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Hydrogeology of a contaminated sole-source karst aquifer, Mérida, Yucatán, Mexico

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RESUMEN

La ciudad de Mérida, Yucatán obtiene su agua potable principalmente de tres campos de pozos localizados en los alrededores de la ciudad. Adicionalmente, existen pozos del sistema de agua potable dentro de la ciudad. Se ha reportado la presencia de plomo, cadmio y cromo excediendo el límite de la Norma de Agua Potable Mexicana en agua del sistema de agua potable. Los siguientes contaminantes orgánicos también han sido detectado en el agua subterránea de la porción sur de la ciudad: TCA, PCE, TCE y CTET. Mérida obtiene aproximadamente 65% de su agua potable del campo de pozos JAPAY-I, el cual extrae el agua de la sección sureste de la ciudad de Mérida. Es en esta zona donde se concentra la actividad industrial. No se cuenta con información de la calidad del agua de este campo de pozos, pero es probable que se encuentre bastante contaminada. Sugerimos que se implemente un sistema de monitoreo del agua subterránea. Una zona de reserva hidrogeológica también debería de ser establecida para permitirles a los habitantes de Mérida contar con una fuente sustentable de agua potable.

PALABRAS CLAVE: Cárst, contaminación, Yucatán.

ABSTRACT

The City of Merida, in the State of Yucatán, obtains its drinking water primarily from three well fields located in the periphery of the city. In addition, there are water supply wells within the city. Water from the public water supply contains lead, cadmium, chromium in excess of the Mexican Drinking Water Norm. The following organic contaminants have also been identified in the ground water in the southern portion of the city: TCA, PCE, TCE, and carbon tetrachloride (CTET). Mérida currently obtains about 65 % of its drinking water supply from the JAPAY-1 well field which draws water from the southeastern section of the city, where most of Merida's industrial activity is concentrated. No information is available on the water quality from this well field, but it is likely to be also heavily contaminated. A ground water monitoring scheme is suggested. A hydrogeological reserve zone should be established to allow the inhabitants to have a sustainable source of drinking water.

KEYWORDS: Karst, contamination, Yucatán.

INTRODUCTION

The upper hundreds of meters of the Yucatán peninsula consist of almost pure carbonates. They leave practically no residue when dissolved. A result is a well developed karstic system of interconnected fractures, joints, and solution openings with little top soil. The only identified aquitard is a narrow band of caliche parallel to the coast that locally confines the aquifer (Back and Hanshaw, 1970; Perry *et al.*, 1989). On a regional scale, Marín (1990) has simulated ground water flow assuming an equivalent porous medium. However, on a local scale, Steinich (1996) and Steinich and Marín (1997) have shown that the aquifer behaves as a karstic aquifer southeast of Mérida. Beddows (1999) has shown similar behavior on the eastern side of the peninsula.

Buckley and Macdonald (1994) have found secondary fractures beneath the city using geophysical borehole logging. The aquifer in northwestern Yucatán is a thin fresh-water lens that extends more than 110 kilometers inland (Steinich and Marín, 1996). This is the sole-source aquifer for northwest Yucatán. It is highly vulnerable to contamination due to its high permeability and numerous sources of anthropogenic pollution (Marín and Perry, 1994). Mérida is the largest city in the peninsula, with a population greater than 500 000 inhabitants. There is no integrated sewage collection system for the city, and all of the domestic, industrial, and medical wastes are discharged without treatment directly into the aquifer through injection wells.

The climate is tropical with a mean annual precipitation of 1200 mm and a temperature of 26.3°C (INEGI, 1992). The hydraulic gradient is extremely flat, on the order of 7 to 10 mm/km (Marín 1990; Steinich and Marín, 1996). Measured heads in northwestern Yucatán range from 0.45 m above mean sea level to 2.1 m in Sotuta, southeast of Mérida. The water table maps show that ground water flow is predominantly from south to north in the northern coastal region and from north to south just south of Mérida (Marín and Perry, 1994; Steinich and Marín, 1996). The north-to-south ground water flow direction is a result of the Ring of Cenotes, a regional feature that acts as a preferred ground water flow zone (Marín, 1990; Perry *et al.*, 1995; Steinich and Marín, 1996). One consequence of this high permeability zone is a ground water divide located just south of Mérida, at Uman (Figure 1) (Marín, 1990; Steinich and Marín, 1996).

