# The hydrogeology and contamination potential of northwestern Yucatán, Mexico

L.E. Marín[1] and E.C. Perry[2]
[1] *Instituto de Geofísica-UNAM, México.*
[2] *Visiting professor, Department of Geology, Northern Illinois University, DeKalb, Illinois, USA*

Received: March 16, 1994; accepted: August 25, 1994.

## RESUMEN

La única fuente de agua potable para el noroeste de la Península de Yucatán es un lente delgado de agua dulce que flota sobre una intrusión salina que ha sido detectada a más de 40 km de la costa. El marco hidrogeológico de este acuífero es un sistema cárstico maduro con conductos, cavernas y cenotes. El gradiente hidráulico es muy pequeño, del orden de 7-10-mm/km, sugiriendo permeabilidades muy altas. Estas permeabilidades han resultado en un acuífero muy vulnerable que tradicionalmente recibe tanto descargas domésticas como industriales. El noroeste de la Península está aparentemente aislado hidrogeológicamente del resto de la península por una zona de extremadamente alta permeabilidad (semicírculo de cenotes), el cual probablemente está relacionado con el Cráter de Chicxulub.

**PALABRAS CLAVE:** Hidrogeología, contaminación, Yucatán.

## ABSTRACT

The sole source aquifer for northwestern Yucatán is a thin freshwater lens that floats above denser saline water. The saltwater intrusion has been detected more than 40 km inland. The hydrogeologic setting of this aquifer is a mature karstic system with an extensive network of conduits, caverns and cenotes (sink holes). The hydraulic gradient in the area is very low, on the order of 7-10 mm/km, suggesting very high permeabilities. These high permeabilities have resulted in a highly vulnerable aquifer that traditionally receives both domestic and industrial waste. The northwestern section appears to be isolated hydrogeologically from the rest of the peninsula by a zone of exceptionally high permeability (ring of cenotes), which is probably related genetically to the Chicxulub Impact Crater.

**KEY WORDS:** Hydrogeology, contamination, Yucatán.

## INTRODUCTION

The study area comprises the northwestern section of the Peninsula of Yucatán, located in southwestern Mexico (Figure 1). The upper hundreds of meters of the Yucatán Peninsula consist of almost pure carbonates and evaporites which, when dissolved, leave practically no residue. This has resulted in the development of a mature karstic system with a very high permeability with little soil and no extensive aquitards except for a narrow band parallel to the coast (Perry *et al.*, 1989; Perry and Marín, 1990). The aquifer in northwestern Yucatán contains a thin freshwater lens that floats above a denser saline water intrusion that penetrates more than 40 km inland (Back and Hanshaw, 1970; Durazo *et al.*, 1980; Back and Lesser, 1981; Gaona *et al.*, 1985; Perry *et al.*, 1989). The aquifer is the sole freshwater source in northwestern Yucatán. This karstic aquifer is highly vulnerable to contamination due to its hydrogeologic characteristics and to anthropogenic pollution. The hydraulic properties of the aquifer are poorly known due to the well developed karst system. For example, although pumping tests have been attempted, no good data exist. Groundwater flow velocities are an important parameter for contamination studies, yet no measurements have been made in northwestern Yucatán.

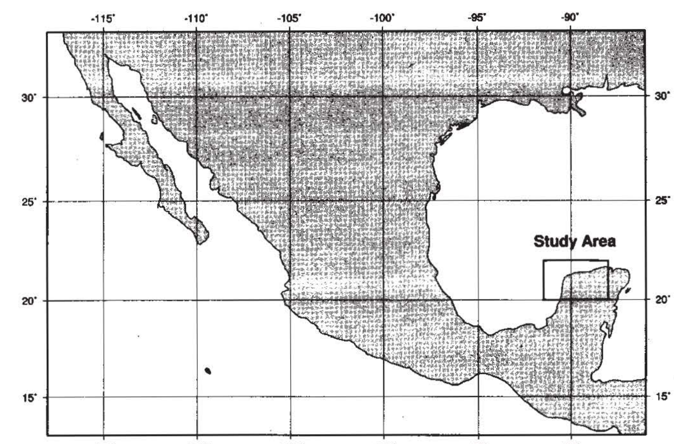


Fig. 1. The study area is located in the northwestern section of the Península of Yucatán.

