# HYDROGEOLOGY AND CONCEPTUAL MODEL OF THE KARSTIC COASTAL AQUIFER IN NORTHERN YUCATAN STATE, MEXICO.

# [GEOHIDROLOGIA Y MODELO CONCEPTUAL DEL ACUIFERO CARSTICO COSTERO DEL NORTE DEL ESTADO DE YUCATAN, MEXICO]

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## RESUMEN

La franja costera del norte de la península de Yucatán (PY) se caracteriza por estar constituida principalmente por calizas del Terciario cubiertas por calizas del Pleistoceno y ambos ambientes geológicos combinados con sistemas palustres y lacustres conformados por ciénagas y estuarios donde hay bocanas conectadas al mar y rías por donde se descargan cantidades importantes de agua subterránea, como en Ría Lagartos y Celestún. A profundidad las calizas presentan estratos que se localizan entre 8 y 16 metros por debajo de la superficie del suelo o tzekel (zona palustre ubicada al sur de las ciénagas) por donde los flujos del agua subterránea transitan hacia la costa y descargan dentro de las ciénagas y mar adentro por debajo de la duna de arena, algunos de ellos como manantiales submarinos y acusan su presencia en la superficie marina por la fuerza o carga hidráulica de los mismos. La caliza superficial del Pleistoceno dentro de esta franja costera, que puede variar entre 5 y 10 kilómetros de ancho en la zona de estudio (Chuburna-Progreso-Chicxulub), forma una capa semi-confinante que impide que las aguas superficiales penetren directamente al agua subterránea y tengan contacto con ella. Se ha medido la fuerza o carga hidráulica del agua subterránea por debajo de esta capa confinante, que se encuentra ligeramente inclinada en forma de cuña hacia el sur y se encuentra por arriba del nivel medio del mar y del nivel del agua de las ciénagas y lagunas costeras. En esta franja costera se presentan al menos dos fenómenos hidrológicos de importancia que se han medido y actualmente son paradigmas: 1) no existe recarga al acuífero (agua subterránea) debido a la existencia de la capa semi-confinante y 2) no se pierde presión ni asciende la interfase salina si se rompe la capa confinante del Pleistoceno. La vulnerabilidad a la contaminación del agua subterránea en esta franja costera es menor que la del agua superficial salina de las ciénagas y esteros, debido a que esta capa confinante aísla el ingreso directo de contaminantes al agua subterránea que proviene desde tierra adentro a nivel regional y descarga dentro del mar.

**Palabras clave**: caliche; acuífero cárstico costero; intrusión salina

## SUMMARY

The coastal zone of northern Yucatan Peninsula (YP) is mainly constituted by Tertiary limestone, covered by Pleistocene limestone, where there exist swamps and estuary systems, locally called "rías", with mouths connecting them to the sea and hence being a way for an important amount of groundwater to discharge, like in Ría Lagartos and Celestún. These limestones have karstic layers located at depths from 8 to 16 meters below terrain surface. It is in these layers where groundwater mainly flows toward coast, passing below the sand dune and discharging in the sea in the form of submarine springs which in many cases manifest themselves on the marine surface depending on the hydraulic or piezometric fresh water head. The width of the superficial limestone within this coastal fringe, called "caliche", varies from 5 to 10 kilometers in the study zone (Chuburna-Progreso-Chicxulub). Its permeability is extremely low, so it constitutes a confining layer that impedes superficial waters to percolate toward groundwater. The hydraulic head of the groundwater below this confining layer is over the mean sea level and also over the swamp water level, coastal lagoons and estuaries. There are two important hydrogeological phenomena that occur in this coastal belt and are currently paradigms: 1) there is no recharge to the aquifer (groundwater) due to the existence of a Pleistocene semi-confining layer and 2) there is no loss of the aquifer pressure nor does the saline interface elevation due to the Pleistocene layer breaking. The groundwater pollution vulnerability within this coastal fringe is less than that of the superficial saline waters of swamps and estuaries, because of the low permeability of the caliche layer that impedes percolation.

**Key words**: caliche, coastal karstic aquifer, saline interface, vulnerability.

## INTRODUCTION

The contamination vulnerability of the aquifers depends both exclusively, of the type of the soil layer and the depth of the phreatic water level aquifer from the surface of the land1.

Auge (2004) writes that there are two schools of thought in the definition of the contamination vulnerability of the groundwater: one it is represented by that researchers that consider to the vulnerability like a referred property exclusively to the medium (aquifer type and cover, permeability, depth, recharge, etc.), without keeping in mind the incidence of the polluting substances (intrinsic vulnerability); and in the other trend, those who form a group that grant transcendence to the kind and amount of pollutant, besides the behavior of the medium (specific vulnerability). He classifies the contamination vulnerability of the aquifers in intrinsic and specific, he writes…"In the understanding of the undersigned, the *intrinsic vulnerability* has more utility in projects about planning both the use of the territory and water, particularly in the case of quality preservation of the resource, in locations where it is not affected neither perform practices like fertilization, pesticide application, watering, concentrated animal breeding, neither domestic, urban, or industrial activities, that could be affected for their intensity. The *specific vulnerability* includes the concept of risk partially, referring always to the danger of deterioration in relationship to polluting by specific substances."

It is possible that vulnerability studies to present day on the Yucatan Peninsula (to assess the specific vulnerability and not the intrinsic), even to establish safety measures, should not be the right tools to make planning decisions for the use and conservation of groundwater systems. Here is where there is a necessity to conduct studies that measure the geohydrological parameters and groundwater variables to generate conceptual models and mathematical simulation, to be able to provide planning resources for management and protection of the aquifers.

In the northern area of the Yucatan Peninsula, it has the presence of a recrystallized limestone surface layer that is semipermeable. This layer, confines the groundwater discharge to the sea. Perry (et al.1989) hypothesized that the breakdown of the semipermeable layer could cause the invasion of the sea into the aquifer, thus reducing the usable fresh water for human consumption. Marin (et al. 2003), implemented and calibrated a numerical model of the groundwater aquifer on the north plain of the Yucatan State, for predictive purposes. From this mathematical aquifer model exercise, they concluded that the rupture of the caliche layer would result in sustained reduction of the fresh water lens. This theoretical supposition has been used by the Yucatan State Government to restrict land uses along the northern coast, as a statement of safety measurement.

The caliche layer is a lens of material of recent geological deposition with impermeable properties that changes hydraulically the groundwater to a confined aquifer. If this impermeable layer is drilled and breaks its base, an elevation of the hydraulic head of the groundwater is produced, until it reaches a height over the mean sea level. Originally, the hydraulic head of the groundwater in this caliche layer, is lower than the mean sea level and that of the hydraulic head of the main aquifer that discharges below the sand dune in the sea.

The effect of the breakup of the confining layer is analogue to the effect of breaking a pressurized tube that is joined by a gauge that prevents water from spreading. The pressure inside the tube remains and the gauge only indicates the height of the water pressure.

To verify this phenomenon, it was carried out the diagnosis of the physicochemical conditions of water bodies or lagoons of Mitza Plant Products SA, located at Km 30 of the Merida-Progreso highway. These lagoons are the result of 30 years of stony material extraction. The diagnosis was carried out by measuring the water quality of the water bodies and the height of the water above the mean sea level.

The study area (Figure 1), is located at the northern part of the Yucatan Peninsula, and is conformed mainly for Pleistocene limestone and sand and mud materials of the Holocene, which constitutes the littoral. Below this surficial geological formation, a coastal aquitard of low permeability, so-called caliche, develops underlay. Its relief is less accidental and its origin is associated to descents and ascents of the seawater during the Lower Pleistocene -Holocene periods.

[1] The aquifers could be basically of 3 types: free, confined and semi-confined (semi-free). The phreatic water level is exclusively of the so-called free aquifers .

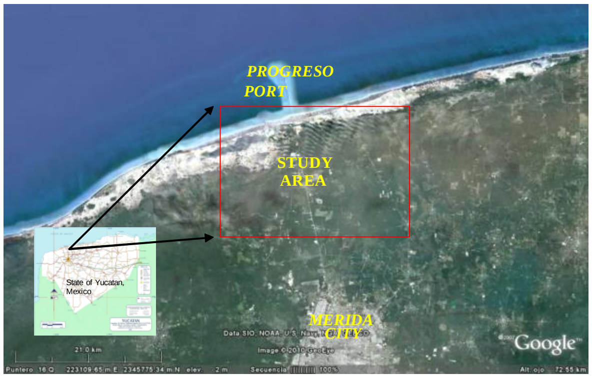



Figure 1: Study area location.

The aquifer of the study area has been defined as a semi-confined type; proof of this condition is the existence of springs in coastal lagoons and at sea. The main aquifer is free and can be recharged with rainwater that infiltrates and flows through cracks, fractures of the land, pores and cavities, and discharge in the coastal lagoons and the sea. Consequently, is a karstic coastal aquifer characterized by having a dual porosity type, where the water flows both through the pores of the rock matrix and through the cracks, fractures and solution conduits. Therefore, the flow rate varies depending on whether it is measured in preferential fractures and solution conduits or in the porous matrix.

At the coastline there is usually a narrow coastal cord, consisting of marine carries, separated from the mainland by mangrove area. Mangrove areas are formed by calcareous mud, clay and sand accumulated, that has connection with the sea through tidal channels of possible fracturing product. These land areas are subject to flooding and to the effect of the tides. The origin of the contributions of water in the basins of the mangrove is the rainfall, or the groundwater that flows through cave mouths or necks that crop in the ground by springs. On the other hand, the discharge of groundwater through coastal springs (locally known as "Ojos de Agua") within the watershed is an important contribution to be taken into account for purposes of the annual water balance in these systems.