In the downtown area, the limestone bedrock is typically exposed on the surface. The upper part consists of a hard, impermeable caliche layer of variable thickness with cracks that allow rapid infiltration. Beneath this layer there is an unsaturated zone. Depth to the saturated zone ranges from 8 to12 meters, where the freshwater lens may extend to a depth of 55 meters below land surface. Brackish water ranges from 55-70 meters below land surface. Below 70 meters there is salt water. Thus, the aquifer is vulnerable both from above by contaminant sources and below by salt water intrusion. Since the aquifer is karstic, flow rates are rapid, in high permeability pathways, allowing contaminants to reach the water table quickly. On the other hand, pumping of the thin fresh water lens may allow salt water to rise (Marín, 1990; Marín and Perry, 1994). The bacteriological contamination of this aquifer is well documented in the literature (i.e Dohering and Butler, 1974; Pacheco and Cabrera, 1997).

We conduct a detailed geochemical evaluation to determine the water quality of this sole-source aquifer with respect to heavy metals and some organic contaminants underneath the city of Mérida, Yucatán.

Hydrogeology

Marín (1990) reported a ground water mound north of Mérida based on water table maps constructed between July, 1987 and April, 1990 and Morris (1994) suggested that a ground water mound exists underneath Mérida as a result of water being imported from the periphery of the city through

