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HYDRODYNAMIC BEHAVIOR OF THE YUCATAN AQUIFER. A PERSPECTIVE ON THE HYDRAULIC CONDUCTIVITY ESTIMATION.

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***RESUMEN*.**

La naturaleza hidrogeológica de los acuíferos cársticos determina su singular comportamiento hidrodinámico. La hidráulica de pozos, las fluctuaciones del nivel del agua subterránea, y el patrón de flujo son algunos aspectos de la hidrodinámica de los acuíferos sobre los que las heterogeneidades cársticas influyen notablemente. El conocimiento de estos aspectos hidrodinámicos representan un recurso potencial para la estimación de parámetros hidrogeológicos representativos del sistema. Se pretende presentar en éste trabajo la relevancia del comportamiento hidrodinámico singular del acuífero cárstico yucateco haciendo énfasis en la obtención de valores representativos de los parámetros hidrogeológicos. Asimismo, se plantearán algunas consideraciones relativas al estudio del transporte de contaminantes en relación con la hidrogeología.

***ABSTRACT*.**

The hydrogeologic nature of karstic aquifers determines its singular hydrodynamic behavior. Well hydraulics, water table fluctuations, and flow pattern, are some aspects of the aquifer hydrodynamics over which karstic heterogeneities notably interfere. Knowledge of these hydrodynamic aspects is a potential resource to estimate representative hydrogeologic parameters of the system. This paper shows the importance of this in the Yucatan karstic aquifer. Some hydrogeologic and hydrodynamic characteristics are used in this system, in estimating the hydraulic conductivity, as recourse to handle the scale effect problem. Some considerations are also suggested when studying solute transport problems regarding karst hydrogeology.

INTRODUCTION

Many numerical models have been used to simulate ground water flow in the Yucatan karstic aquifer considering it as a porous medium (BGS et al., 1994; González, 1992; Marin, 1990). Best calibrations have been achieved using hydraulic conductivity (K) values up to 96,300 m/d. These values are higher than those reported in karst terrains, from 0.1 to 4,000 m/d (Freeze and Cherry, 1979); those obtained in laboratory tests from rock cores, from 2.92 x 10^{-3} to 37 m/d; and packer tests (6.51 m/d) carried out in deep boreholes located in Merida, capital city of Yucatan (Buckley et

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al., 1994; Brewerton, 1993). The minimum K value measured corresponds to a recrystallized limestone, while the maximum one was obtained from a fossiliferous limestone.

The difference, in many orders of magnitude, between the hydraulic conductivity, estimated using ground water flow modeling, and the hydraulic conductivity measured, is due to the secondary permeability which results from fractures and karstic processes operating on the Tertiary limestone, generating an aquifer system with a complex hydrodynamics. With no doubt, very high values of this parameter have produced uncertainties on the implemented models; therefore, reliable K estimations, representative of the aquifer are needed. Knowledge of the Yucatan aquifer hydrodynamics opens optimistic possibilities to obtain hydraulic conductivity values representative of this highly transmissive system.

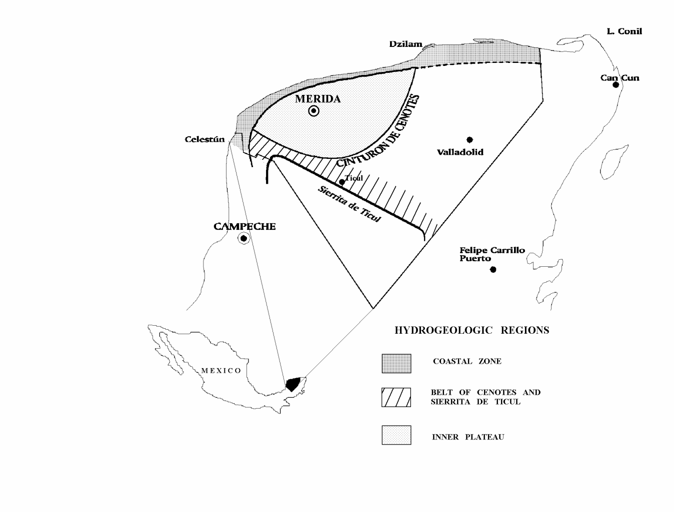
Pumping tests are methods used in evaluating, among other parameters, the hydraulic conductivity. The importance of these methods rests in that the aquifer volume involved while pumping is such, that heterogeneities could be considered in the estimated K value. K values estimates obtained from pumping tests are considered to be representative of the aquifer tested. However, in highly transmissive aquifer systems, such as the Yucatan aquifer, pumping tests have not had the expected success. The lack of drawdown and rapid stabilization of the dynamic water level, while pumping proceeds, make water level measurements difficult to record; therefore an uncertainty exists in the estimated K values.

