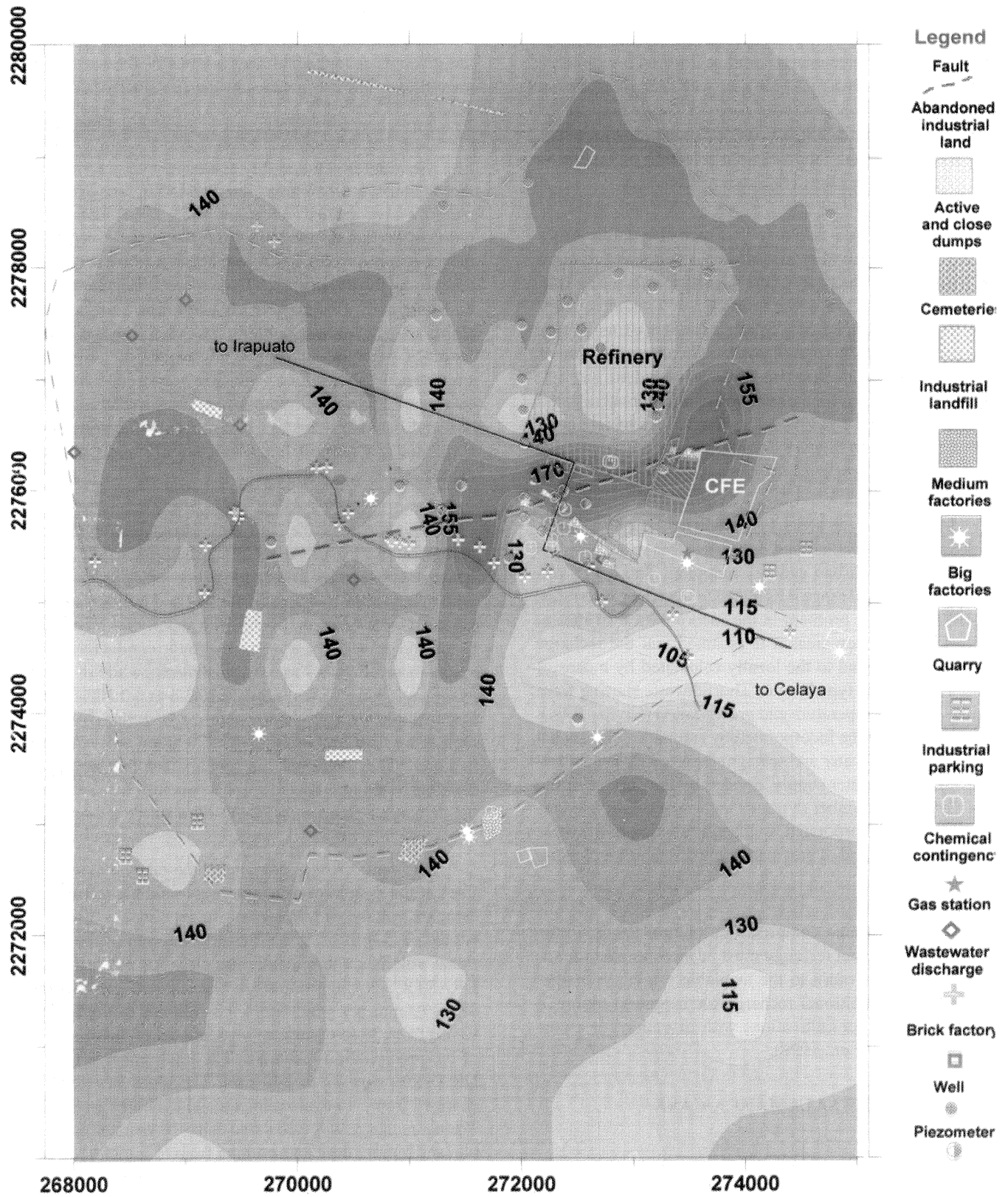


Fig. 1. DRASTIC map of the Salamanca, Gto., urban area with potential sources of contamination.