## HYDROGEOLOGY

Water-table maps can be used to determine the directions of groundwater flow and to map areas of recharge and discharge. However, in order to do this, accurate bench marks are needed. By measuring the depth to the saturated zone from any well lip, and subtracting this distance from the well elevation, the height of the water-table above a certain datum may be obtained. A recently completed first-order topographic survey of most of the northwest study area (Echeverría, 1985) allowed the water-table of northwest Yucatán to be mapped with respect to mean sea level

(MSL). Bench marks and elevations are available from the Instituto Nacional de Estadística, Geografía e Informática (INEGI) office in Merida, Yucatán. From selected INEGI bench marks, 86 near-by wells were surveyed in 1987 and 1988. Thirty-one wells were surveyed with closed loops using a stadia and a NIKON theodolite model NTDS-20 with a seven-second error. The site where the stadia was placed on the well lip was marked to allow subsequent water-level measurements.

From this survey, Marín (1990) established water-level elevations for a network of more than 100 points. Figure 3 shows the water-table for July, 1987. The hydraulic gradients of northwest Yucatán are extremely flat, on the order of 5-10 mm/km (Marín *et al.*, 1987). The small water-table gradient, which is difficult to measure, suggests very high permeabilities. Measured heads in northwestern Yucatán range from a low of 0.45 m above mean sea level (MSL) near Chuburna to a high of 2.1 m above MSL in Sotuta, in the southeastern portion of the study area. The water-table maps show that groundwater flow is predominantly from south to north in the northern coastal region and north to south in the southern part of the study region, with a minor east-to-west component. The north-to-south direction is unusual and will be discussed below.

Water levels on the eastern side of the study area are higher than in the central region. This is probably a reflection of the spatial distribution of precipitation in the peninsula of Yucatán. The average annual precipitation along the eastern coast of the peninsula is on the order of 1,500 mm, whereas the average annual precipitation at Progreso (Figure 2) is 500 mm (INEGI, 1973).

Two north-south transects cross the ring of cenotes (Figure 3). Water level increases with distance from the coast for 40-60 km (San Ignacio-Kopoma transect) and for 30 km (Dzilam Gonzalez-Sotuta transect); but still farther south, water level decreases slightly until the transects cross the ring of cenotes. These patterns have been observed for more than two years (1987-1989). The north-to-south flow regime is caused by a high permeability zone known as the "ring of cenotes" (sink holes) that appears to isolate hydrogeologically the "Mérida Block" from the rest of the landmass to the south and east. The ring of cenotes is a 5-20 km-wide band that extends in a semicircle of approximately 80-90 km radius centered at Mérida (Marín *et al.*, 1991). The alignment of these cenotes appears in the geologic map published by the Instituto Nacional de Estadística, Geografía, e Informática (INEGI, 1983). The ring of cenotes, which is a remarkably regular circular arc, has recently been attributed to enhanced permeability associated with the Chicxulub Impact Crater formed at the limit of the Cretaceous/Tertiary boundary (Pope *et al.*, 1991; Hildebrand *et al.*, 1991; Sharpton *et al.*, 1992, 1993). This crater has a diameter on the order of 300 km, making it the largest impact structure on Earth. It is buried underneath 400 - 1100 m of Tertiary sediments. The only superficial evidence of the crater is the Ring of Cenotes. Evidence for high permeability in the ring is discussed elsewhere (Marín *et al.*, 1987, 1990; Perry *et al.*, in press). The ring acts as a complete or partial hydrogeologic boundary isolating the study area, by intercepting groundwater flow and discharging it to the sea (Marín *et al.*, 1987, 1990). The data presented in this paper were used to simulate groundwater flow in northwestern Yucatán, Mexico (Marín *et al.*, in review).

