Hydrogeological investigations and numerical simulation of groundwater flow in the karstic aquifer of northwestern Yucatan, Mexico

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ABSTRACT
A freshwater lens underlain by saltwater exists beneath the entire northern Yucatan karst plain, Mexico. Water levels recorded in this plain, during the period June 1987 - April, 1989, were used to map the water table, identify inland hydrogeologic boundaries, and estimate the thickness of the freshwater lens using the Ghyben-Herzberg relation. The water table under most of northwestern Yucatan is less than two meters above mean sea level. Normal dry/wet seasonal variations during the period of study were about 0.5 m. The Ghyben-Herzberg estimated thickness of the freshwater lens ranges from a low of 18 m near the coast to more than 80 m in the southeastern section of the study area.

A quasi-three dimensional finite-difference model, in which freshwater and saltwater flow are separated by a sharp interface, was used to simulate groundwater flow in the study area. The conceptual model that best reproduces measured water levels is a two-layer system with a deep layer of high hydraulic conductivity (1 m/s) overlain by a layer of lower hydraulic conductivity (0.1 m/s). The layer of high hydraulic conductivity corresponds to a zone where chemical erosion probably occurred between 35 and 120 thousand years ago, when sea level oscillated around a level about 50 m below the present level. Simulation of a breach in a shallow coastal aquitard showed that proposed construction, which would cause such a breach, could result in a substantial reduction of the water resources of the Yucatan plain.

INTRODUCTION
The aquifer in northwestern Yucatan contains a freshwater lens that floats above a denser saline water wedge 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). Recently, it’s been shown to penetrate more than 90 km (Perry et al., 1995; Steinich and Marín, 1996). The aquifer, which is unconfined except for a narrow band along the coast (Perry et al., 1989), is the sole freshwater
source in northwestern Yucatan. Development of industry and agriculture, and other land use changes, pose a potential threat to the quantity and quality of freshwater resources on the Yucatan peninsula. This report documents field investigations used to construct a groundwater flow model developed for the purpose of increasing our understanding of the groundwater system, and estimating the hydraulic response to aquifer stresses. The groundwater flow model should also be useful in detailed studies of saltwater intrusion, and tracking of contaminants from industrial or agricultural sources. Ultimately it should form a basic information source for local groundwater resources management.

**Objectives**
The objectives of this research were to: 1) describe the hydrogeologic system for northwestern Yucatan including the identification of hydrogeologic boundaries; 2) determine whether it was possible to simulate groundwater flow using a sharp interface model in this karstic aquifer; 3) examine how the system responds to stresses such as breaching of the coastal aquitard.

**Previous studies**

The hydrogeology of the eastern coast of the Yucatan Peninsula has been studied extensively by Back and Hanshaw (1970), Weidie (1982), Stoessell et al., (1990), Moore et al., (1992) but the hydrogeology of the northwestern part of the Yucatan Peninsula has received little attention until recently (Perry et al., 1989, 1990; Marín, 1990; Marín et al., 1990; Steinich and Marín, 1996, & in press). Back and Hanshaw (1970) called attention to important characteristics of the hydrogeology of Yucatan such as the high permeabilities found in this area and the presence of a saltwater wedge that extends tens of kilometers inland. They observed that no integrated drainage system existed in northwestern Yucatan, and that no rivers exist in this part of the Peninsula. They inferred a low gradient of the water table (based on the very low topographic relief), a high permeability of the aquifer, which they suggested probably contains large interconnected openings, they assumed that no confining beds were present (due to the thin fresh water lens) and suggested that ground water flowed in a north-northeastern direction. The upper geologic section of the northern Yucatan Peninsula consists of nearly flat-lying carbonate and evaporitic rocks and sediments (Lopez Ramos, 1973).

Papers by Stoessell et al (1990) and by Herman and Back (1986) discuss hydrogeochemical and hydrogeologic features of the east coast of the Yucatan peninsula (which differs significantly in its hydrogeologic characteristics from the north coast). Aspects peculiar to the hydrogeology of the northwestern Yucatan coast have been described by Perry et al., (1989, 1990, 1995; Steinich and Marín, 1996, and in press). One of the main differences between the east coast and the north coast is that, in northwestern Yucatan, there is a narrow, chemically-produced aquitard that separates the
freshwater lens below from unconfined saline groundwater above. A summary of the permeability characteristics of the northwestern Yucatan Peninsula are presented in Table 1.