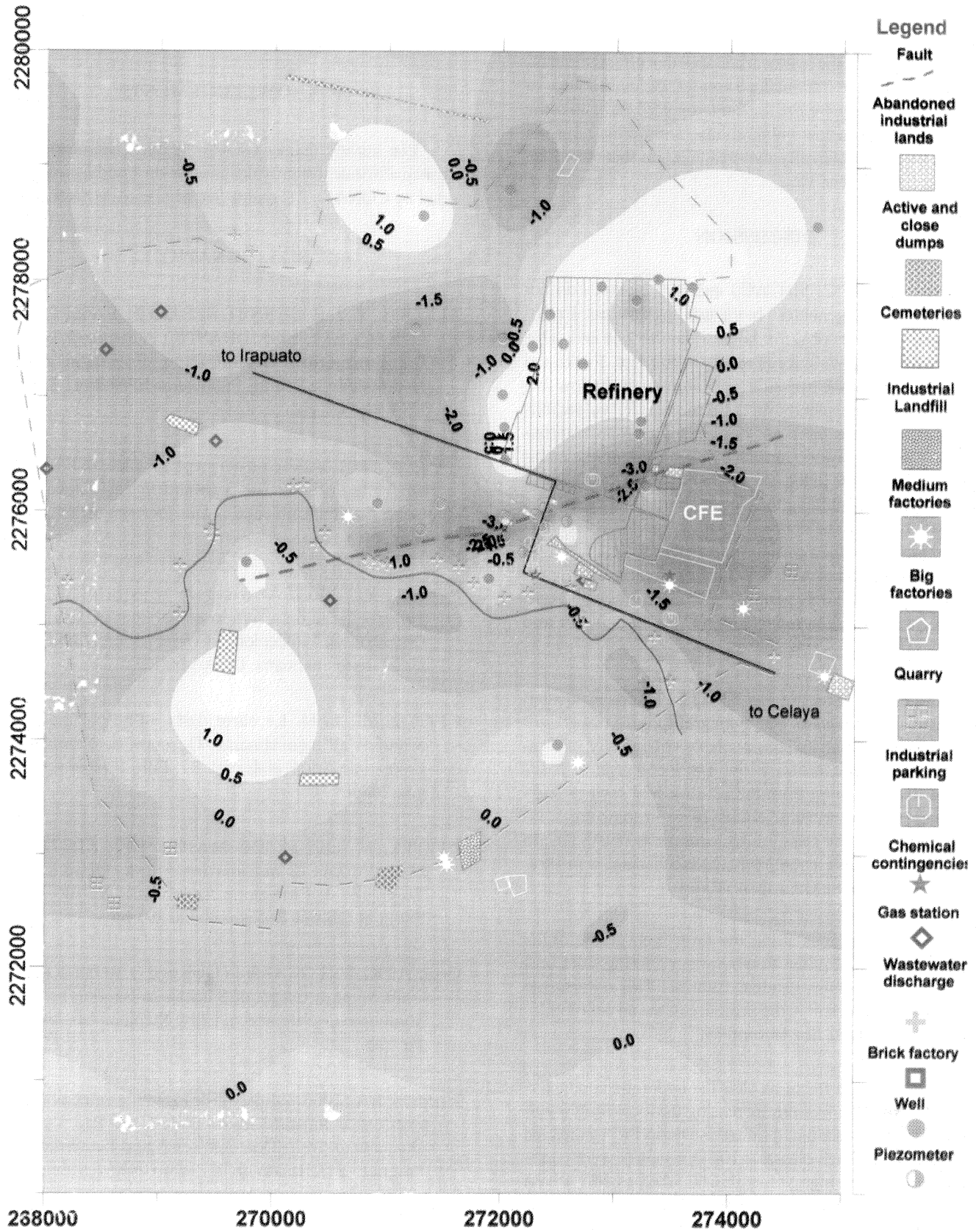


Fig. 2. AVI map of the Salamanca, Gto., urban area with potential sources of contamination.

and only use two. In both it is possible to observe that the fault altered the status of vulnerability of the urban area. The refinery is crossed in its portion south-east for the fault what surely causes the hydrocarbon spill that affects the shallow aquifer and the intermediate aquifer, the main source of urban water supply. Before the fault, reported early 80's, the area would show a low vulnerability. The Lerma river not only divides hydraulically the area, also do that from the vulnerability point of view.

## DISCUSSION

The DRASTIC, SINTACS and AVI methods do not consider "inhomogeneities" in the used parameters. Faults, fractures, riverbeds or water bodies like lagoons and dams influence the vulnerability of the local aquifers. Faults and fractures increase the hydraulic conductivity of shallow formations and consequently increase the aquifer vulnerability. These methods were not designed for urban environments. Their application in such media also requires the incorporation of some of the characteristics of the urban zones; green areas, non building terrains and industrial areas. The incorporation must be done especially when the vulnerability assessment is been carried out to local scales, 1:20,000 or less. A variation of AVI, SAVI has been proposed for urban areas, but SAVI only permits to consider individual aquifers not the cited inhomogeneities (Van Stempvoort and Martin, 2003).

In semi-arid regions as El Bajío where is located Salamanca, Guanajuato, the evapotranspiration is greater than the precipitation and the available volumes for infiltration, local recharge, are very low. The incorporation of additional flows coming from the pipeline and sewage leakages increased the recharge almost twice in some areas, increasing one unit the class for net recharge in DRASTIC. In Salamanca the preferential recharge mechanism is infiltration of rainfall in the Guanajuato Range.

Sewage leakages along the fault incorporate organic matter to shallow aquifer. Potable water coming from broken pipelines contains residual chlorine. This unfortunate combination can result in the presence of the so called chlorination by products like chloroform.

The fault and fractures alter the hydraulic conductivity,  $k$ , of shallow formations increasing the local aquifer vulnerability. They were incorporated in DRASTIC by the type of vadose zone (high classes);  $10E-3$   $k$  values were correlated with class 8 (high vulnerability) whereas  $10E-4$  with class 7. In AVI the fault was also incorporated by mean of  $k$ . In both maps (Figures 1 and 2) the fault area appears with a high vulnerability. An indirect validation of this vulnerability assessment is the presence of arsenic, lead and free phase

in norias (shallow hand made wells), piezometers and wells located in the fault and refinery neighborhood (Rodríguez *et al.*, 2000).

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- Ramiro Rodríguez C.  
*Instituto de Geofísica, UNAM, México*  
*Email: rrdz@geofisica.unam.mx*