The phenomenon of seawater intrusion is present in the underground system and appears as a wedge of sea water that penetrates below the thin freshwater aquifer from 10 to 20 m thick in the study area. This phenomenon is based on the principle that the hydraulic head of groundwater is governed by the position of sea level, and as they having different densities, fresh water floats on salt water. In this way, fresh water flowing through the aquifer exerts a thrust against saltwater from the sea.

Throughout the peninsular coastline we have present the phenomenon of water deficit due to evaporation and evapotranspiration, with lagoons of mangroves that consume large volumes of groundwater per year and therefore the water balance in this coastal belt are always negative. Water from precipitation that falls in this coastal part runoff to lakes and it is incorporated into the subsurface water that is flowing towards the shoreline below the sand dune.

In this study, it was conducted a hydrogeological (static) and geohydrological (dynamic model) investigation, focused mainly on measuring and mapping the physical boundary of the "semi-confining layer or confining of caliche" in respect to the coastline.

The objective of the present study is to characterize the aquifer system of the region and to prove that the caliche layer acts like a confined aquifer, and also, to map its extension towards the south. The results of the study will define the water quality of the main aquifer against the water bodies, due to the extraction of materials below groundwater level in the quarry of the Facility of Mitza.

## METHODOLOGY

Through the application of geological, geophysical and hydrogeological techniques, the conceptual model of the hydrodynamic performance of the local aquifer system is defined.

Because of all the groundwater in continents and islands on the planet converge towards the coastal areas, is the mean sea level (MSL) the basis or reference that allows the water flows to discharge zones, resulting into the Hydraulic Gradient (or slope of the groundwater level). This hydrogeologic parameter is obtained based on the network flow and it is a basic element to apply the laws of groundwater movement. The flow network was obtained based on the hydraulic head (or water potential), which is essential to level with millimetric precision all well points that are part of the piezometric monitoring network, taking as benchmark the mean sea level (MSL), which is transported to the measurement sites from a geodesic level bank BNPZ04, established by the National Institute of Statistics, Geography and Informatics (INEGI, 1989).

To identify the existence of the caliche layer, several techniques were used: geological field survey, geophysical survey (electrical method was used), exploratory controlled holes were drilled, and shallow boreholes constructed.

A monitoring network was used to measure the water level and quality of this semipermeable confining layer extension (Figure 2).

To demonstrate that the caliche layer breaking that confines the aquifer will not cause a rise in the sea water interface, two lines of hydrogeological research were followed: the measurement and the variation of the hydraulic head in all water sources versus the mean sea water level reference and the physicochemical water quality in the lagoons and boreholes drilled around the study area.

On the other hand, to define the conceptual model of the hydrodynamics of both the coastal aquifer and aquitard, was required to measure the influence of the tidal force in groundwater. This information was achieved using electronic devices that record data of water level in wells, boreholes, lakes, shallow or short boreholes, to preset time intervals. This continuous record of changes in the level of groundwater under the influence of tidal force allows, for a certain period of time, to obtain the model of groundwater flow and the preferential direction. Also should be quantified the flow volume into the aquifer.

## RESULTS

### Geology of the site

The study area outcrops from north to south, recent coastal sands, calcareous muds, clays and unconsolidated sands in the bottom of the marsh and Upper Pleistocene limestone capped by a compact caliche layer.

Limestone from the Miocene-Pliocene outcrops in the southern part of the study area, and are represented by a compact massive limestone with traces of fossil (Figure 3)

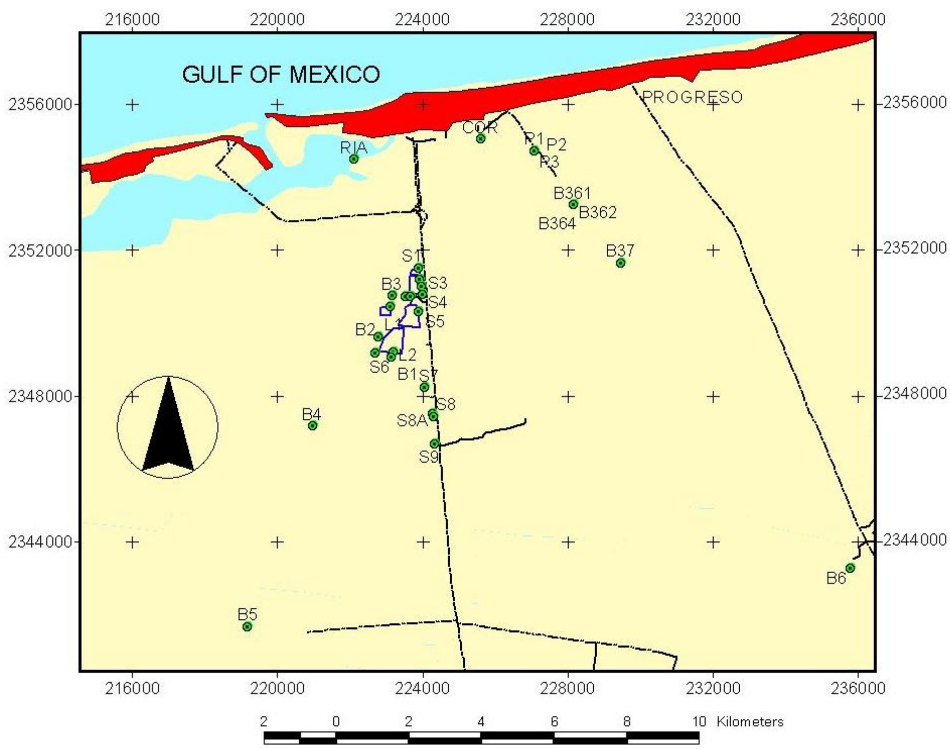
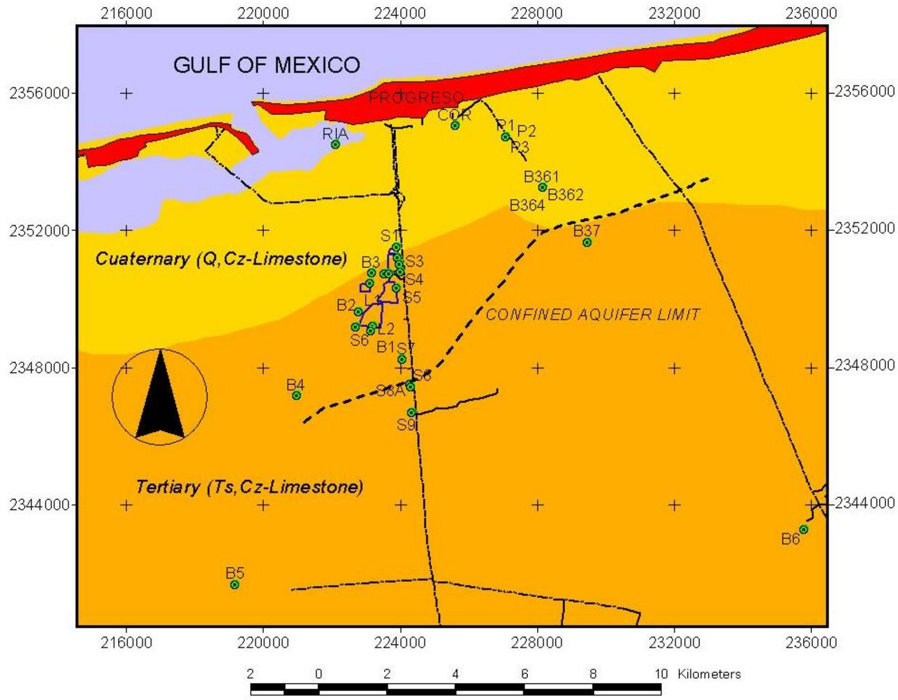



Figure 2. Location of boreholes, wells and lagoons




.Figure 3. Geology of the study area.

## Stratigraphy of the site

The stratigraphy sequence in the study area of Mitza, Flamboyanes and Ejido Paraiso, was defined by the analysis of drilling detritus collected during the construction of shallow or short boreholes. In this geological sequence appears first a layer of quarry material and has a thicknesses between 0,5 and 1,5 m according to the data collected from short boreholes S1 to S6 (Figure 4). Underlying this layer was determined a compact limestone layer with thickness between 0,5 and 2,9 m. The water level variations measured during the drilling of this layer indicates that it corresponds to an aquitard that confines the underlying aquifer; because of the water level ups and down above the mean sea water level reference. This unconfined layer extends to the south of the study area to the borehole S8a, located just at the south of the Fraccionamiento Flamboyanes border (Figure 4).

In the borehole S9, located more to the south, the surficial layer changes to an altered limestone with fossils and dissolution features with a thickness of 0,7 to 1,2 m. This limestone corresponds to the Carrillo Puerto formation of Miocene-Pliocene age. Consequently, it is assumed that the contact of these limestones is located between the boreholes S8 and S8A. Also it is assumed, that the geological contact between the surface rocks outcropping in the study area are the contact between the both unconfined and confined aquifers. Apparently, the contact between the two aquifers occurs at the boundary between the limestone of the Tertiary and Quaternary rocks.

Pleistocene layer is a limestone with shells, while the Miocene-Pliocene layer is a silty clay limestone (sahcab, mayan named). In the boreholes B4, B5, B6, B7 and P1 (Figure 2) was found a compact limestone formed by the shells and dissolution caves with thicknesses of 5 to 20 m.