Chappell and Shackleton (1986) have shown that sea level oscillated at approximately 50 m below present mean sea level (MSL) between 35,000 and 120,000 years before the present. This suggests that considerable secondary cavern porosity and permeability may have developed (in a zone below present sea level) during this late Pleistocene period of stasis. This further suggests that there may be a layer of high permeability at depth. There is limited evidence of a high permeability layer 50 m below MSL (Gmitro, 1987; Rosado, oral com., 1987; Marín, 1994).

RESULTS AND DISCUSSION: HYDROGEOLOGY

Hydrogeologic setting

We propose that the northwestern Yucatan Peninsula contains three somewhat overlapping zones (Fig. 1) whose major differentiating characteristic is the type of permeability that dominates in each (Table 1). A large and hydrogeologically homogeneous part of the northwest Peninsula, here labeled "Merida Block," lies within a semicircle of approximately 180-km-diameter centered about 35 km north-northeast of Merida. This is bounded by the second zone, which has become known as the "Ring of Cenotes" (cenote = sinkhole), a 5-20 km-wide band (Fig. 2; Marín et al., 1990). The hydrogeologic properties and its significance is described in the section describing the hydrogeologic boundaries. The third zone is the north coast confining layer which is distinguished by a near-surface aquitard that affects both the piezometric head, and the thickness of the coastal edge of the freshwater lens.

The north coast confining layer is a unique, chemically produced layer that forms a band several km wide along much of the north Yucatan coast from Celestun to the east of Dzilam Bravo (Fig. 1) (Perry et al, 1989; Tulaczyk et al, 1993; cf Smart and Whitaker, 1990; Perry et al, 1990). Perry et al (1989) postulated that the 0.5-m-thick confining layer, found at depths that range from the surface to 5 m below, has been produced behind the north coast dune in a zone (tsekel) where the freshwater table intersects and moves seasonally across the gently sloping (approximately 20 cm/km) land surface. Here, CaCO₃-saturated groundwater precipitates calcite in small pore spaces of exposed rock (but not in large cavities such as the drowned cenotes that form springs (petenes) Marín et al., 1988). The result of this precipitation is a thin, nearly impermeable calcrete aquitard. Presumably, this layer has propagated inland during the last 5-6000 years of slowly rising sea level (Coke, et al., 1990). The coastal confining layer causes a thickening of the freshwater lens (Perry et al, 1989; Marín, 1990; Tulaczyk et al, 1993) so that in the north coast fishing port of Chuburna (for example), just west of Progreso (Fig. 1), the lens has a calculated thickness of about 18 m at the shore.
A first-order topographic survey of most of the northwest study area (Echeverria, 1985; Echeverria and Cantun, 1988) makes possible the determination of the extremely flat hydraulic gradients (on the order of 5-10 mm/km (Marín et al., 1987; Marin, 1990)) of the area. The low gradient, which is difficult to measure, suggests very high permeabilities. Sampling points were the shallow private wells present in many towns and cities. These wells typically are hand-dug, have an approximate diameter of one meter, and are finished 0.5 - 1.0 meter below the water table.

From this survey, Marín (1990) established water-level elevations for a network of more than 100 points. Water levels at these stations were measured one to six times (July, 1987; January, April, July, and September, 1988; April, 1989); and water table maps of northwestern Yucatan have been prepared for those dates. Figure 2 shows the water table for July, 1987. This map was chosen because it is representative of the water table in Yucatan for the study period. Measured heads in northwestern Yucatan range from a low of 0.45 m above MSL near Chuburna to a high of 2.1 m above MSL in Sotuta on the southeastern portion of the study area. Depth to the water table ranges from the surface along the coast to 18 meters at Sotuta (Fig. 1) 60 km inland. During the period of observation, variations in the water table between the dry and wet seasons ranged from 5 to 61 cm during the study period (which was less than two years) that water levels were measured. Steinich and Marín (in press) have identified an area in the aquifer were there are important variations in the water levels within a short period of time. They have identified this zone as the “Highly Variable Zone” (Fig. xx). Water levels on the eastern side of the study area are higher than those in the central region. This is probably a reflection of the spatial distribution of precipitation on the Yucatan Peninsula. 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 (Fig. 1) is 500 mm (INEGI, 1981). Evapotranspiration has been reported to be 90 -95% of the precipitation that falls on the Yucatan Peninsula (INEGI, 1983).