Despite the above hydrodynamic constraints in carrying out pumping tests in the Yucatan karstic aquifer, water table electronic recorders represent an alternative to avoid this obstacle. On the other hand, studying tide fluctuations and its influence on the water table, representative K values could also be obtained; tide effects can be measured at a considerable distance from the coast involving high aquifer volumes.

Knowledge of the hydrogeology of a system also represents a powerful resource through which adequate procedures and proper techniques could be chosen to obtain representative values of the different hydrogeologic parameters. Numerical models are a powerful tool in aquifer studies and management; however, to minimize uncertainties in the output depends among other factors on minimizing uncertainties in the parameters used for calibration purposes.

From this point of view and given the nature of the Yucatan aquifer system, this paper presents some hydrogeologic and hydrodynamic aspects of some regions of Yucatan, studying it in three regions: the coastal zone; an inner plateau surrounded by the belt of cenotes and the lower boundary of the coastal zone; and the region limited by the belt of cenotes, the Sierrita de Ticul and the lower boundary of the coastal zone (Fig. 1) the main goal is to direct future attempts in estimating hydraulic conductivity in each region taking advantage of the above aspects.

Fig. 1. Location of the study area.



GEOLOGICAL SETTING

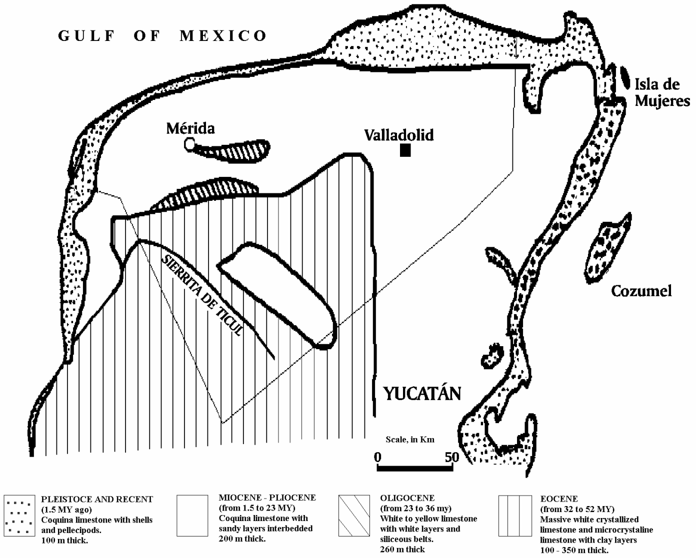
Yucatan is composed of Tertiary carbonate rocks, mainly limestones and dolomites, lying almost horizontally with a slow deep to the north. The maximum thickness of these sediments is almost 1000 m overlying Cretaceous limestones and evaporites (Lesser and Weidie, 1988). Fig. 2 shows the stratigraphic sequence of the Yucatan Peninsula. Older rocks crop out to the south and younger ones towards the coast. A highly fractured caliche layer, less than 2 m thick, covers almost all the surface in this region.

The Sierrita de Ticul and a circular structure formed as a result of a crater, 180 km in diameter with the center in the northern coast of Yucatan, are the most important geologic structures in this region. The Sierrita de Ticul is located south of Yucatan, extending 160 km in the N 55° W direction.

From scarce data, its origin has been interpreted as resulting from a normal fault generated between the Upper Cretaceous and the Lower Tertiary (Weidie, 1985). It is composed of Lower Eocene dolomitized and silicified crystalline limestone rocks (Lesser and Weidie, 1988; SARH, 1989). In the limits between the Cretaceous and the Tertiary, it is assumed that an extra terrestrial body impacted the Earth, giving origin to an enormous circular structure with a 180 km diameter approximately (Pope et al., 1991; Hildebrand et al., 1991).

Sediments deposited in the crater, due to this impact, settled generating faults giving origin to a fracture system. The fracture systems resulting from both events have not been well understood yet. However, hydrochemical and hydraulic evidence manifest their hydrogeologic influence in the ground water flow pattern as wells as its direction, in this region.

Fig. 2. Geology of the northern portion of the Yucatan peninsula.