## Well census

Piezometric monitoring and water quality network in the study area was formed by boreholes (20 m), drilled sounding t holes (3-4 m), springs in the marsh and lagoons (10 to 16 m). An important criterium of the distribution of the monitoring network has to see with a geometrical shape, in order to draw a logical flow net and to obtain the groundwater gradient.

The monitoring network was formed by 34 water sources: 15 exploratory boreholes, 10 sounding holes, 2 springs (La Ría and Corchito) and 5 piezometers at different depths, (Figure 2).

The following Table lists each of the points with their main characteristics.

The monitored system was geopositioned and leveled with millimetric-precision using satellital technology. The leveling was performed from a geodetic point of the National Institute of Statistics, Geography and

Informatics (INEGI). This point corresponds to a benchmark located in Progreso that is located in the beginning of the Malecon. Its elevation is 2.118 m above sea level and its coordinates are UTM 2356346.65 E and 223623,721 N in the 16Q. The elevation benchmark for each monitoring point is shown in column 4 of Data Table 1.

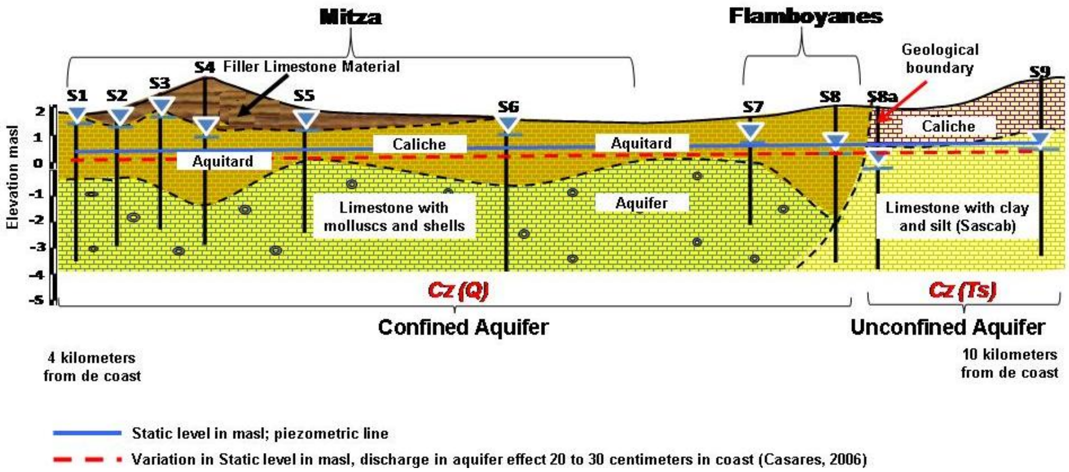



Figure 4: Hydrogeological section N-S.

Table 1. Water well census

| WATER TYPE | ID | UTM COORDINATES X | UTM COORDINATES Y | BENCHMARK masl | PHREATIC LEVEL meters | HYDRAULIC POTENTIAL masl | TOTAL DEPTH meters | DIAMETER inches | TIME | DISTANCE TO COAST meters | DATE |
|---|---|---|---|---|---|---|---|---|---|---|---|
| EL CORCHITO | COR | 225626.00 | 2355052.00 | 0.887 | 0.586 | 0.301 | --- | --- | 11:50 | 1065 | 24-nov-08 |
| LA RIA | RIA | 222121.00 | 2354502.00 | 0.829 | 0.722 | 0.107 | --- | --- | 12:25 | 1065 | 24-nov-08 |
| PIEZOMETER-1 | P1 | 227095.30 | 2354737.22 | 1.110 | 0.688 | 0.422 | 3.00 | 2.00 | 11:26 | 1700 | 24-nov-08 |
| PIEZOMETER-2 | P2 | 227095.30 | 2354737.22 | 1.148 | 0.720 | 0.428 | 10.57 | 2.00 | 11:30 | 1700 | 24-nov-08 |
| PIEZOMETER-3 | P3 | 227095.30 | 2354737.22 | 1.116 | 0.980 | 0.136 | 20.45 | 2.00 | 11:28 | 1700 | 24-nov-08 |
| PIEZOMETER-4 | P4 | 227095.30 | 2354737.22 | 1.128 | 0.966 | 0.162 | 16.53 | 2.00 | 11:27 | 1700 | 24-nov-08 |
| PIEZOMETER-5 | P5 | 227095.30 | 2354737.22 | 1.157 | 0.730 | 0.427 | 5.67 | 2.00 | 11:25 | 1700 | 24-nov-08 |
| PM-036-1 | B361 | 228161.29 | 2353249.15 | 0.644 | 0.220 | 0.424 | 6.69 | 6.00 | 11:00 | 3250 | 24-nov-08 |
| PM-036-2 | B362 | 228161.29 | 2353249.15 | 0.554 | 0.115 | 0.439 | 7.14 | 6.00 | 11:10 | 3250 | 24-nov-08 |
| PM-036-3 | B363 | 228161.29 | 2353249.15 | 0.817 | 0.385 | 0.432 | 7.32 | 6.00 | 11:02 | 3250 | 24-nov-08 |
| PM-036-4 | B364 | 228161.29 | 2353249.15 | 0.634 | 0.194 | 0.440 | 6.50 | 6.00 | 11:06 | 3250 | 24-nov-08 |
| PM0-36-5 | B365 | 228161.29 | 2353249.15 | 0.718 | 0.280 | 0.438 | 6.00 | 6.00 | 11:05 | 3250 | 24-nov-08 |
| PM0-36-6 | B366 | 228161.29 | 2353249.15 | 0.869 | 0.194 | 0.675 | 13.00 | 6.00 | 11:01 | 3250 | 24-nov-08 |
| SOUNDING-1 | S1 | 223900.77 | 2351525.24 | 0.740 | 0.316 | 0.424 | 4.50 | 2.00 | 13:05 | 4410 | 24-nov-08 |
| SOUNDING-2 | S2 | 223933.15 | 2351204.00 | 0.544 | 0.101 | 0.443 | 4.00 | 2.00 | 13:10 | 4700 | 24-nov-08 |
| SOUNDING-3 | S3 | 223981.69 | 2351008.73 | 1.180 | 0.725 | 0.455 | 3.77 | 2.00 | 13:15 | 4850 | 24-nov-08 |
| BOREHOLE 3 | B3 | 223173.36 | 2350764.21 | 1.266 | 0.839 | 0.427 | 12.88 | 6.00 | 13:55 | 4900 | 24-nov-08 |
| BOREHOLE 7 | B7 | 223543.85 | 2350751.40 | 0.907 | 0.475 | 0.432 | 17.89 | 6.00 | 13:58 | 5300 | 24-nov-08 |
| BOREHOLE 8 | B8 | 223663.66 | 2350726.54 | 0.806 | 0.474 | 0.332 | 17.26 | 6.00 | 14:00 | 5300 | 24-nov-08 |
| SOUNDING-4 | S4 | 224004.16 | 2350785.64 | 2.322 | 1.891 | 0.431 | 4.30 | 2.00 | 13:16 | 5407 | 24-nov-08 |
| LAGOON 1 | L1 | 223127.52 | 2350473.45 | 0.790 | 0.376 | 0.414 | --- | --- | 13:50 | 5556 | 24-nov-08 |
| PM-037 | B37 | 229479.09 | 2351660.93 | 2.036 | 1.568 | 0.468 | 21.28 | 6.00 | 10:45 | 5920 | 24-nov-08 |
| BOREHOLE 2 | B2 | 222792.26 | 2349632.86 | 1.709 | 1.274 | 0.435 | 18.05 | 6.00 | 13:45 | 6000 | 24-nov-08 |
| SOUNDING-5 | S5 | 223900.88 | 2350319.49 | 1.024 | 0.613 | 0.411 | 3.80 | 2.00 | 13:21 | 6000 | 24-nov-08 |
| SOUNDING-6 | S6 | 222697.93 | 2349186.65 | 1.048 | 0.607 | 0.441 | 4.50 | 2.00 | 13:40 | 6694 | 24-nov-08 |
| LAGOON 2 | L2 | 223193.47 | 2349225.31 | 0.807 | 0.384 | 0.423 | --- | --- | 13:35 | 6700 | 24-nov-08 |
| BOREHOLE 1 | B1 | 223163.23 | 2349079.12 | 1.860 | 1.444 | 0.416 | 17.30 | 6 | 13:28 | 6840 | 24-nov-08 |
| SOUNDING-7 | S7 | 224054.16 | 2348240.99 | 1.636 | 1.153 | 0.483 | 3.00 | 2.00 | 14:10 | 8000 | 24-nov-08 |
| BOREHOLE 4 | B4 | 220980.46 | 2347186.99 | 1.573 | 1.002 | 0.571 | 20.00 | 6.00 | 14:55 | 8100 | 24-nov-08 |
| SOUNDING-8 | S8 | 224288.61 | 2347530.92 | 2.345 | 1.868 | 0.477 | 4.90 | 2.00 | 14:16 | 8624 | 24-nov-08 |
| SOUNDING-8A | S8A | 224301.77 | 2347423.63 | 2.780 | 2.287 | 0.493 | 4.70 | 2.00 | 14:20 | 8773 | 24-nov-08 |
| SOUNDING-9 | S9 | 224339.94 | 2346692.99 | 2.705 | 2.172 | 0.533 | 4.20 | 2.00 | 14:29 | 9452 | 24-nov-08 |
| BOREHOLE 5 | B5 | 219192.94 | 2341681.22 | 4.371 | 3.705 | 0.666 | 20.00 | 6.00 | 15:30 | 13150 | 24-nov-08 |
| BOREHOLE 6 | B6 | 235793.16 | 2343274.84 | 4.267 | 3.504 | 0.763 | 18.60 | 6.00 | 10:15 | 16409 | 24-nov-08 |

**Water quality in lagoons and boreholes at Mitza**

In order to understand the physical and chemical characteristics of the ground water; profiles were run. The temperature, electrical conductivity, hydrogen potential, total dissolved solids, dissolved oxygen and oxido-reduction potential, were measured at intervals of 20 or 50 cm to get the detail of the aquifer water quality . The locations of the monitoring sites are shown in Figure 5.