Hydrogeologic boundaries

Two hydrogeologic boundaries were identified: the Ring of Cenotes and the Gulf of Mexico. The alignment of cenotes appears in the geologic map published by the Instituto Nacional de Estadística, Geografía, e Informática (INEGI, 1983). The Ring of Cenotes, (hereafter "Ring") which is a remarkably regular circular arc, has recently been attributed to enhanced permeability associated with a large extraterrestrial impact structure formed at the end of the Cretaceous Period (Pope et al., 1991; Perry et al., 1995; Hildebrand et al., 1991; Sharpton et al., 1992, 1993; Hildebrand et al., 1995). The Ring is located between the second and the third ring of the Chicxulub Multiring Impact Basin as defined by Sharpton et al (1993). The association of the Ring with the buried impact structure bears on the regional hydrogeology because it implies that the high permeability of the Ring are ultimately controlled by relatively deep subsurface geologic features that are not subject to
direct observation (Perry et al., 1995; Steinich and Marín, 1996). The hypothesis of deep control over permeability is supported by the observation that at least one cenote of the Ring (Xcolak, Fig. 1) extends vertically for 120 m below the present water table. Presumably, such a vertical shaft could only develop within the vadose zone where downward movement of water prevails (Noel and Choquette, 1987). This implies an extensive, deep zone of high permeability associated with a paleo-water table much lower than the present water table.

The Ring is a zone of high permeability as shown by: 1) transects characterized by a decline in water levels toward the ring and 2) high density of springs and breaks on sand bars at the intersection of the ring with the sea. Thus, the Ring affects groundwater flow by diverting some or all of the groundwater flowing across the Ring and discharging it to the sea (Marín, 1990; Marín et al., 1987, 1990). Evidence supporting this hypothesis also comes from Perry et al (1995) and from Velázquez (1995) who found a similar Cl⁻/SO₄²⁻ ratio in the Ring near Kopoma as well as near Celestun and from Steinich and Marín (in press-a) who determined that the Ring south of Merida is a high permeability zone using electrical methods. Since little question remains that the Ring of Cenotes is related to the buried Chicxulub Impact Structure, it can be presumed that the high permeability zone extends hundreds of meters into the subsurface. This observation is corroborated with the geochemical and geoelectrical data (Perry et al., 1995; Velázquez, 1995; Steinich and Marín,). The origin of this Ring is discussed elsewhere (Pope et al., 19xx; Hildebrand et al., 1995; Perry et al., 1995).

The Gulf of Mexico forms a natural hydrogeologic boundary of the study area on the north and west. The Ring, which acts as a high permeability zone, affects groundwater flow to the south and east. This was established by three transects: two north-south transects of the study cross the Ring (Fig. 2 a & b). Water levels increase with distance away from the coast for 40-60 km (San Ignacio-Kopoma transect) and for 30 km (Dzilam Gonzalez-Sotuta transect); but still farther south, water levels decrease slightly until the transects cross the Ring. The third transect, a west-east transect located on the northeastern section of the study area shows the same behavior. These patterns were observed for almost two years (1987-1989). These results support the hypothesis that the Ring is a zone of high permeability with respect to its surroundings. The Ring does not, however, affect groundwater flow equally throughout the Ring. Steinich et al (1995) have identified the ground water divide within the Ring of cenotes with a study that combined hydrogeology, and geochemistry. Figure 1 shows a mound along the southeastern portion of the study area suggesting that water may flow into the study area near Kantunil from a bordering region of higher recharge about 55 km from the coast as well as from the groundwater divide (Marín, 1990; Steinich et al., 1995; Steinich and Marín, in press).