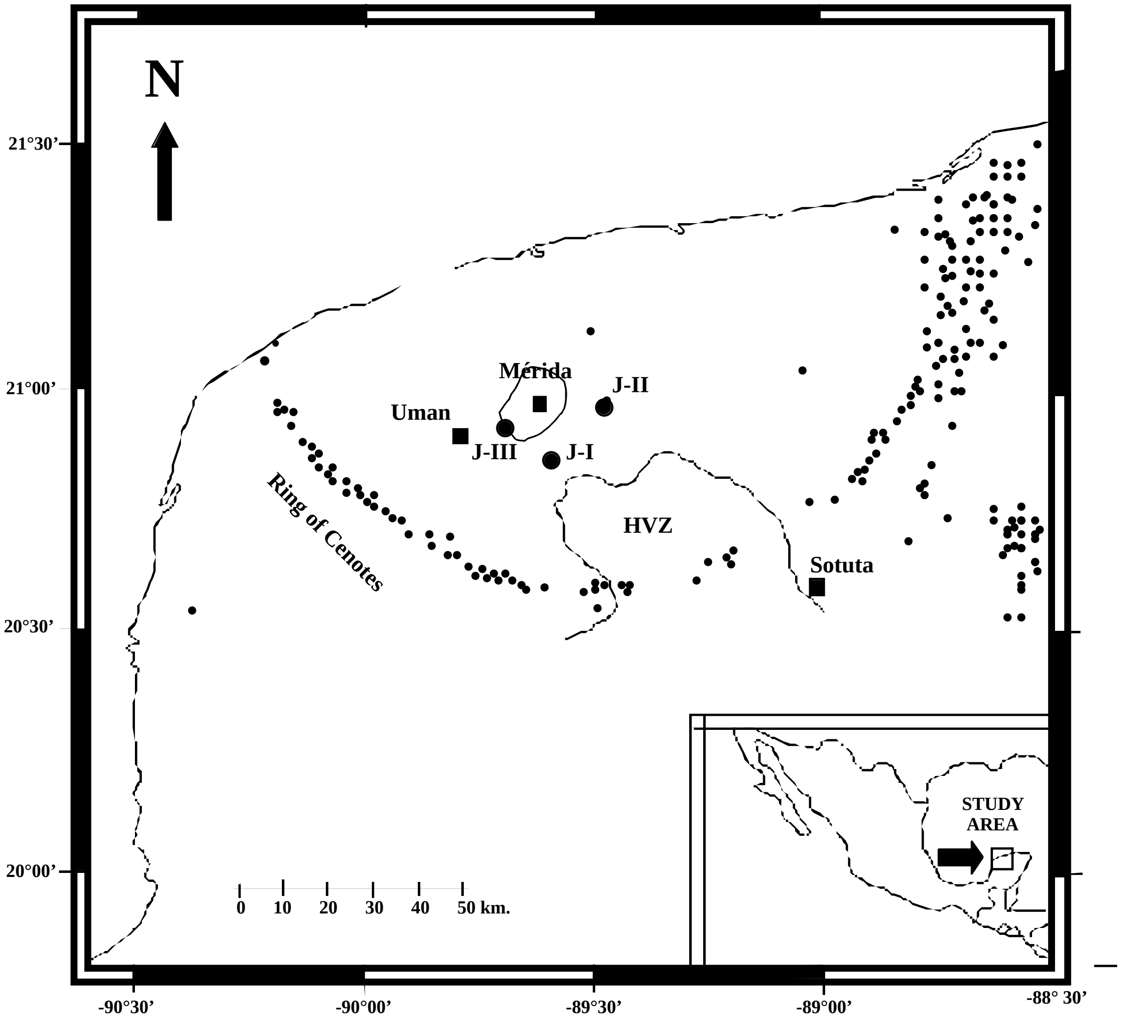

Fig. 1. Location of the study area. J-I, J-II, J-III are JAPAY wellfields one, two, and three, respectively. HVZ is highly variable zone, as defined in the text by Steinich and Marín (1997).

three well fields located to the southwest, southeast, and east of the city. Due to the very low hydraulic gradient and to the lack of a network of accurately surveyed wells within the city, it has not been possible to map the extent of this mound in detail. The well fields that provide most of the water for the city of Mérida are JAPAY-1, JAPAY-11, and JAPAY-III (Figure l). Steinich and Marín (1997) have reported that southeast of Mérida, there is an area known as the "Highly Variable Zone" where rapid transient reversals in the hydraulic gradient are common.

Several factors that cause the hydraulic gradient to reverse, thus forcing ground water to flow upgradient. (A) The water-table mound in Mérida, as a result of drinking water being "imported" from the periphery of the city; (B) the cone of depression formed at the JAPAY-I wellfield; (C) the shifting hydraulic gradients located in the Highly Variable Zone (HVZ), and (D) the presence of the Ring of Cenotes, which forms a ground water divide.

Chávez Guillén (1989) has reported drawdowns for ten wells in wellfield JAPAY-I, ranging from 3 cm to 92 cm, with an average of 25 cm. The water level for July, 1987 was 1.21 mamsl (meters above mean sea level). Subtracting the average drawdown for the JAPAY-I wellfield gives an elevation of the water table of 0.96 mamsl. This value was used to calculate the hydraulic gradient from the highest piezometric point in Mérida, 1.25 mamsl, yielding 41 mm/km in the southeast direction. This value is four to six times greater than the regional gradient (7-10 mm/km). Thus ground water from the southern part of the city is moving in the opposite direction of the regional ground water flow direction, toward the wellfield JAPAY-I.

Figure 2 shows the induced ground water zone due primarily to the drawdown cone that has been generated by withdrawals from this well field. Secondary factors may contribute water to the JAPAY-I cone of depression: (1) The presence of the ground water divide, which in effect, encourages ground water flow to travel in a southerly direction; (2) The water table mound, and (3) The reversal of the hydraulic gradients within the Highly Variable Zone. These secondary effects have not been quantified, but we estimate that their contribution is of a lower order of magnitude as that generated by the cone of depression at wellfield JAPAY-I.

Water cycle for Mérida

Sixty-five percent of Mérida's urban supply (326 Mld^{-1}) is obtained from the three JAPAY well fields outside the urban limits. Approximately 20 wells within the city are still used by the municipal water supply agency (Junta de Agua Potable y Alcantarillado de Yucatán, JAPAY). As of 1994, approximately 80 percent of the population of Mérida was connected to the municipal water supply. The water consumption is about 460 liters per day per person, including losses in the distribution system. Due to the extremely flat terrain and low hydraulic gradient, there is no storm or waste water sewage system, because of the expense of trenching in the hard limestone. Nor are there any storm sewage treatment plants in the area. Typically, houses in Mérida dispose untreated sewage in three meter deep pits. The sewage infiltrates rapidly into the aquifer. Other effluents including domestic, industrial and medical are disposed in septic tanks or through injection wells finished 200 meters below land surface.

There are more than 83 000 septic tanks within greater Mérida. González (1992) estimated that 70-75 percent of the population of the city uses septic tanks, and 5 percent deep disposal of untreated waste water into the saline aquifer. In two wells the wastewater receives primary treatment to reduce the total dissolved solids load. Twenty per cent uses pit latrines. The typical septic tank design only retains solids, and provides for retention times of only a few hours (Morris, 1994). Currently, the Comisión Nacional del Agua (National Water Commission) has determined that the upper 15 meters of the aquifer are unfit for use as a source of drinking water (Vidal, oral com.). This corresponds to at least one third of the potentially available drinking water. Morris (1994) concluded that the absence of a city-wide system of sewer age in Mérida and the disposal of the majority of the urban wastewater into the ground provides the main multipoint pollution source and the principal groundwater quality concern.