## POTENTIAL FOR GROUNDWATER CONTAMINATION

Mérida, the largest city in the peninsula, is of special interest. The population in this city is greater than 500,000 making it a critical area for water management practices. In Mérida, the limestone bedrock is typically exposed on the surface. The upper part consists of a hard impermeable caliche layer with cracks which allow rapid infiltration; underneath this layer there is an unsaturated zone of 8-12 m, below which there is a freshwater lens with an approximate thickness of 45 m, underlain by saltwater intrusion. Thus, the aquifer is threatened from above by pollution and from below by saltwater upconing. Industrial supply wells are finished at approximately 35 m below the surface and dump waste water in the deeper part of the aquifer, at a depth of approximately 200 meters (J. Vidal, oral comm). All wastes generated in the City of Mérida also end up in the aquifer without treatment.

There are no municipal sewage treatment plants in the area. Typically, houses in Mérida have pits dug three meters below the house, from which untreated sewage infiltrates into the aquifer. Most of the houses in rural areas and in the smaller cities use shallow wells. These wells typically are hand-dug, have an approximate diameter of 1 m, and are finished 0.5-1.0 m below the water table. Often they are tightly cemented to the caliche surface; some wells have no lips at all. Because they are hand-dug, they tend to be located on the lowest point in the property. Thus, many of these wells also serve as direct recharge points for surface storm runoff. In both rural and urban settings, the inhabitants often keep domestic animals on their property. Furthermore, many inhabitants do not have latrines or other sanitary facilities. As a result, much of the combined human and animal waste produced in these communities flows by direct paths to the water-table, contaminating the aquifer. Lips around wells delay the entry of organic waste into the aquifer, permitting some biological degradation, but they do not prevent organic waste from reaching the aquifer. Serious pollution of village water-table wells by nitrates occurs throughout the peninsula. In one area, measured $NO_3^-$ concentrations in village wells ranged from 4 mg/l to more than 70 mg/l (Pacheco, 1984). A potentially larger health risk is posed by the careless use of organic pesticides and herbicides, some of which may be carcinogenic at very low concentrations (Miller, 1990; Hoar *et al.*, 1986, Lee and Randall, 1984). Widespread pollution is accompanied by a host of endemic water-borne diseases. Until recently, and perhaps, more than 40% of the deaths of children under six years old were attributable to gastrointestinal diseases caused by pathogens transported by