Geometry of the Freshwater Lens
The thickness of the freshwater lens was estimated from measured water levels using the Ghyben-Herzberg relation, which balances a column of seawater with an equivalent fresh/saltwater column. This relation assumes that simple hydrodynamic conditions exist, that the boundary separating the fresh and saltwater layers is sharp, and that there is no seepage face (Freeze and Cherry, 1979):

\[ z = \frac{\rho_f}{(\rho_s - \rho_f)} \]  

Where: \( z \) = thickness of the freshwater lens from the interface to mean sea level (MSL)  
\( \rho_f \) = density of freshwater, assumed to be 1.000 g/cm\(^3\)  
\( \rho_s \) = density of saltwater, assumed to be 1.025 g/cm\(^3\)  
\( h_f \) = head above MSL

Substituting the values for \( \rho_f \) and \( \rho_s \) one has:

\[ z = 40 * h_f \]  

Thus, the model depth to the interface is 40 times the freshwater head.

Water elevation data of July, 1987, was used to calculate the thickness of the freshwater lens. July measurements were chosen because that is about the middle of the May-through-September rainy season and thus about midway through the annual recharge cycle. The postulated geometry of the freshwater lens is shown in Figure 3. Note that the thickness of the lens should vary from a low of 18 m near Chuburna along the coast to more than 80 m in Sotuta, located in the southeastern portion of the study area. Limited data (Table 2) suggest that the Ghyben-Herzberg relation does not significantly overestimate the thickness of the freshwater lens in northwestern Yucatan. Recent work (Steinich and Marin, 1996) in which electrical resistivity surveys were correlated with water level measurements have shown that the Ghyben-Herzberg relation holds well for northwestern Yucatan.

Conceptual model

Following is a description of the conceptual model used to simulate ground water flow in northwestern Yucatan: The aquifer is unconfined except for a narrow band parallel to the coast. This confining layer extends on the order of five km seaward. Recharge occurs throughout the aquifer, with water flowing from south to north, except for a zone parallel to the Ring of Cenotes, where the ground water flow direction is reversed (Fig. xx); discharge from the aquifer occurs throughout the coast, with a higher concentration occurring at the two intersections of the Ring of Cenotes with the sea. The aquifer was assumed to be heterogeneous with the Ring of Cenotes being a higher
permeability zone (one order of magnitude higher than the surrounding area). The aquifer was assumed to behave as an equivalent porous media. The aquifer was simulated using a two layer model with a layer of high permeability 50 m below the present surface. This assumption is justified since sea level has oscillated at this depth between the last 35,000 and 120,000 years. Recharge varied from 100-220 mm/yr. It follows the same spatial distribution as the precipitation, according to the INEGI (Anonymous, 19xx) maps.

NUMERICAL MODELING

The numerical model used for the Yucatan aquifer was SHARP, a quasi-three dimensional finite difference model for the simulation of fresh and salt-water flow in a coastal aquifer system (Essaid, 1990). Large Representative Elementary Volumes (REV’s) were used to treat the simulated area as an equivalent porous media (Marín, 1990). Gonzalez-Herrera (1992), who has subsequently attempted to model groundwater flow in this karstic aquifer, has also approached the problem using large REV’s. The model, SHARP, is quasi-three dimensional because it assumes horizontal flow in the aquifers and vertical flow in the confining layers. The model uses two governing equations, one for the freshwater domain and one for the saltwater domain. The fresh- and salt-water flow equations, coupled by the boundary at the interface, are integrated over the vertical dimension because it is assumed that there are no vertical gradients within the aquifer (Dupuit assumption). The model may be used for a heterogeneous, anisotropic, multi-aquifer system. The governing equations are (Essaid, 1990):