Thus, a major problem concerning domestic wastewater as well as industrial and hospital effluents exists in Yucatán. Three alternative management options are being considered by the National Water Commission. (1) Injecting the raw, untreated sewage several hundred meters below land surface; (2) piping and discharging the untreated sewage to the ocean 33 km from Mérida, and (3) using the untreated sewage to irrigate gardens around Mérida. The three possibilities are less than ideal. Injecting untreated effluents at 200 meters below land surface may backfire, since warm, fresh water would be injected below the salt water. This water might rise in the future, causing the water quality to degrade in the upper part of the aquifer due to induced mixing with contaminated saline water. Pumping the raw effluents over a distance of 30 km and discharging them out at sea is not economical due to the large volume involved. Ocean dumping is also questionable from an ecological point of view. Finally, using the effluents for irrigation, while feasible, may pollute the aquifer rapidly. We suggest that this third possibility should be considered in combination with some treatment, especially for industrial effluents and hospital wastes.

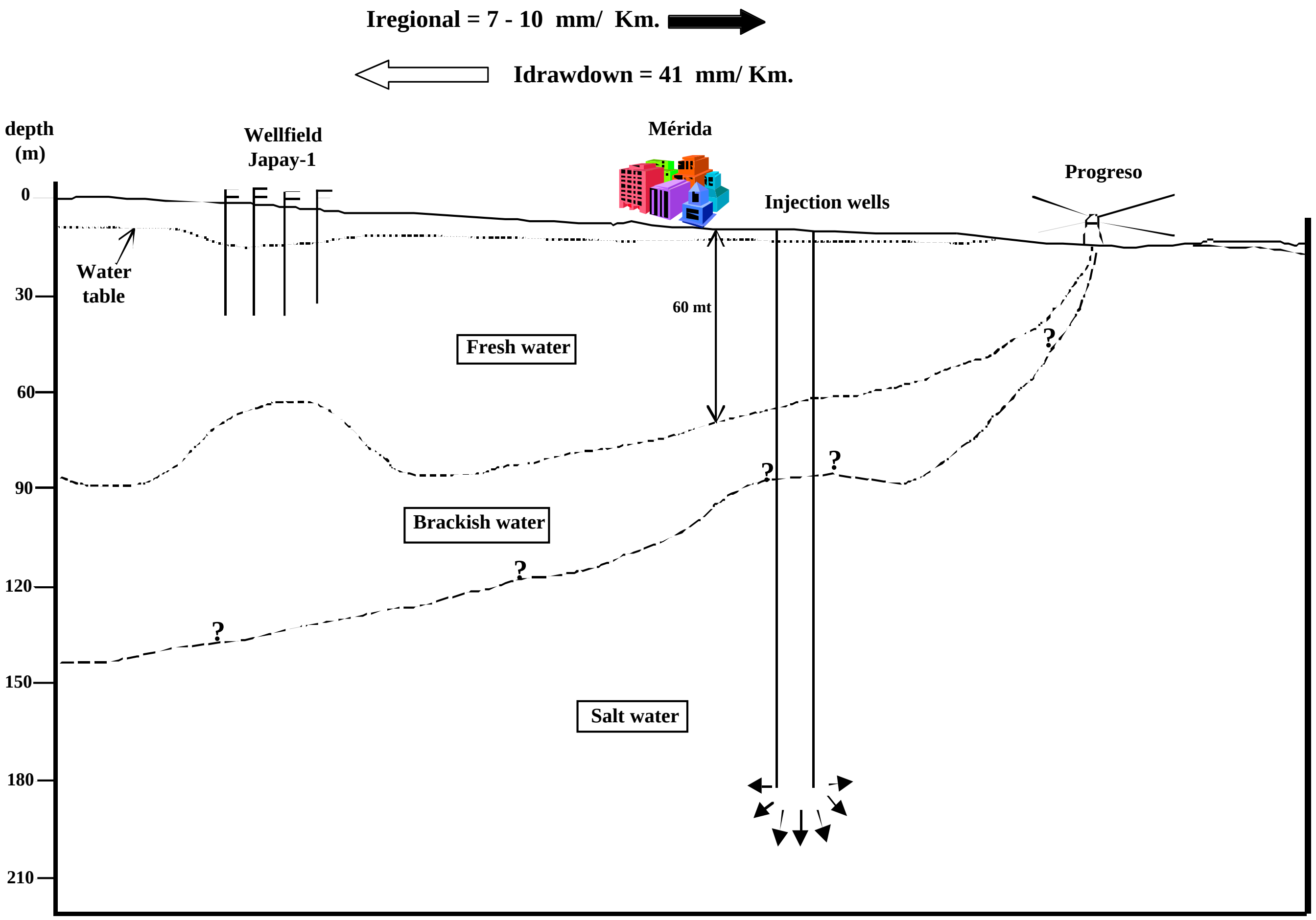

Fig. 2. Schematic representation of the hydrogeologic setting of Mérida. This figure shows the thin fresh water lens that provides the City of Mérida with its drinking water. The arrows show the regional ground water flow gradient and the induced gradient due to ground water extractions at wellfield JAPAY-I. We propose that a cone of impression has formed underneath the JAPAY-I wellfield as a result of the cone of depression that has resulted from the ground water extractions. It is also likely that some salt water is migrating upwards as a result of the injection wells in Mérida. However, currently no monitoring of the interface is in place, so these hypotheses can not be evaluated.

Chlorinated solvents