These profiles were performed with an Quanta-Hydrolab Multiparameter Water Quality equipment. The parameter values information were plotted versus depth in the aquifer, taking the mean sea level of the groundwater as a reference level, in order to have a logical interpretation of these parameters and to identify dynamic phenomena that takes place into the aquifer. This method of plotting the data of the physico-chemical values permits to match with the same depth, position and thickness the geological layers.

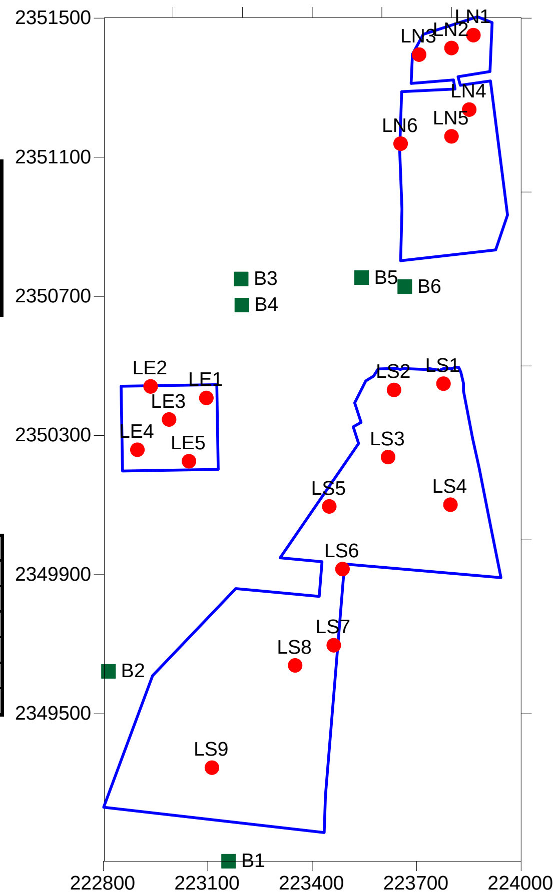
The measured data is considered representative of the aquifer wells because they have a small size compared with the size of the lagoons of the quarries. In the 3 lagoons were measured several water quality profiles at every 1 m, and from the beginning of the saline interface the intervals change to every 20 cm to get all the saline interface shape. In the northern lagoon (LN) were collected data at 6 sites, in the southern lagoon (LS) in 9 sites and in the western lagoon (LE) 5 sites (Figure 5).

**LE = WEST PONDS**

| I.D. | X | Y |
|---|---|---|
| LE1 | 223096 | 2350408 |
| LE2 | 222936 | 2350441 |
| LE3 | 222989 | 2350346 |
| LE4 | 222898 | 2350259 |
| LE5 | 223046 | 2350226 |

**B = BOREHOLES**

| I.D. | X | Y |
|---|---|---|
| B1 | 223160 | 2349076 |
| B2 | 222815 | 2349622 |
| B3 | 223196 | 2350750 |
| B4 | 223198 | 2350675 |
| B5 | 223542 | 2350754 |
| B6 | 223666 | 2350728 |




**LN = NORTH PONDS**

| I.D. | X | Y |
|---|---|---|
| LN1 | 223863 | 2351451 |
| LN2 | 223800 | 2351414 |
| LN3 | 223707 | 2351395 |
| LN4 | 223851 | 2351237 |
| LN5 | 223800 | 2351160 |
| LN6 | 223654 | 2351139 |

**LS = SOUTH PONDS**

| I.D. | X | Y |
|---|---|---|
| LS1 | 223777 | 2350449 |
| LS2 | 223635 | 2350431 |
| LS3 | 223618 | 2350238 |
| LS4 | 223797 | 2350101 |
| LS5 | 223449 | 2350096 |
| LS6 | 223487 | 2349916 |
| LS7 | 223462 | 2349697 |
| LS8 | 223351 | 2349639 |
| LS9 | 223112 | 2349345 |

Figure 5. Monitoring sites on the campus of Mitza Lagoons

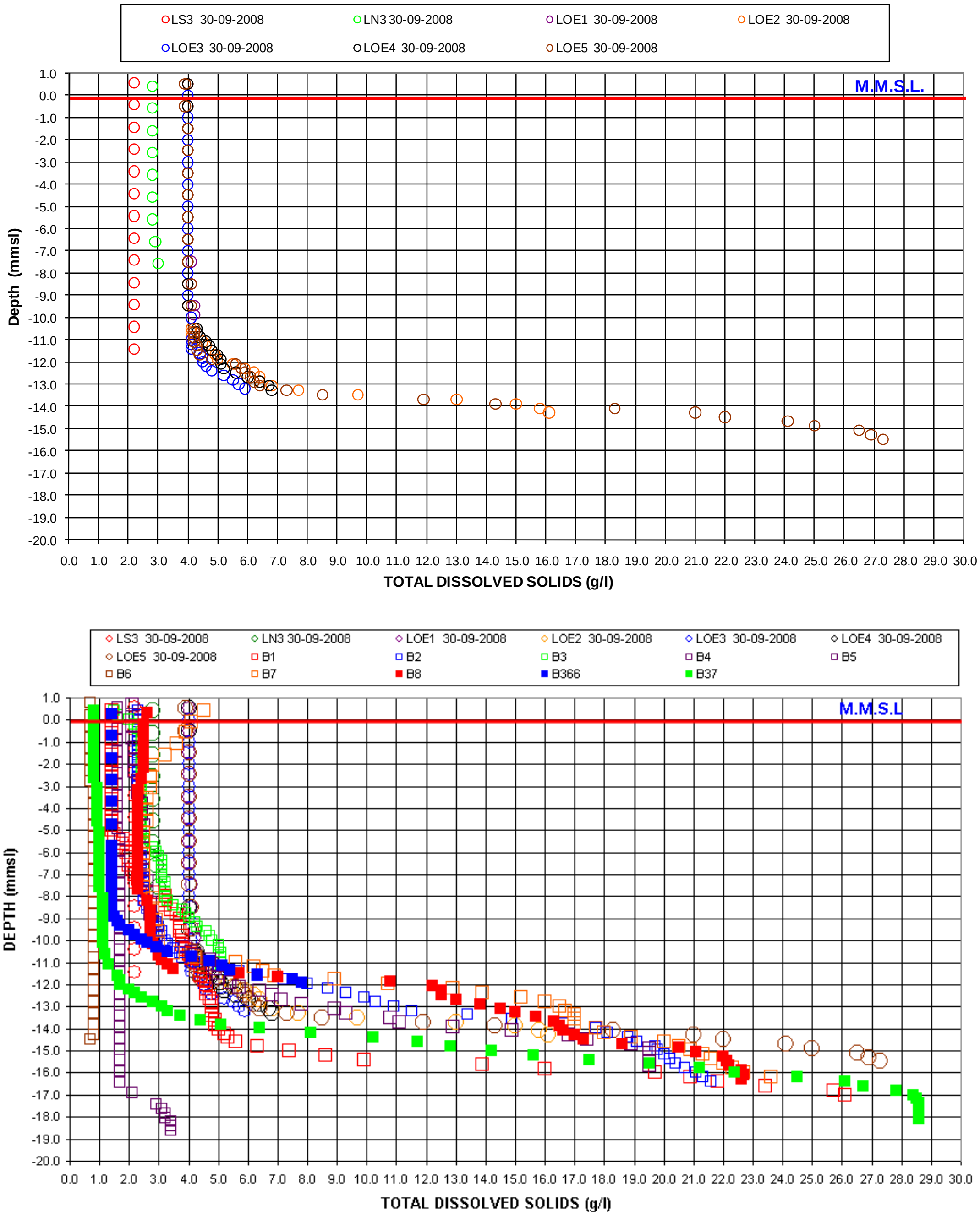



Figure 6. Total dissolved solids in the lagoons and boreholes of Mitza.

A graph of the Total Dissolved Solids of water in the lagoons and boreholes versus depth (Figure 6) shows the average depth of the saline interface, which is the theoretical point where the value of salinity is 50% of the value concentration equivalent to seawater (Custodio y Llamas, 1983) . In both cases (boreholes and lagoons) saline water interface has an average value of 17,500 mg $L^{-1}$ of Total Dissolved Solids (TDS) and it was measured -14 m below the mean sea water level.

At the date of the profile measurements, only the lagoon named West (LE) had activity in extraction of limestone material. The other two lagoons: North (LN) and South (LS) do not have activity and its average depth of excavation with respect to ground level is 12 m. In contrast, the West Lagoon has an average depth of 12 m but recent activity reached a depth of 16 m below the ground level in some places.

In all the boreholes made for exploration and monitoring the saline interface were found below 12 m of depth respect to the position of the water table.

**Hydraulic head of the aquifer**

The hydraulic head or potential of the aquifer was calculated by subtracting the height of the benchmark obtained from leveling in each borehole or lagoon (in meters), to the depth of water level (static level). These data are presented in the Data Table 1.

It was planned a route consisting in the measurement of the piezometric groundwater level in each of the boreholes and drilled probe boreholes, as well as the existing monitoring points in the study area, to then calculate the water level potential or elevation with respect to mean sea water level.