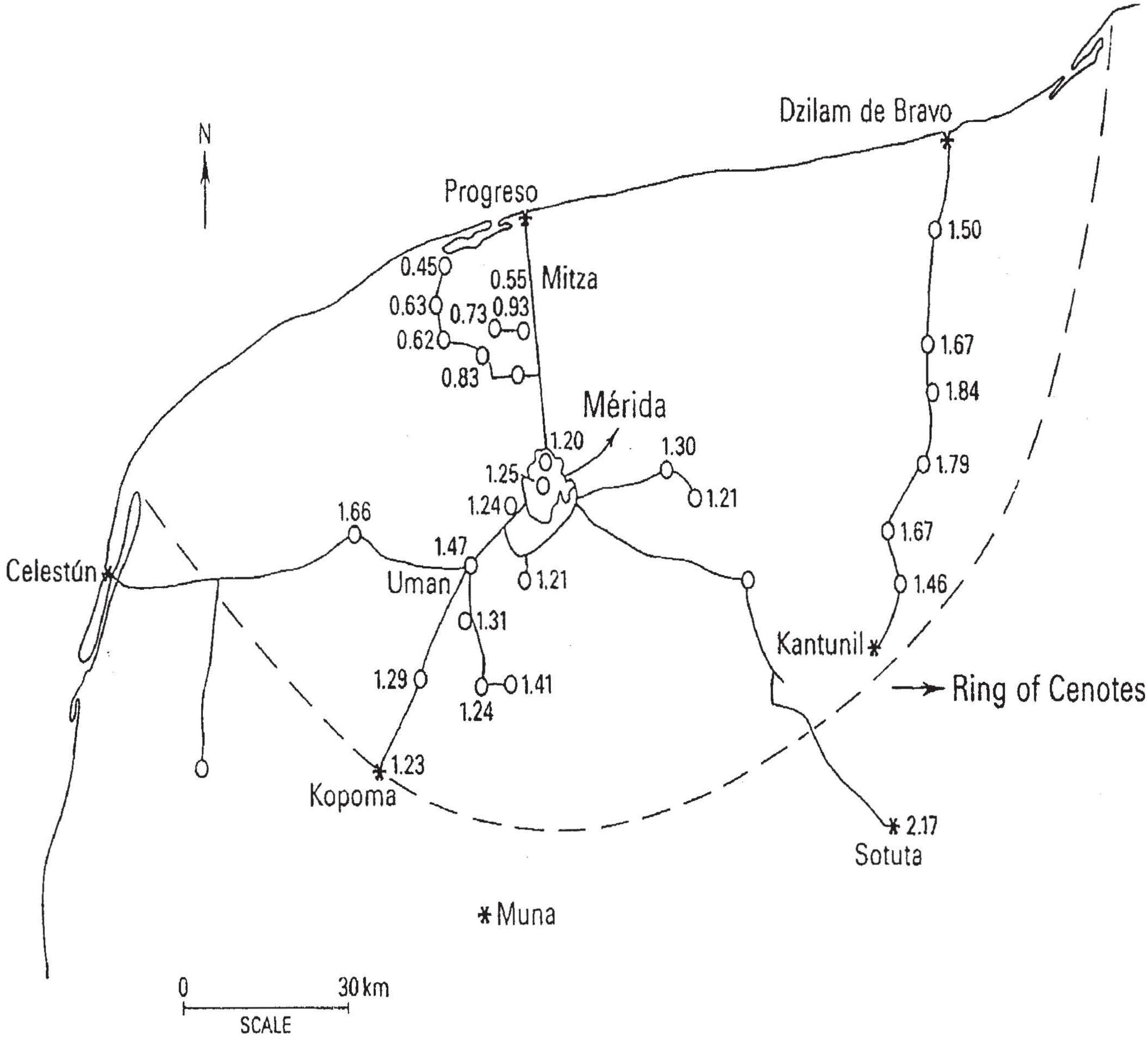


Fig. 2. Water-table map, July, 1987. Heads are in meters above MSL. The continuous lines are highways. The shaded region delineates the approximate location of the Ring of Cenotes. Note the low elevation of the water-table above MSL and the very low hydraulic gradient (avg. 10 mm/km, over the region).

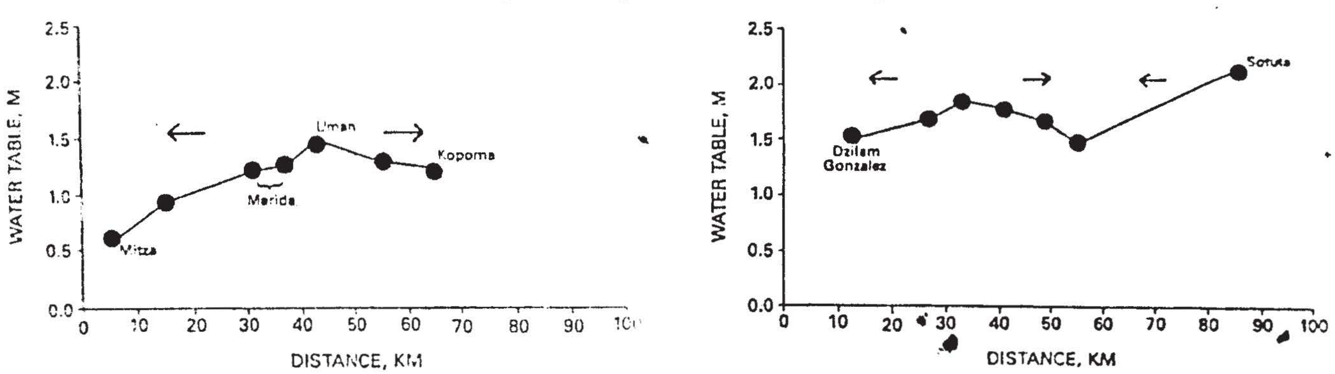


Fig. 3. North-south cross-section for the July, 1987, water-table map. a) San Ignacio-Kopoma transect. Water levels increase with distance away from the sea. Water levels drop at Kopoma, located in the Ring of Cenotes. b) Dzilam-Sotuta transect. This transect shows a similar behavior as the previous one. However, water levels drop at Kantunil (located in the Ring of Cenotes) and continue to increase south of the Ring.