Vázquez *et al.* (1997) identified dissolved organic compounds in the aquifer underneath Mérida. They found of the following compounds up to 10µg per liter:1, 1, 1 -trichloroethane (TCA), trichloroethene (TCE), tetrachloroethene (PCE) and carbon tetrachloride (CTET). The highest concentrations were detected in deep and shallow wells in the southeastern part of the city where most of the industry is concentrated. The actual concentrations may be higher due to delays on the order of two weeks between sample collection and analysis. The solvent concentrations appear to increase during the rainy season and may indicate that the bulk of the residual solvent pollution resides in the unsaturated zone and is washed down by rainfall recharge. Total organic carbon is highly variable but includes values in excess of 40 mg/1 and the widespread presence of chlorinated solvents, with the most extensively contaminated boreholes in the southeastern industrial district (BGS, 1995).

Heavy metals

A study was conducted in the months of December 1991, through March 1992 to determine Pb, Cr, Cd, and As in selected water supply wells. Twelve wells in the southern part of Mérida were selected (Anonymous, 1992) (Table 1). Two wells are part of JAPAY's public water system (well 36 and 58). Wells 23 and 24 correspond to beverage bottling plants, well 4 corresponds to a brewery, and the other wells are from other industries. Table 1 gives the concentrations of As, Cd, Cr, and Pb and the corresponding Mexican drinking water norm. In some cases only the results for one sampling period are reported.

All wells were found to contain lead, chromium (except for well 4, Dec. '91), and cadmium above the 0.05 mg/l

Table 1

Selected concentrations of potentially hazardous elements from selected wells located in the southern part of Mérida

	Lead		**Chromium**		**Cadmium**		**Iron**		**Arsenic**	
Well #	**Dic-91**	**Mar-92**	**Dic-91**	**Mar-92**	**Dic-91**	**Mar-92**	**Dic-91**	**Mar-92**	**Dic-91**	**Mar-92**
61	0.51		0.37		0.04		nd		12.80	
18	0.34	0.21	0.19	0.20	0.01	0.04	3.26	2.88	0.67	6.75
15	0.26	0.16	0.09	0.26	nd	0.02	0.69	0.55	2.36	1.68
23	0.34	0.30	0.26	0.11	0.02	0.03	4.24	3.02	1.68	2.03
24	0.26	0.10	0.19	0.24	0.01	0.03	0.98	0.78	9.12	11.40
1	0.34	0.10	0.10	0.11	0.01	0.02	0.88	0.65	1.01	1.35
4	0.34	0.26	0.01	0.10	0.03	0.05	1.03	0.92	2.70	2.30
7	0.34	0.10	0.10	0.11	0.03	0.05	3.02	2.99	1.35	1.67
11	0.51		0.10		0.02		0.89		nd	
36	0.42	0.20	0.19	0.20	0.01	0.10	3.57	2.99	2.36	1.66
58		0.10		0.18		0.06		3.00		4.00
21		0.21		0.12		0.03		0.81		nd