\[
\begin{align*}
\frac{\partial h_f}{\partial t} + n \alpha \frac{\partial h_f}{\partial t} + n \delta \left(1 + \delta\right) \frac{\partial h_s}{\partial t} &= \frac{\partial}{\partial x} \left( B_f K_{fx} \frac{\partial h_f}{\partial x} \right) + \frac{\partial}{\partial y} \left( B_f K_{fy} \frac{\partial h_f}{\partial y} \right) = Q_f + Q_g \\
\frac{\partial h_s}{\partial t} &= \frac{\partial}{\partial x} \left( B_s K_{sx} \frac{\partial h_s}{\partial x} \right) + \frac{\partial}{\partial y} \left( B_s K_{sy} \frac{\partial h_s}{\partial y} \right) = Q_s + Q_{1s},
\end{align*}
\]

where: \( h_f \) is the freshwater head, \( h_s \) is the saltwater head, \( S_f \) is the freshwater specific storage, \( S_s \) is the saltwater specific storage, \( B_f \) is the thickness of the freshwater zone, \( B_s \) is the thickness of the saltwater zone, \( t \) is time, and \( \delta \) is the ratio of the density of the freshwater and the difference between the salt/freshwater densities (\( \rho_f / \rho_s - \rho_f \)), \( K_{fx}, K_{sx} \) are the fresh and saltwater hydraulic conductivities in the x-direction (LT\(^{-1}\)); \( K_{fy}, K_{sy} \) are the fresh and saltwater conductivities in the y-direction (LT\(^{-1}\)); \( Q_f, Q_s \) are the fresh and saltwater source/sink terms (LT\(^{-1}\)); \( Q_{1f}, Q_{1s} \) are the fresh
and saltwater leakage terms \((LT^{-1})\); the parameter \(\alpha = 1\) for an unconfined aquifer, \(= 0\) for a confined aquifer, and \(n\) is the porosity.

**MODEL FRAMEWORK**

The study area was divided into a grid of 19 rows by 31 columns. The horizontal cell dimensions were 6.3 by 6.3 km. The model SHARP isolates the study area by imposing no-flow boundary conditions around it. Because the boundaries were considered remote to the particular area of interest, the City of Merida and the north coast, the condition was justified except for the northern boundary. The boundary condition to the north was a head-dependent boundary (Gulf of Mexico). For the head dependent boundary, equivalent freshwater-heads were specified for the offshore nodal areas. This allowed for the leakage of freshwater through the coastal aquitard to the sea.

For the purpose of these simulations, we assumed that: a) the aquifer is heterogeneous (with a higher permeability along the Ring), b) the aquifer is isotropic within each layer, c) the aquifer has a sharp interface dividing the fresh and saltwater, d) the aquifer is unconfined except near the coast, and e) the coastal confining layer described by Perry et al. (1989) starts 5 km from the coast and extends 5 km seaward.

Model calibration and sensitivity

Aquifer parameters selected from the literature were used initially for calibration of the model. These are given in Table 2. The range in hydraulic conductivity given by Reeve and Perry (1990) was determined for the aquifer near Chuburna, on the north Yucatan coast, 18 km west of Progreso. The value from Freeze and Cherry (1979) is their reported high value given for karstic terrains. The value from Back and Lesser (1981) was back-calculated from the annual average discharge they reported per kilometer of coast. The permeabilities listed by Gonzalez-Herrera (1984) are for laboratory cores taken from wells in Merida that ranged from 10 to 80 m deep. The laboratory core measurements are minimum values because they do not include the permeability associated with fractures, conduits, and caverns.

Model sensitivity analysis consisted of a determination of the effects of varying the following parameters with respect to the simulated water table elevations: depth of high permeability zone, recharge, hydraulic conductivities, and use of one vs. a two layer model (Marín, 1990). Better results were obtained using a two layer model. As part of the sensitivity analysis, it was determined that the two most important parameters where the distribution of the hydraulic conductivity and the recharge.

Best results were obtained using a two-layer model with a high permeability layer overlain by a layer of lower permeability. The thickness selected for the bottom layer was 300 m and that of
the upper layer was 50 m. Table 3 shows the parameters used for the steady-state solutions. Values for porosity and for storativity were used because the model was run in transient-state until steady state was achieved. The time needed to achieve steady-state under these conditions was 25 years. Geologically, the two layer model may be justified based on past sea level stands. We propose that a high permeability layer developed at approximately 50 m below MSL as a result of chemical erosion taking place at the paleo water table.