It is noted that the values of the hydraulic head at the study zone fluctuated between 40 and 76 cm respect to the mean sea water level. Hydraulic heads of greater magnitude (close to 0,763 m) were recorded at points farther from the coast (boreholes 5 and 6), while points near the coast (shallow holes 1 to 7) show hydraulic heads between 0,424 and 0,483 m. (Figure 7).

Based on the location of points of the monitoring network, it was drawn a potentiometric profile ranging from Mitza to Dzizilché, located this town 13.5 km south of the coast. In this potentiometric profile, the monitoring points measured the 24th of November of 2008 are arranged according to their distance from the coastline.

In Mitza-Dzizilché profile (Figure 8) we can see that there are different hydraulic gradients. This difference in the hydraulic gradient occurs precisely at the border between the unconfined and confined aquifer. The graph shows that the hydraulic gradient in the unconfined aquifer is higher than in the confined aquifer area, where the lagoons are located. Note also that the unconfined aquifer lithology in the study area is a limestone with clay and silt (Tz), while Quaternary limestone consists of shell fragments, which perhaps is more permeable than the limestone of the Tertiary. Consequently, the presence of lagoons and lithological change may be the factors contributing to this change in the hydraulic gradient between the free and the confined aquifer.

The physical evidence of drilling and sounding in the area, as well as the geological model of the study area show that the boundary between the confined aquifer and the unconfined aquifer are in between the soundings boreholes S8 and S8-A.

**Electronic Records Water Level**

To measure the hydrostatic pressure in the probe boreholes S1 and S9, the piezometer and the boreholes B4 and B5, and springs located in the estuary (Ría and Corchito), electronic transducers were installed. These records reflect the influence of the tidal effect on the level of groundwater, and can be observed the periods of aquifer recharge and discharge. The sensor was programmed to measure the water level every 10 min.

The behavior of the amplitude variation of water level in the Ría and the seawater, corresponding to the port of Progreso, Yucatan, Mexico is similar. Both records show a range of approximately 70 cm. In contrast, the amplitude in the spring called El Corchito was 35 cm and is equivalent to the amplitude of 40 cm measured in the other monitoring sites located within 4 km of coastline (Figure 9). The range of amplitude variation of groundwater level decreases exponentially when the monitoring wells are away from the coast, until the effect of tides on the aquifer water level is imperceptible.

The tidal range recorded during the measurement period from 19 to 24 November 2008 was 70 cm (Figure 9). This same range was reflected in the variation of water level measured in the spring called "Ría". Note in Figure 9 that, as water sources away from the coast, the amplitude of the periodic variation of groundwater level due to the tide falls. Boreholes located 1.5 km from the coast recorded amplitudes of 40 cm. A greater distance from the coast to 13 km of tidal effect on groundwater level decreases to finally disappear completely.

The efficiency of the tide has an inverse relationship with distance from the coastline where the tidal variation was measured in groundwater level, i.e. further away the source of water (the sea) the efficiency of propagation of the effect of tides on the groundwater will be minor.

Points S1, B4 and S9 show efficiencies of 15%, 6% and 2% and are located at 4.410 m, 8.100 m and 9452 m from the coastline, respectively in the same order. On the other hand, the efficiencies observed in the piezometer and the Corchito are 20% and 18% respectively. Both water sources are located at the same distance from the coast. It is noteworthy that in the borehole B5 located 13 km from the coast, i.e., 3 km after sounding hole S9, no tidal effect was recorded. From this evidence it can be inferred that the tide effect on groundwater is dissipated or damped to reach the unconfined aquifer.

## Estimating Aquifer Hydraulic Conductivity

The hydraulic conductivity (m $d^{-1}$) is a useful parameter in the quantification of groundwater flow. With this value it is estimated the volume of groundwater that flows through a given section in the network flow.

The technique used to evaluate the hydraulic conductivity of the aquifer is based on the simulation of the effect that the tide has on the groundwater level of an aquifer connected to the sea. Dimensional model used was Ferris (1951), which applies to homogeneous and isotropic confined aquifers, whose adjustment is done by trial and error.

Thus, the hydraulic conductivity was estimated for the water level records measured in water sources S-1, B-4, S-9, piezometer and also for the Corchito (Figure 10). It is important to note that, with the exception of the sounding S-9, all others are located in the confined aquifer.

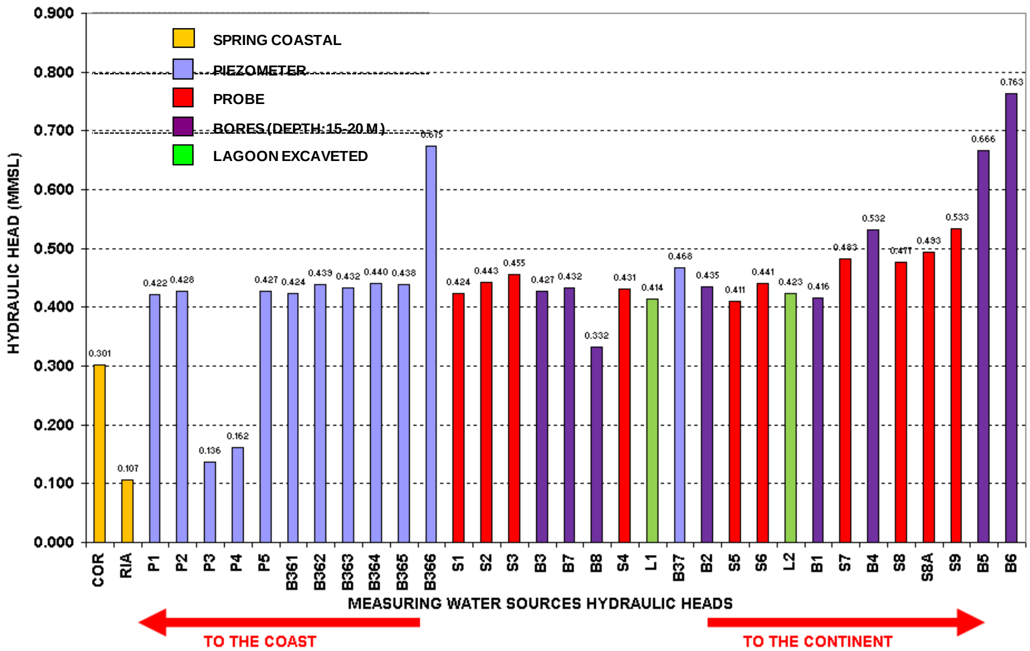



Figure 7. Hydraulic potential (24/Nov/08)