maximum permissible concentration (Secretaría de Salud, 1988). In at least two cases, the lead concentrations were above five mg/l, which is 100 times higher than the maximum allowable concentration in drinking water. The chromium concentration was two to seven times above the limit. Cadmium was up to ten times above the norm. The arsenic concentrations were below the maximum permissible value of 50 micrograms per liter. Lead, cadmium, chromium and arsenic in the aquifer represent a health hazard and we are unaware of any natural source of these elements in northwestern Yucatán. Cadmium (17.6 μg/1), chromium (2.8 μg/l), copper (1233 μg/l), lead (87.5 μg/l) and zinc (6690 μg/1) have also been reported in the ground water of Mérida in the industrial zone (Castillo *et al.*, 1995).

Drinking Water Demand

The population in Mérida is growing rapidly. In 1890 there were 90 015 inhabitants, in 1970, 212 097; in 1980, 424 529; and in 1990, 556 819. As the city grows, it swallows the surrounding towns. Presently, 119 million cubic meters per year (Mm^3 /y) are extracted from the aquifer. Thus the daily use per capita is on the order of 603 liters per day, including industrial consumption by factories connected to the municipal network. This is an unusually high volume. However, the National Water Commission has estimated that on the order of 50% of pumped water is lost in the distribution system.

The actual capacity installed for the public water supply system is about 145 Mm^3/y and reaches 85% of the population, the lack in water service is not due to lack of water, but rather from network cover limitations. Considering the population growth, the current hydraulic infrastructure will meet the demands for the next ten years for 80 to 85 % of the population. This will happen only if the existing network is improved and maintained.

DISCUSSION AND CONCLUSIONS

All of the wells operated by JAPAY withdraw water continuously, so all of the public water supply wells that supply Mérida with drinking water are probably drawing in contaminants on a regular basis. The drawdown from the extractions at well field JAPAY-I has resulted in a reverse gradient that is four to six times greater than the opposing regional hydraulic gradient suggesting that contaminants may be drawn from the southern part of Mérida. The reversals that Steinich and Marín (1996) have reported may only aggravate the problem because they may contribute to the hydraulic gradient reversal.

The unique hydrogeologic and demographic characteristics of an urban area in northwestern Yucatán have resulted in the contamination of a highly vulnerable aquifer. Although it is not unusual to find ground water contamination underneath any major city nowadays, it is troubling to find it in an aquifer that serves as the sole source of drinking water.

The city of Mérida faces a very serious situation with regards to its drinking water supply and disposal of industrial, and domestic effluents. Due to financial constraints, it is unlikely that a city-wide drainage system will be constructed. Already, the upper 15 meters, or upper one-third of the aquifer is not considered fit for consumption by humans.

The presence of potentially toxic elements in several of the public drinking water supply wells, such as lead, chromium, nickel, arsenic and cadmium, as well as some organic compounds, well in excess of the Mexican Norm for drinking water has been documented in this almost pure limestone aquifer. This situation is particularly worrisome in the area north of Mérida since there are communities along the ground water flow path that also rely on ground water as their sole source of drinking water.

These observations call for attention to possible remediation. In addition, a regular ground water monitoring system should be implemented as soon as possible to identify the sources of contamination. Also, industry located within Mérida should be required to treat their effluents, in order to immediately stop the discharge of raw industrial effluents into the aquifer immediately. Due to the precarious hydrogeologic and water quality situation in which Mérida finds itself, Escolero *et al.* (in press) have conducted a detailed study and proposed that a hydrogeologic reserve zone be established for the city of Mérida.

Currently, the only regular monitored parameter at the well field JAPAY-1, is for chloride ion concentration. We would suggest that iron, conductance and coliform bacteria be added to the parameters at least annually for all wells or the combined production from individual well fields.

We suggest that an immediate water quality program also be initiated of the public water supply wells that furnish water to the inhabitants of Mérida. We also suggest that the well field JAPAY-1 should be relocated and perhaps instead of building one well field with ten large capacity wells, to build two well fields. This would reduce the principal stress on the system and minimize the reversal of the hydraulic gradient. Finally, due to the high vulnerability of this sole-source aquifer, we suggest that a ground water reserve zone be established with a strict code that will guarantee a continuous supply of potable water for the city of Mérida.

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