RESULTS AND DISCUSSION OF THE NUMERICAL SIMULATION

The predicted head distribution from the two-layer model compares favorably to the field data (Fig. xx). The hydraulic conductivity for both the x (E-W) and y (N-S) directions of the lower layer was 1 m/s and that of the upper layer 0.1 m/s (for both x and y directions) except for a 5 km band representing the Ring that was assigned a hydraulic conductivity of 1 m/s.

The steady-state simulation of groundwater flow in northwest Yucatan predicts a distribution of the saltwater intrusion that is consistent with field data (Fig. 7) (Back and Hanshaw, 1970; Perry et al., 1989, Steinich and Marín, 1996). In particular, the model predicts the collapse of the fresh/salt water interface in the southern part of the study area shown in Figure 7 (Steinich, et al., 1993; Perry et al, 1995).

Simulation of breached confining layer

The Mexican government is committed to develop tourist complexes and to build shelter ports along the coast of Yucatan. In order to do this, the confining layer described by Perry et al. (1989) will be breached, since the site where the shelter port is built must to be excavated. Perry et al. (1989) postulated that continued breaching of the confining layer would result in a partial collapse of the freshwater lens. This hypothesis was tested by comparing the results of a simulation with the confining layer and without it.

The breaching of the confining layer was simulated by setting a high leakance value. When a high leakance value is specified, the value in the offshore nodal area defaults to the constant head value given in the input file. In Figure 8, once the confining layer has been breached, the coastal nodal areas default to 0.25 m. Heads drop from approximately 55 cm to approximately 25 cm. If these predictions are accurate, this would result in a loss of approximately 12 m of freshwater at the coast. A head loss of 30 cm at Chuburna would result in a freshwater lens of only 10 m as opposed to the estimated 20 m present now (Perry, et al., 1989). According to this model, the thickness of the whole lens would decrease, with the most dramatic proportional impact along the coast (Fig. 8).

CONCLUSIONS
The water table maps for northwestern Yucatan reveal a very low hydraulic gradient, indicating very high permeabilities. The calculated thickness of the freshwater lens using the Ghyben-Herzberg ratio varies between a low of 18 m near the coast to over 80 m more than 60 km inland. The large REV's used for this study justified the use of a "porous media" approach. Both the field and the simulated data were consistent. Thus, the model was used in a predictive mode. This model supports the hypothesis that continued breaching of the confining layer may result in a loss of head of up to 30 cm in the coast. This loss would correspond to a freshwater loss of about 12 m. The Mexican National Commission on Water (CNA) has been informed about this model and the predictions made with it.

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FIGURE CAPTIONS

1) Location of study area and water table map for July, 1987
Heads are in meters above MSL. The continuous lines are highways. The shaded region delineates the approximate location of the Ring. Note the low elevation of the water table above MSL and the very low hydraulic gradient (avg. 10 mm/km, over the region). Also shown is the “Highly Variable Zone” and the ground water divide located within the Ring of Cenotes discussed in the text.

2) San Ignacio-Kopoma (a) and Dzilam - Sotuta transect (b)
Water levels increase with distance away from the sea. Water levels decrease as the Ring is intersected and continue to increase with distance away from the sea. Arrows indicate groundwater flow directions.

3) Estimate of the depth of the fresh/saltwater interface below MSL
Water levels from July, 1987, were used to estimate freshwater lens. Lens in northwestern Yucatan is less than 100 meters throughout studied area.

4) Confining layer

5) Measured vs. predicted heads, San Ignacio-Kopoma transect.
The dark squares are the field data for July, 1988, open squares are predicted heads from the two-layer model, and dark diamonds are predicted heads from the one-layer model.

6) Study area with model grid

8) Cross-section showing effect of breaching layer.
Maximum effect occurs at the coast (drop of 30 cm in head).
Table 1. Hydrogeologic characteristics of the Yucatan Peninsula.