HYDROLOGY AND HYDROGEOLOGY

The mean annual average precipitation in Yucatan has been estimated in 1025 mm. To the south higher precipitations occur, up to 1300 mm, whose distribution gradually lowers reaching 500 mm towards the coast. Usually the heavy rain period begins during May ending by October, November trough April being the dry period. The annual average temperature is 26°C, minimum values are recorded between December and January and maximum ones between July and August (SARH, 1989). Average annual evapotranspiration in Yucatan has been estimated in 900 mm considering the average annual temperature (Lesser, 1976).

The almost plain relief, the thin and discontinuous, or lack of, soil and the limestone rock (caliche) fracturing are the main factors responsible for the absence of surface waters in Yucatan; as a consequence, part of the rainfall that infiltrates recharges the aquifer. Infiltration occurs almost immediately after the rain event, through the caliche fractures. Thus, between 15 to 20 % of the annual precipitation constitutes net recharge to the aquifer (Lesser and Weidie, 1988; SARH, 1989). BGS et al., (1994) using a chloride mass balance, estimated the recharge due to rainfall as 9% of the mean annual precipitation in the city of Merida.

Therefore, the main recharge in the Yucatan aquifer is due to precipitation; regions with higher precipitation being the ones with the higher recharge. There are some regions, parallel to the coastline where rainfall is temporarily retained to be evaporated afterwards.

Fresh water in the Yucatan aquifer is available from a thin lens overlying saline water of higher density. This saline water results form saline intrusion. Saline water depth along the coastline has been estimated, using Ghyben – Herzberg principle, to be 18 m and 60 m, 30 km south of Merida (Perry and Marin, 1987; Steinich, 1996). The aquifer is unconfined in almost all its extension, except near the coast, where a thin crystalized limestone layer, confines it (Perry et al., 1989).

Dissolution processes taking place on the limestone rock, have developed a karstic system that, together with the fractures present in the region, confers a high transmissivity to the aquifer. This feature is manifested in the very low hydraulic gradient (0.007 m/km; Marin, 1990).

Sinkholes, locally called cenotes, are the most abundant and extensively distributed karstic features in Yucatan. South of Merida, a singular belt of cenotes exist describing an arc of circumference with a radius, measuring almost 90 km, whose center is located in the coast, north of Merida. One end of this belt intercepts the north coast, near Dzilam; and the other one, the west coast, near Celestun.

As mentioned before, the origin of this belt of cenotes has been associated to the fracture system resulting from an impact crater (Pope, et al., 1991; Hildebrand et al., 1995). This peculiar karstic form is a projection of the subterraneous karst to the surface. In this sense, various karstification levels have been detected with depth. East of the oriental segment of the belt of cenotes, a maximum depth of 125 m has been recorded logging cenotes; the maximum elongation measured is 46 m. Stringfield and Legrand (1974) suggested that this karstification levels resulted from sea level fluctuations during the Pleistocene.

Groundwater regional flow occurs radially from the southeastern limit of Yucatan towards the coast. The cero hydraulic head, along the coast, is the main factor determining the radial nature of the regional flow. Karstic heterogeneities such as dissolution cavities, as well as fracture systems and the geology itself, control the local groundwater flow. Water flow occurs either in a diffuse form, through granular media, or via preferential pathways, when moving through fractures or dissolution cavities in the rock mass.