groundwater (Doehring and Butler, 1974). The rainy season (May-September) is also known as the "diarrhea season" (Marín, 1990).

## CONCLUSIONS

The water-table map for northwestern Yucatán shows that the hydraulic gradient is very low, suggesting very high permeabilities. In combination with the lack of soil filtration, this makes the aquifer highly vulnerable to contamination. The freshwater lens is thin, with an approximate thickness of 45 meters underneath the city of Mérida. It is probably isolated hydrogeologically from the rest of the peninsula by the ring of cenotes. This should suggest that a sound water management scheme for the area should rigorously monitor industrial or other activities to assure that they will not irreversibly contaminate the groundwater within the Mérida Block.

## ACKNOWLEDGEMENTS

Marín was supported with an Illinois Minority Graduate Incentive Program fellowship and with a Doctoral Completion Award from Northern Illinois University. Field support was granted by the American Association of Petroleum Geologists, the American Geological Institute, the Geological Society of America, the National Speleological Society, Sigma-Xi, and the Department of Geology at Northern Illinois University. Marín also acknowledges support from Dirección General de Asuntos del Personal Académico-UNAM (IN106891) and from Consejo Nacional de Ciencia y Tectonología (9302-+2057).

Personnel from the Universidad Autónoma de Yucatán provided logistical support. Our thanks are expressed to M. Villasuso, J. Gamboa, and V. Coronado.

Perry acknowledges support from the Northern Illinois University Graduate School Research Fund, the Petroleum Research Fund, and the National Science Foundation (EAR 8508173).

## BIBLIOGRAPHY

BACK, W. and W. HANSHAW, 1970. Comparison of chemical hydrogeology of the carbonate peninsulas of Florida and Yucatán. *J. Hydrol., 10,* 330-368.

BACK, W. and J. M. LESSER, 1981. Chemical constraints of groundwater management in the Yucatán Peninsula, Mexico. *In:* L.R. Beard, ed., Water for Survival. *J. Hydrol., 51,* 119-130.

DOEHRING, D. O. and J. H. BUTLER, 1974. Hydrogeologic constraints on Yucatán's development. *Science, 186,* 591-595.

DURAZO, J., S. GAONA, J. TREJO and M. VILLASUSO, 1980. Observaciones sobre la interfase salina en dos cenotes del centro-norte de Yucatán. XXIII Congreso Nacional de Investigación en Física, Sociedad Mexicana de Física, Guadalajara, Jalisco, 24-28 de noviembre.

ECHEVERRIA, E., 1985. Unpublished report on file, INEGI, Paseo Montejo, Mérida, Yucatán, México.

ECHEVERRIA, E. and C. CANTUN, 1988. Unpublished report on file, INEGI, Paseo Montejo, Mérida, Yucatán, México.

GAONA, S., M. VILLASUSO, J. PACHECO, A. CABRERA, J. TREJO, T. GORDILLO DE ANDA, C. TAMAYO, V. CORONADO, J. DURAZO and E. C. PERRY, 1985. Hidrogeoquímica de Yucatán 1: perfiles hidrogeoquímicos profundos en algunos lugares del acuífero del noroeste de la Península de Yucatán. Boletín, Instituto de Geofísica, UNAM, México.

HILDEBRAND, H. A., G. T. PENFIELD, D. A. KRING, M. PILKINGTON, A. CAMARGO, Z., S. B. JACOBSEN and W. V. BOYNTON, 1991. Chicxulub Crater: A possible Cretaceous-Tertiary boundary impact crater on the Yucatán Peninsula, Mexico. *Geology, 19,* 867-871.