<table>
<thead>
<tr>
<th>Location, Reference (s)</th>
<th>Geologic/Hydrogeologic Feature(s)</th>
<th>Physiographic Examples/Evidence</th>
<th>Hydrogeologic Characteristic(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Merida Block (Marín et al, 1990)</td>
<td>Intergranular permeability dominant. Block consists of highly permeable sedimentary rocks</td>
<td>Flat, immature karst surface, relatively few cenotes or caves</td>
<td>Flat water table (typical gradient 7-10 mm/km). Water table responds quickly and uniformly to seasonal or local precipitation.</td>
</tr>
<tr>
<td>Ring of Cenotes (Marín et al, 1990)</td>
<td>High cavern permeability inferred from abundance of cenotes and caves</td>
<td>Many cenotes aligned in a semicircle of radius 90 km</td>
<td>High groundwater flow; abundant springs where Ring intersects coast.</td>
</tr>
<tr>
<td>North Coast Confining Layer (Perry et al, 1989, 1990; Marín et al., 1988) [Note: overlies part of Ring of Cenotes and Merida Block]</td>
<td>Near-surface aquitard that divides saltwater (above) from fresh/brackish water (below). [Both water layers overly saltwater intrusion]</td>
<td>Petenes (flowing springs that are cenotes drowned by rising sea level/rising water table)</td>
<td>Confined water transmits tidal pressure for up to 20 km inland.</td>
</tr>
</tbody>
</table>
Table 2. Measured interface depths vs. those calculated using the Ghyben-Herzberg principle

<table>
<thead>
<tr>
<th>Location</th>
<th>Date</th>
<th>Head, m above MSL</th>
<th>Depth to interface below msl, m measured</th>
<th>Depth to interface below msl, m calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Merida *</td>
<td>4/89</td>
<td>0.96</td>
<td>37</td>
<td>38</td>
</tr>
<tr>
<td>Noc-Ac</td>
<td>4/89</td>
<td>0.84</td>
<td>&gt;27</td>
<td>34</td>
</tr>
<tr>
<td>Dzibilchaltun</td>
<td>7/89</td>
<td>0.73</td>
<td>&gt;27</td>
<td>28</td>
</tr>
<tr>
<td>MITZA</td>
<td>7/88</td>
<td>0.55</td>
<td>&gt;15</td>
<td>22</td>
</tr>
<tr>
<td>Labon</td>
<td>7/89</td>
<td>1.58</td>
<td>&gt;40, &lt;50</td>
<td>62</td>
</tr>
</tbody>
</table>

* (Depth to interface measured by Villasuso (pers. com.)

Note: the top of the interface was located at 27 meters at cenote Noc-Ac. The interface was not reached at Dzibilchaltun. MITZA is an artificial lake.

Table 3. Literature values for aquifer parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydraulic Cond.</td>
<td>$5 \times 10^{-1} - 3 \times 10^{-4}$ m/s</td>
<td>Reeve and Perry, 1990</td>
</tr>
<tr>
<td></td>
<td>$10^{-2}$ m/s</td>
<td>Freeze and Cherry, 1979</td>
</tr>
<tr>
<td></td>
<td>$10^{-2}$ m/s</td>
<td>Back and Lesser, 1981</td>
</tr>
<tr>
<td></td>
<td>$5 \times 10^{-3} - 10^{-6}$ m/s</td>
<td>Gonzalez-Herrera, 1984</td>
</tr>
<tr>
<td>Porosity</td>
<td>7 - 41%</td>
<td>Gonzalez-Herrera, 1984</td>
</tr>
<tr>
<td>Recharge</td>
<td>100-200 mm</td>
<td>Anonymous, 1980</td>
</tr>
</tbody>
</table>

Table 4. Parameters used for steady-state simulation of the aquifer in northwest Yucatan.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Layer 1 (lower)</th>
<th>Layer 2 (upper)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydraulic conductivity</td>
<td>$10^{-0}$ m/s</td>
<td>$10^{-1}$ m/s</td>
</tr>
<tr>
<td>Thickness</td>
<td>150</td>
<td>55 m</td>
</tr>
<tr>
<td>Storativity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Porosity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recharge</td>
<td>100-300 mm</td>
<td></td>
</tr>
<tr>
<td>Leakance</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>