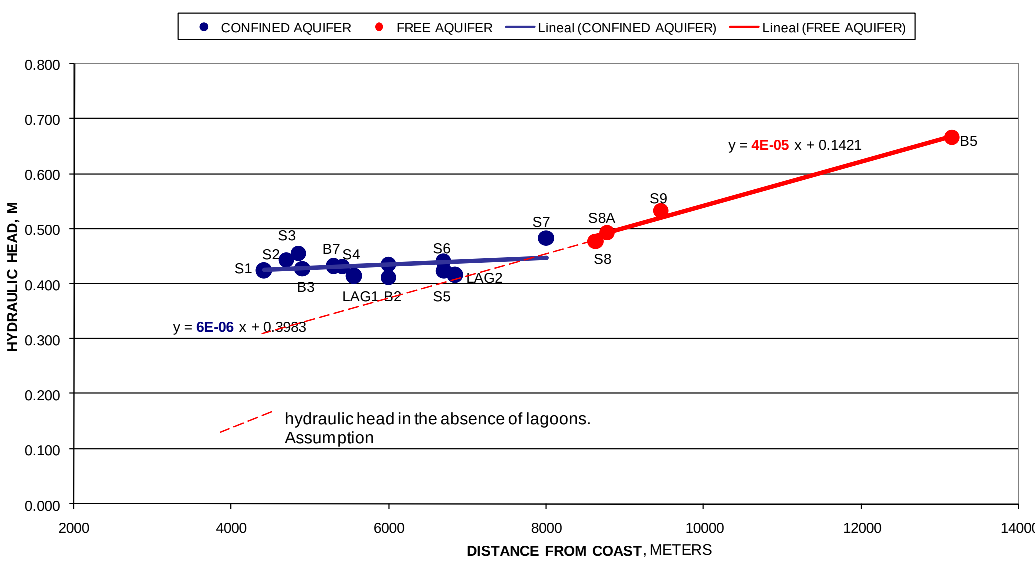



Figure 8. Hydraulic potential profile Mitza - Dzizilché, November 24, 2008

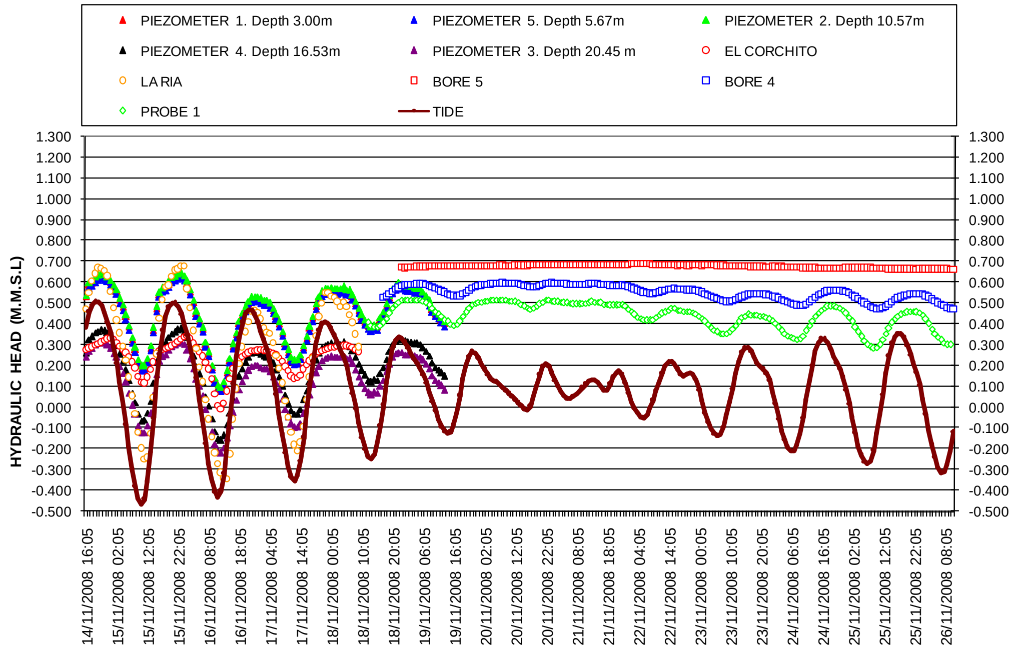
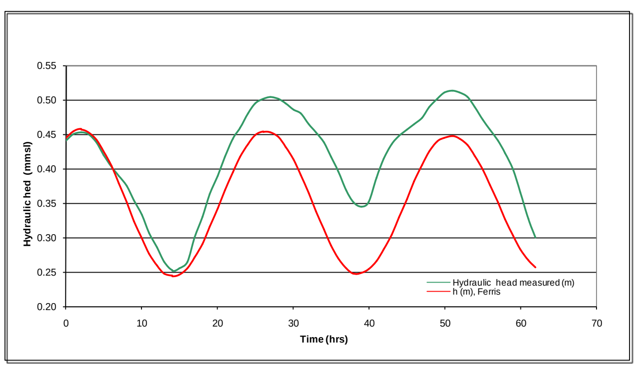



Figure 9: Variation of the hydraulic potential and tidal monitoring points (14 Nov to 01 Dic-08).

**Ferris model fit for estimating K**
**Bore 1. From 28 Nov to 01 Dec 2008.**




**Ferris model fit for estimating K**
**Bore 4. From 28 Nov to 01 Dec 2008.**

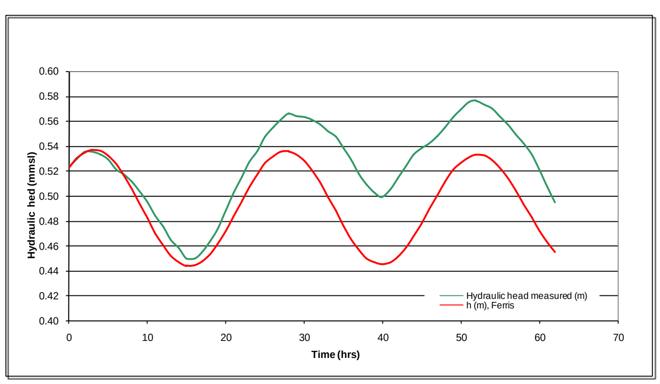



Figure 10: Graph match for the calculation of hydraulic conductivity

Table 2. Representative Hydraulic Conductivity of the Aquifer

| Site | Distance to the coast (m) | Efficiency (%) | I.D. | Storage Coefficient | Hydraulic Conductivity (m/d) | K Average(m/d) |
|---|---|---|---|---|---|---|
| **S-9** | **9452** | **2** | **K1** | 0.2 | 16,000 | 21,500 |
| | | | | 0.3 | 27,000 | |
| | | | | 0.4 | 32,000 | |
| | | | | 0.5 | 40,000 | |
| | | | | 0.6 | 48,000 | |
| | | | | 0.7 | 56,000 | |
| | | | | 0.8 | 64,000 | |
| | | | | 0.9 | 72,000 | |
| | | | | 1 | 80,000 | |
| **B-4** | **8100** | **6.2** | **K2** | 0.0005 | 670 | 6,700.00 |
| | | | | 0.005 | 6,700 | |
| | | | | 0.05 | 67,000 | |
| | | | | 0.2 | 214,400 | |
| | | | | 0.3 | 321,600 | |
| | | | | 0.4 | 428,800 | |
| | | | | 0.5 | 536,000 | |
| | | | | 0.6 | 643,200 | |
| | | | | 0.7 | 750,400 | |
| | | | | 0.8 | 857,600 | |
| | | | | 0.9 | 964,800 | |
| | | | | 1 | 1,072,000 | |
| **S-1** | **4410** | **15** | **K3** | 0.0005 | 540 | 5,400.00 |
| | | | | 0.005 | 5,400 | |
| | | | | 0.05 | 54,000 | |
| | | | | 0.2 | 108,000 | |
| | | | | 0.3 | 162,000 | |
| | | | | 0.4 | 216,000 | |
| | | | | 0.5 | 270,000 | |
| | | | | 0.6 | 324,000 | |
| | | | | 0.7 | 378,000 | |
| | | | | 0.8 | 432,000 | |
| | | | | 0.9 | 486,000 | |
| | | | | 1 | 540,000 | |
| **PIEZOMETER** | **1700** | **20** | **K4** | 0.0005 | 170 | 6,290.00 |
| | | | | 0.005 | 1,700 | |
| | | | | 0.05 | 17,000 | |
| | | | | 0.2 | 22,667 | |
| | | | | 0.3 | 34,000 | |
| | | | | 0.4 | 45,333 | |
| | | | | 0.5 | 56,667 | |
| | | | | 0.6 | 68,000 | |
| | | | | 0.7 | 79,333 | |
| | | | | 0.8 | 90,667 | |
| | | | | 0.9 | 102,000 | |
| | | | | 1 | 113,333 | |
| **EL CORCHITO** | **1605** | **18** | **K5** | 0.0005 | 62 | 2,294.00 |
| | | | | 0.005 | 620 | |
| | | | | 0.05 | 6,200 | |
| | | | | 0.2 | 8,133 | |
| | | | | 0.3 | 12,200 | |
| | | | | 0.4 | 16,267 | |
| | | | | 0.5 | 20,333 | |
| | | | | 0.6 | 24,400 | |
| | | | | 0.7 | 28,467 | |
| | | | | 0.8 | 32,533 | |
| | | | | 0.9 | 36,600 | |
| | | | | 1 | 40,667 | |

The hydraulic conductivity average K m $d^{-1}$ in the measurements point varies from 2,294 m $d^{-1}$ to 21,500 m $d^{-1}$; taking into account the physical properties of the confined caliche (S1, B4) and unconfined limestone (S9, piezometer, Corchito) related to the storage coefficient conditions of the layers (Frezze and Cherry, 1979), and the measured efficiencies of the tide (Table 2).

**Network Flow and Flow Rate Estimation**

The estimate of groundwater flow was made for the fresh and brackish water aquifer below the study area. To calculate the volume of groundwater flowing in the aquifer was used the network technical flow, which has its foundations in the D'arcy's Law. This law states that the volume flowing through a cross section of aquifer is directly proportional to the gradient of pressure loss, in which the constant of proportionality relates to the hydraulic conductivity of the system.

Equation of D'arcy: $Q = AKdh/dl$

where:
Q = the volume of groundwater flowing through a cross section of the aquifer, in $m^3$ $day^{-1}$
A = cross section of the aquifer equivalent to the thickness of the aquifer per unit width, in $m^2$
K = hydraulic conductivity in m $d^{-1}$
dh/dl = hydraulic gradient

A flow network consists of two sets of curves or planes, one of which represents the curves of equal hydraulic head or potential of the aquifer and the other, the path of trend of groundwater flow or current lines. According to the theorems of Gauchy-Riemman, these curves intersect orthogonally (Frezze and Cherry, 1979).

For the study area was used piezometric data of November 24, 2008. The net flow shows that the groundwater flow is almost perpendicular to the coastline and follows South to North main trend with a slight tilt towards the West (Figure 11.)

Note that the equipotential lines approach each other, as the groundwater flow approximates to the discharge into the sea. The flow network also shows the effect that lagoons have on the flow pattern. Groundwater flow converges into the lagoons due to the increment of the storage and the reduction of the hydraulic gradient. Upstream of the lagoons the gradient is smaller than the discharge area (See Figure 8), but higher in the vicinity of the lakes.

To calculate the volume rate of the aquifer was defined 9 flow cells in the study area. To each area was assigned a hydraulic conductivity (K) calculated with the Ferris & Frezze & Cherry methods and a hydraulic gradient defined by the distance between each equipotential line. It was also assumed that the thickness of the freshwater aquifer is variable between 10, 15 and 20 m, due to the shape of the depth average of the saline interface measured in the boreholes.