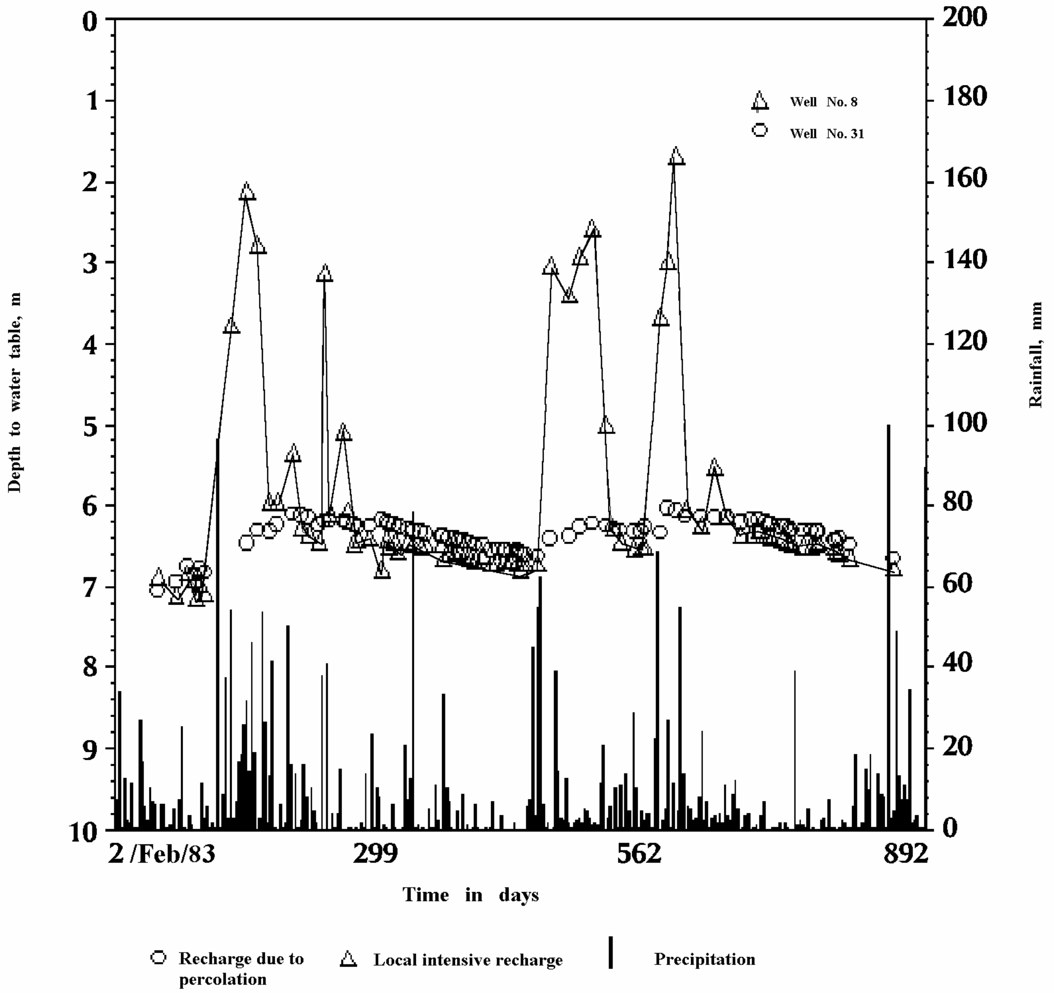
The presence or absence of fractures and cavities and their density determine the type of water movement through the porous media. Hydrogeologic effect of heterogeneities in the karstic aquifer is also manifested similar to well hydraulics, water table fluctuations due to tide influence, etc. Water table inland varies with precipitation, from a minimum value at the end of the dry season, to a maximum value during the rainy season (Fig. 3). When precipitation reaches approximately the mean annual value, the water table in Merida rises between 1.0 and 1.3 m, higher seasonal fluctuations are recorded south and west of the city.

COASTAL ZONE

A thin recrystallized limestone layer confines the aquifer along the coast of Yucatan. In the west, this confining layer extends almost 20 km inland and in the north, near Dzilam, it only covers 2 km approximately (Perry et al., 1989). Presumably, the aquifer hydraulic head along the coastline is approximately 24 cm higher than in the sea; this difference was measured in two piezometers, less than one meter distant, at different depths in the coast, north of Merida (Villasuso, 1994).

Differences in hydraulic heads, probably due to confined conditions explain the existence of springs discharging fresh water to the sea. In this region, ground water level variations are induced by tide fluctuations, whose influence extends some kilometers away from the coast (**Fig.** 1). Reeve and Perry (1990) state that ground water level varied, as a result of tide fluctuations, 2 cm, north of Merida, 13 km inland.

Fig. 3. Water table fluctuation and rainfall vs. time.



Tide influence was also detected in a cenote located 20 km from Celestun, using an electronic water level logger. The distance, from the coast, where tide propagates inland affecting ground water, depends on the hydraulic conductivity of the system. Cooper (1959) said that, in theory, saline interface penetrates inland resulting in higher dispersion of salts in highly conductive strata than in those with low K value, because of tide elevation.

North of Merida, ground water electric conductivity logs, carried out in two boreholes located 11 and 18 km from the coast, in the N – S direction, show that in the one located further inland a higher saline concentration exist. It seems that horizontal layers with high hydraulic conductivity exist in this zone, where seawater penetrates higher distances inland.

These layers are probably associated to the regional karstic characteristics. Marin (1990), based on physiographic and karstic evidences, stated that the intersection points of the belt of cenotes with the coast represent important ground water discharge zones, which have been conveyed to these point by the belt of cenotes. Apparently, these discharge zones represent high hydraulic conductivity sections, where the tide effects are transmitted to long distances from the coast; this is evident from water level records from Celestun where an existence of a combined effect, on the water table, was observed, probably as a result of two waves colliding, one of them due to tide fluctuations and the other one generated by preferential flows from the belt of cenotes to the sea.