HOAR, S.K., A. BLAIR, F.F. HOLMES, C.D. BOYSEN, R.J. ROBEL, R. HOOVER and J. F. FRAUMENI Jr., 1986. Agricultural herbicide use and risk of lymphoma and soft-tissue sarcoma. *J. Amer. Med. Assoc., 256,* 1141-1146.

INEGI, 1973. Carta Yucatán, Precipitación Anual para la Península de Yucatán, 1: 1 000 000.

INEGI, 1983. Carta Yucatán, Geología, 1:1 000 000.

LEE, M.H., J.F. RANDSELL, 1984. A farmworker's death due to pesticide toxicity, a case report. *J. Toxic. and Environ. Health, 14,* 238-246.

MARIN, L. E., 1990. Field investigations and numerical simulation of the karstic aquifer of northwest Yucatán, Mexico. Ph.D. thesis, Northern Illinois University, DeKalb, IL, 183 p.

MARIN, L. E., E. C. PERRY, C. BOOTH and M. VILLASUSO, 1987. Hydrogeology of the northwestern Península of Yucatán, Mexico. *EOS, Transactions, Amer. Geophys. Union, 69,* 16, 1292.

MARIN, L.E., E.C. PERRY and H.I. ESSAID. Numerical simulation of groundwater flow in the karstic aquifer of northwestern Yucatán, Mexico. In internal review, United States Geological Survey.

MILLER, J. C., 1990. Relative vulnerability of the Floridian and Yucatán aquifers to groundwater contamination. Extended abstract, Simposio Internacional sobre Planeación, Manejo e Investigación de los Recursos Hidráulicos, Universidad Autónoma de Yucatán, Mérida, Yucatán, México, Jan. 24-26.

PACHECO, J. G., 1984. Evaluación del contenido de nitratos del agua subterránea en una región rural al norte de la Península de Yucatán, M.S. thesis, Facultad de Ingeniería, Universidad Autónoma de Yucatán, Mérida, Yucatán.

PERRY, E. C., J. SWIFT, J. GAMBOA, A. REEVE, R. SANBORN, L. E. MARIN and M. ViLLASUSO, 1989. Environmental aspects of surface cementation, north coast, Yucatán, Mexico. *Geology, 17,* 818-821.

PERRY, E. C. and L. E. MARIN, 1990. Possible adverse impact of coastal development on the Yucatán Aquifer, Mexico. Simposium Internacional sobre Planeación, Manejo e Investigación de los Recursos Hidraúlicos, Mérida, Yucatán.

PERRY, E. C., L. E. MARIN, J. McCLAIN and G. VELAZQUEZ. The Ring of Cenotes sinkholes) northwest Yucatán, Mexico: its hydrogeologic characteristics and possible association with the Chicxulub Impact Crater. In press, Geology.

POPE, K.O., A.C. OCAMPO and C.E. DULLER, 1991. Mexican site for K/T impact crater? *Nature, 351,* 105.

SHARPTON, V. L., G. B. DALYMPLE, L. E. MARIN, G. RYDER, B. C. SCHURAYTZ and J. URRUTIA-FUCUGAUCHI, 1992. New links between the Chicxulub impact structure and the cretaceous-tertiary boundary. *Nature, 359,* 819-821.

SHARPTON, V. L., K. BURKE, A. CAMARGO, S. A. HALL, L.E. MARIN, G. SUAREZ, J.M. QUEZADA, P. D. SPUDIS and J. URRUTIA-FUCUGAUCHI, 1993. The gravity expression of the Chicxulub multiring impact basin: size, morphology, and basement characteristics. *Science, 261,* 1564-1567, 1993

VIDAL, JORGE, 1992. Oral communication, December.

---

L.E. Marín[1] and E.C. Perry[2]

[1] *Instituto de Geofísica-UNAM, Cd. Universitaria, 04510 México, D.F., México.*

[2] *Visiting professor, Department of Geology, Northern Illinois University, DeKalb, Illinois, 60115 USA.*