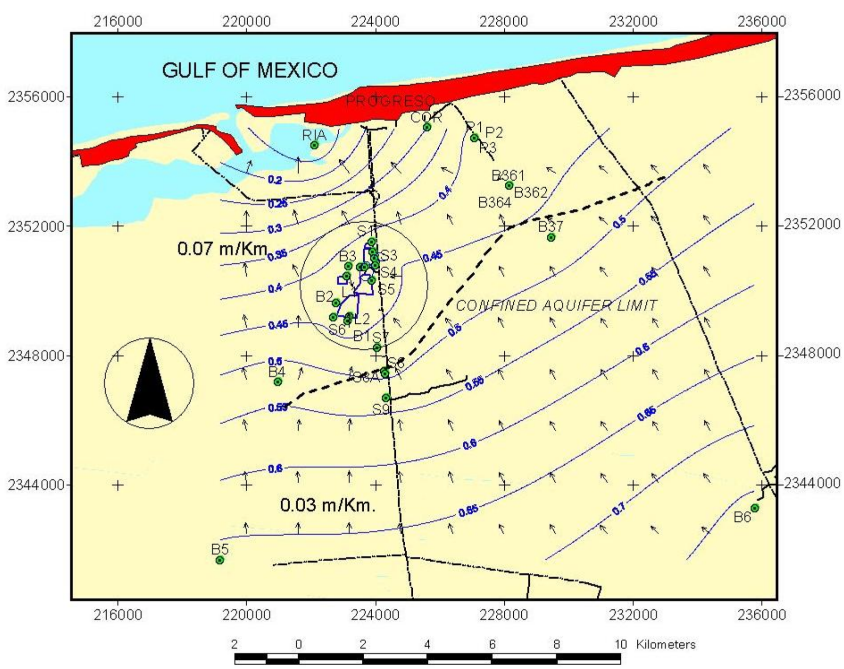



Figure 11 Network Flow on 24 November 2008.

For the calculation of groundwater flow in the study area were used average values of hydraulic conductivity for both the confined aquifer and for free.

The average flow of 0,08 l $s^{-1}$ per linear meter of aquifer or the equivalent of 7,0 $m^3$ $d^{-1}$ for each meter of the aquifer result from the calculation (Data Table 3). In the area where the aquifer is free the flow rate is 0.15 L $s^{-1}$ per meter, but toward the north-northeast there is an important decrease in the amount of groundwater that flows into that area, compared with those in the western area.

## DISCUSSION

The Yucatecan aquifer is considered in almost all its extension as an unconfined aquifer, with the exception of discharge zone which occurs under a scheme of confinement. Greater extent the discharge occurs to the sea and to a lesser extent, into the marshes and swamps. Weathered rock (by precipitation of calcium carbonate) that confines the aquifer of Yucatan in the discharge area has been recognized as a thin surface layer of caliche (with thicknesses of several tens of centimeters to 2,5 m in study area). The surface layer of caliche in the study area is the coastal aquitard mentioned in several technical articles written concerning the northern coast of Yucatan (Perry et al, 1990, Marin et al, 2003; Batllori et al, 2006). This layer was identified in this study by indirect (geophysics) and direct (controlled exploratory drilling) geohydrological techniques.

This superficial layer of caliche outcrops in much of northern Yucatan aquifer, however, the region where the aquifer is free caliche is highly fractured, which confers high permeability and enables almost 20% of the average annual rainfall to quickly infiltrate into the free aquifer.

The prospective study of hydrogeology, water quality, geophysics and hydrogeology made in the study area (which includes part of the unconfined and confined aquifer) has established the boundary between two systems (Figures 3 and 4). The boundary between free and confined aquifer has been established to identify areas where the caliche is fractured and where not. The area where the caliche is broken results in the existence of the unconfined aquifer. Where fracturing of the aquitard is present, vertical permeability increases. It is through this fracturing that the water table is in contact with atmospheric conditions. On the other hand, the confined aquifer starts from where the caliche is unchanged by the fracturing.

The resistivity survey results revealed that this caliche layer appears as a shallow resistive layer with high values of resistivity and variable thickness. Several shallow boreholes of a few meters depth were drilled on this resistive layer to verify its lithological nature. The data collected showed the existence and thickness of caliche, which varied in the study area from 1 to 3 meters. However, in the same area of study also reported less than one meter thick.

To verify the confinement of the aquitard was drilled several boreholes (up to 5 m deep). During the drilling of them, the water level was measure in the borehole. Column 2 of shows the depth of the drilling of the borehole. Note, for example in Table 4, during the drilling of the S-2, when the depth of the hole was 1 m, the rock was into the caliche (aquitard) (Column 5). In that depth of the hole the depth of water was 0,95 m. When the borehole reached 1,70 m depth, the water level rose to 0,2 m from the ground level; increased 0,75 m, (Column 4). This rise in water level represents the aquitard confining. Consequently, if the water level rise is zero that indicates the absence of the confinement, like in S-5 and S-9. Note that this increment in the water level occurs generally when the caliche layer is drilled completely. Note also in comparison with the S-2 of the example, that even though the botrehole depth increases, the water level remains constant. This indicates that the confining layer has a thickness greater than 1 m but less than or equal to 1.70 m.

Table 3. Calculation of volume rate into the flow cells of the study area.

| FLUX ZONE | HYDRAULIC COND ID | HYDRAULIC COND VALUE (m/d) | CROSS SECTION B (M) | CROSS SECTION L (M) | DL (M) | HYDRAULIC GRADIENT | RATE FLUX IN CELL Q (M3/D) | RATE FLUX IN CELL Q(L/S) | UNIT RATE Q (M3/D/M) | UNIT RATE Q(L/S/M) |
|---|---|---|---|---|---|---|---|---|---|---|
| Q1 | K1 | 21500 | 20 | 2250 | 670 | 0.00003 | 28881 | 334 | 13 | 0.15 |
| Q2 | K1 | 21500 | 20 | 2050 | 650 | 0.00003 | 27123 | 314 | 13 | 0.15 |
| Q3 | K1 | 21500 | 20 | 2150 | 700 | 0.00003 | 26414 | 306 | 12 | 0.14 |
| Q4 | K2 | 6700 | 20 | 1410 | 740 | 0.00003 | 5106 | 59 | 4 | 0.04 |
| Q5 | K2 | 6700 | 20 | 2020 | 730 | 0.00003 | 7416 | 86 | 4 | 0.04 |
| Q6 | K4 | 6290 | 20 | 1130 | 950 | 0.00002 | 2993 | 35 | 3 | 0.03 |
| Q7 | K3 | 5400 | 15 | 1320 | 330 | 0.00006 | 6480 | 75 | 5 | 0.06 |
| Q8 | K3 | 5400 | 15 | 1660 | 280 | 0.00007 | 9604 | 111 | 6 | 0.07 |
| Q9 | K3 | 2294 | 10 | 950 | 300 | 0.00007 | 1453 | 17 | 2 | 0.02 |
| | | | | | | **AVERAGE** | **12830** | **148** | **7** | **0.08** |

Table 4. Water level variation in the S boreholes during drilling

| ID | Depth of borehole (m) | Water Level (m) | Water Level Rise(m) | Observations |
|---|---|---|---|---|
| S-1 | 1.50 | 1.05 | | Caliche |
| | 2.20 | 0.29 | 0.76 | Limestone with Mollusc and Shells |
| S-2 | 1.00 | 0.95 | | Caliche |
| | 1.70 | 0.20 | | Limestone with Mollusc and Shells |
| | 2.70 | 0.20 | | Limestone with Mollusc and Shells |
| | 3.90 | 0.20 | 0.75 | Limestone with Mollusc and Shells |
| S-2a | 1.40 | 1.35 | | Caliche |
| | 1.60 | 0.65 | | Boundig Caliche/Limestone with Mollusc and Shells |
| | 2.40 | 0.60 | | Limestone with Mollusc and Shells |
| | 3.90 | 0.60 | 0.75 | Limestone with Mollusc and Shells |
| S-3 | 0.90 | 0.68 | | Caliche |
| | 2.75 | 0.65 | | Limestone with Mollusc and Shells |
| | 3.77 | 0.60 | 0.08 | Limestone with Mollusc and Shells |
| S-4 | 3.70 | 3.32 | | Caliche |
| | 4.70 | 2.12 | 1.20 | Boundig Caliche/Limestone with Mollusc and Shells |
| S-5 | 1.50 | 0.67 | | Caliche |
| | 3.50 | 0.67 | 0.00 | Limestone with Mollusc and Shells |
| S-6 | 0.98 | 0.89 | | Caliche |
| | 1.37 | 0.65 | | Limestone with Mollusc and Shells |
| | 2.20 | 0.60 | | Limestone with Mollusc and Shells |
| | 4.20 | 0.60 | 0.29 | Limestone with Mollusc and Shells |
| S-7 | 1.25 | 1.20 | | Caliche |
| | 1.50 | 1.33 | | Limestone with Mollusc and Shells |
| | 3.00 | 0.99 | 0.21 | Limestone with Mollusc and Shells |
| S-8 | 2.05 | 2.03 | | Caliche |
| | 4.40 | 1.73 | 0.30 | Limestone with Mollusc and Shells |
| S-8a | 2.60 | 2.50 | | Caliche |
| | 4.60 | 2.20 | 0.30 | Limestone with Mollusc and Shells |
| S-9 | 3.00 | 2.15 | | Caliche |
| | 5.00 | 2.15 | 0.00 | Limestone with Mollusc and Shells |

With these data, it is estimated that the boundary between free and confined aquifers is located between the shallow boreholes S8A and S9, i.e. about 8 km from the sea coastline. According to these results the width of the aquitard increases its range to the west and decreases to the east, located 5 km from the coastline.

Under the thin thickness of the confining layer, the limit of confinement may vary. That is, in times of drought, when groundwater levels drop below the bottom of caliche, the confinement can occur beyond (seaward) boundary between the impermeable and permeable caliche, thereby reducing the amplitude of the confined aquifer. In times of recharge, the confinement can spread and reach the boundary between the fractured caliche layer unaltered. Another factor that can vary the width of the confined aquifer are the tides, whose amplitudes can reach 0,9 m. Due to efficient hydraulic connection between the underground system and the sea, through the karst, the tides can propagate for several kilometers inland, temporarily raising and lowering of the aquifer hydraulic head above and below the bottom of caliche confining.

The measurement of changes in groundwater level due to tides is an important tool to identify the existence of confining aquitard. This is possible because the tidal effect is propagated more efficiently in confined aquifers, which in unconfined aquifers as a result of reduced storage of confined aquifers, (Custodio y Llamas, 1983).

Based on the above and according to Figure 9, it is clear that the effect of the tides was detected in borehole B4, but not in the borehole B5. Thus inferred that limit between the two aquifers are located between boreholes B4 and B5 (Figure 2). Note that the B4 borehole is located almost at the same distance from the coast than the shallow well S8A.

The boundary between free and confined aquifer is the discharge area of the unconfined aquifer. In other words, discharge area of the unconfined aquifer is both the recharge zone of the confined aquifer, which in turn discharged into the sea under a pressure flow pattern. The thickness of the confined aquifer in the area of discharge to sea is estimated between 8 and 10 m. The water quality records for total dissolved solids in the holes studied so reveal, (Figure 6). Note that in the first 10 m of depth, total dissolved solids of groundwater remained virtually unchanged. It is through this thickness that groundwater flows to download the sea.

The flow network corresponding to November 24, 2008, reveals that the groundwater discharges into the sea, with the S-NW and NS (Figure 11). It also shows how the local flow pattern is modified by the presence of lagoons. Notice how the flow pattern tends to converge towards the lagoons; this indicates that they act as a sink that is recharged by the aquifer. That is, the lakes represent a local area of groundwater discharge, in their absence groundwater flows toward free to the sea.

Note in Figure 11 how the equipotential lines approach each other as the confined aquifer groundwater is approaching its drainage area is the sea. Thus the hydraulic gradient increases near the sea, while it decreases from the shore, i.e. in the unconfined aquifer. Figure 3 is a graph showing how the presence of lagoons reduces the hydraulic gradient to 0,006 m $km^{-1}$, due to increased hydraulic conductivity. These data suggest that in the absence of lagoons, the hydraulic head in the confined aquifer surrounding them would be lower.

According to the principle of Ghyben/Herzberg, penetration of the salt wedge on the continent depends on the magnitude of the hydraulic head between the sea and the aquifer. Under natural conditions the hydraulic head varies seasonally, due to periods of recharge and discharge, on a daily basis due to evapotranspiration, and because of tides and atmospheric pressure changes (in the case of unconfined aquifers). The reduction of hydraulic head in the aquifer, due to the time of recharge and discharge, makes the saline interface penetrate further into the continent, which makes the volume of contaminated groundwater by salt water increase and decrease while freshwater reserve, (Domenico and Schwartz ,1990). The overexploitation of groundwater is also a reason that gets sea water in the aquifer. A direct consequence of the extraction of ground water is the reduction of groundwater discharge to the sea and a decrease in aquifer hydraulic head. The reduction of the discharge of fresh water to the sea permits that the aquifer loses its ability to clean sea salts of the wedge interface and making it penetrates into the continent.

To exploit the stony material in this area is essential to break the semipermeable layer that confines the aquifer. Piezometric data measured around the lake in shallow holes and boreholes show that the hydraulic loading does not reduce for this reason. Moreover, considering that the lagoons are a local groundwater discharge, and that the only way out of the water in the lagoons is the direct evaporation of water, then as an example, consider a lake an area of 10000 $m^2$ (100 m x 100 m) and assume an average daily evaporation of 10 mm. With this information the rate of flow of water by direct evaporation of the lake would be 0,01 L $s^{-1}$, however, this study has estimated that the output rate of the aquifer to the sea for a length of 100 m aquifer would be equivalent to 8 L $s^{-1}$. A simple calculation shows that the amount of groundwater that is discharged by a lake due to evaporation would be equivalent to an amount less than one-hundredth of a liter of groundwater that is discharged to sea through the aquifer under natural conditions, (Gonzalez et al., 2002). Consequently, as hydraulic head does not decrease due to the rupture of caliche, and that the existence of lagoons does not significantly affect the groundwater discharge to the sea, then the position of saline interface is not affected by these actions.

Because the aquifer of Yucatan is a coastal aquifer, it is experiencing the phenomenon of seawater intrusion. In the study area, the depth of the sea interface was located between 12 and 14 m below the mean sea water level. The depth of the interface was estimated taking into account the criterion, that it is located at a depth of 50% of the total dissolved solids of sea water (Figure 6).

In the study area the thickness of the mixing zone is estimated between 4 and 6 meters. The thin thickness of the mixing zone is due to the Yucatan aquifer quickly discharged to the sea allowing for efficient washing of sea salt under advective process. The variation of the saline interface position is, under natural conditions, regulated by the seasonal fluctuation of recharge and discharge processes. However, so time its position is governed by the tidal effects that are prevalent in the coastal zone due to the hydraulic connection between the sea and the coastal aquifer. Therefore, the width of the mixing zone is governed by the dispersion of the salts caused by tides and the dispersion and advection as a result of groundwater discharge to the sea, both effects acting in conjunction with dispersive characteristics of the medium.

The profiles of total dissolved solids in the lagoon show that the West Lake has more salt in the water in the lakes that of North and South, (Figure 6). This is because in the western lagoon stony material is being extracted for use in construction. The depth of the lake has reached into the aquifer varies between 12 and 16

m. Note that the saline interface is located in boreholes away from the lake, at depths between 12 and 14 m. Thus, the extraction of stony material from the lagoon, carrying some salts from the marine interface to the surface, is increasing the salt content in this lake. Another important aspect revealed in Figure 6, is that the TDS hole profiles (B2, B3 and B8) surrounding the West lake, present values of the salt content of the water lower than the lagoon.

Finally, Figure 6 also illustrates how sea interface of the lagoons are located at a depth similar to those found in the holes that have a lower total dissolved solids in the upper portion of the aquifer. The above information shows categorically that the depth of the marine interface does not rise due to the rupture of caliche. Therefore, does not penetrate into the portion of peninsular aquifers.

## CONCLUSIONS

The karst aquifer is confined between 5 and 8 km. From the coastline to the west the thickness of the confining layer gets to the mainland, while decreasing towards the east, coinciding with the observations made by Perry et al. (1990) where he mentions that towards the zone of caliche Dzilam Bravo is thin up to 2 km from the coastline.

In the confined aquifer, the confining layer rises to the surface and has a variable thickness between 0,5 and 3 m thick, becoming thicker to the east of the study area and decreasing to the west.

The regional ground water flows naturally to the coast from the unconfined aquifer to the confined, in this transition follows a decrease in the flow towards the coast and towards the West because of the physical characteristics that define the hydrodynamics of this area. Given that the thickness of the discharge zone is variable, then the fresh water increases and decreases its rate of flow to the coast.

The geophysical electrical method proved useful in detecting the caliche layer. The measurement of water level during the construction of exploratory wells proved to be an efficient technique to evaluate the confinement of the aquifer, determine the thickness of the aquitard or caliche layer and to define the boundary of this layer.

By analyzing the physiography with satellite imagery, it is possible to establish contact between the free and the confined aquifer. Since there is a close relationship between the Savannah (flood zone) and quaternary limestone outcrops in it (caliche), with evidence of confinement.

Other technique that may be useful in identifying the existence of caliche layer and establish an approximate boundary between the unconfined and confined aquifer is measuring the variation of groundwater level by the effect of the tides. Systematic measurements of groundwater level at various distances from the coast by tidal effects, together with the analysis of the results of other techniques used (geophysical, measuring the water level monitored during the construction of boreholes and image interpretation satellite), can lead to the definition of the contact area between free and confined aquifers with greater precision.

The contact between free and confined aquifer varies seasonally according to the rainy season or during the dry season. During the recharge the confined aquifer increases its range extending to the continent, in contrast, during the dry season reducing its amplitude decreases continental extension. This occurs through the caliche layer is shallow and thin. So that the water level to vary seasonally, may exceed or fall below the bottom of caliche, confining the aquifer or aquifer making it free. Under prevailing tidal regime on the northern coast of the peninsula and the extent thereof, the enclosure is also affected regularly by tides. This behavior of the aquifer occurs in times of high tides for new and full moon when tidal amplitudes vary between 80 and 90 cm.

The construction of lagoons due to the exploitation of stony materials exposed the groundwater to atmospheric conditions under which breaks the thin semipermeable confining the aquifer. The artificial formation of these lakes affect the groundwater flow in two ways: modifies the groundwater flow in such a way that converges to the streamlines to the lagoons and on the other hand, decreases the hydraulic gradient due to the hydraulic conductivity increased locally. Besides (locally), it also increases the aquifer storage.

Lagoons become small areas of groundwater discharge through direct evaporation. It is estimated that the amount of water the aquifer loses and leaves the sea download (0,01 L $s^{-1}$) is negligible in contrast to the natural discharge of 8 l/s, thus breaking caliche not severely affect the parameters (hydraulic head and groundwater discharge to the sea) that affect the marine wedge penetrates further into the continent.

Records of total dissolved solids in water made in lagoons and boreholes do not indicate the presence of salt increased by the breaking caliche. The depth of the marine interface found in the lakes that are not being exploited coincides with the depth detected in the boreholes. This information supports the analysis above and confirms that the breaking caliche inland has no impact on the marine wedge penetration into the aquifer.

The conceptual model of karst coastal aquifer in the study area is characterized by being confined within a strip parallel to the coast of between 5 and 8 km wide. The confined aquifer is more width to the west and the less narrow eastward. In the study area the thickness of the confining layer is 1 to 2,5 m. Regional groundwater flows towards the sea through the unconfined until it reaches the confined aquifer. In this way the groundwater that flows through the unconfined aquifer as confined aquifer recharges, which ultimately discharge into the sea.

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