INNER PLATEAU SURROUNDED BY THE BELT OF CENOTES

Perry et al., (1995), suggested that this zone is part of the sedimentary basin, result of the meteorite impact, generated by a crater 180 km in diameter approximately (Fig. 1). Tertiary marine sediments were deposited in this basin, during the Late Eocene and Oligocene. A thin lens of a dense and highly fractured recrystallized limestone, 0.20 to 1 m thick, called caliche, covers its surface, as in most of the state of Yucatan.

Surveys carried out in shallow wells, cenotes, caves, caverns and quarries, revels the presence of a karstified, discontinuous, stratum underlying the caliche on the surface. This subsystem, from now on called Caliche / Karst (C / K), is located in the unsaturated zone, near the ground surface and its hydrogeological importance is apparent when recharge occurs.

During and after heavy precipitation events, when rain water has infiltrated through the caliche, important horizontal flows can be developed along the horizontal kartified stratum in the C / K subsystem. In some cases, rain water could be stored in some C / K natural depressions where it percolates to the water table through the porous media; on the other hand, rain water can be intercepted by shallow wells or fractures present in the system, directly recharging the aquifer. The effect of this rapid and intense localized recharge results in extraordinary water table elevations, in shallow wells, more than 4 m in some cases (Fig. 3).

The fast dissipation of this hydraulic load, suddenly imposed on the system, is also one of its hydrodynamic characteristics as a consequence of its high hydraulic conductivity. It seems that this hydrogeologic subsystem, C / K, is present many times at depth, probably as many times as sea recessions occurred, taking enough time for these processes to proceed.

Buckley et al., (1994) found, using many boreholes drilled in Merida, some recrystallized limestone thin layers at 12, 20 and 30 m deep. Because of its lithologic features, these layers have been interpreted as old caliche generated when exposed to atmospheric conditions. Similar to the caliche on the surface, these layers overly kartified strata constituting, in this way, C / K subsystems in the saturated zone.

The karstified strata were visualized by means of caliper logs carried out in five boreholes; however, in two boreholes, located south Merida where the Oligocene outcrops, these strata were undetected. Ground water temperature and electric conductivity profiles carried out in deep boreholes, indicate that preferential flows are present at depths where C / K subsystems are also present (Fig. 4). Small changes occur in these parameters when water entering the borehole comes from systems with a different flow pattern and chemical history. Pumping 4 l/s, one meter below the water table, confirms the hydrogeologic importance of this system as far as production capacity of the aquifer is concerned. Because of pumping, ground water temperature and electric conductivity near the water table change until they reached a value similar to the one registered at 12 m deep; this manifest that water pumped came from the C / K subsystem located 12 m deep.

From some pumping tests carried out in boreholes in Yucatan, drawdowns between 0 and 3 meters were registered, even when pumping around 90 l/s. Areas with higher drawdowns are located near the Sierrita de Ticul; in the plateau, the lower drawdowns are recorded. In the southern limits of Merida, a 3 cm drawdown was registered when pumping 60 l/s in a borehole located 2 m distant from the observation well.

Therefore, well hydraulics in this region and, in general, in the plateau of the state of Yucatan is characterized by small drawdowns, a small cone of influence and dynamic level stabilization in a matter of minutes. On the other hand, Buckley et al., (1994), measured a 13 cm higher hydraulic head, in piezometers installed in the C / K subsystem located 12 m deep, than in the one located 30 m deep in Merida (Fig. 4). They suggested that the high urban recharge on top of the aquifer and water exploitation, between 18 and 30 m deep, might be the reason promoting this hydraulic head difference between both subsystems. However, this effect was only detected in two of five piezometers installed.

A continuous water level record was registered for two months in a shallow well in Samahil, a small town located north of the western segment of the belt of cenotes. This record suggests a hydrodynamic behavior of the aquifer, similar to those produced by surface currents or springs as a result of high recharge. This information opens an interesting perspective to study preferential flow hydrodynamics in saturated zones; it also gives an opportunity to study hydraulic connections of this zone and the belt of cenotes.

BELT OF CENOTES AND SIERRITA DE TICUL

Faults and fracture systems associated to the regional geologic structure (Fig. 1) control ground water dynamics. Groundwater flow in this region is characterized mainly by circulation through preferential pathways formed by fractures, dissolution conduits or both of them. Intrinsic permeability of the recrystallized limestone is one order of magnitude lower than that measured in the Miocene – Pliocene limestone that outcrops in the northern plateau; therefore, flow through granular interstices is presumably less important.

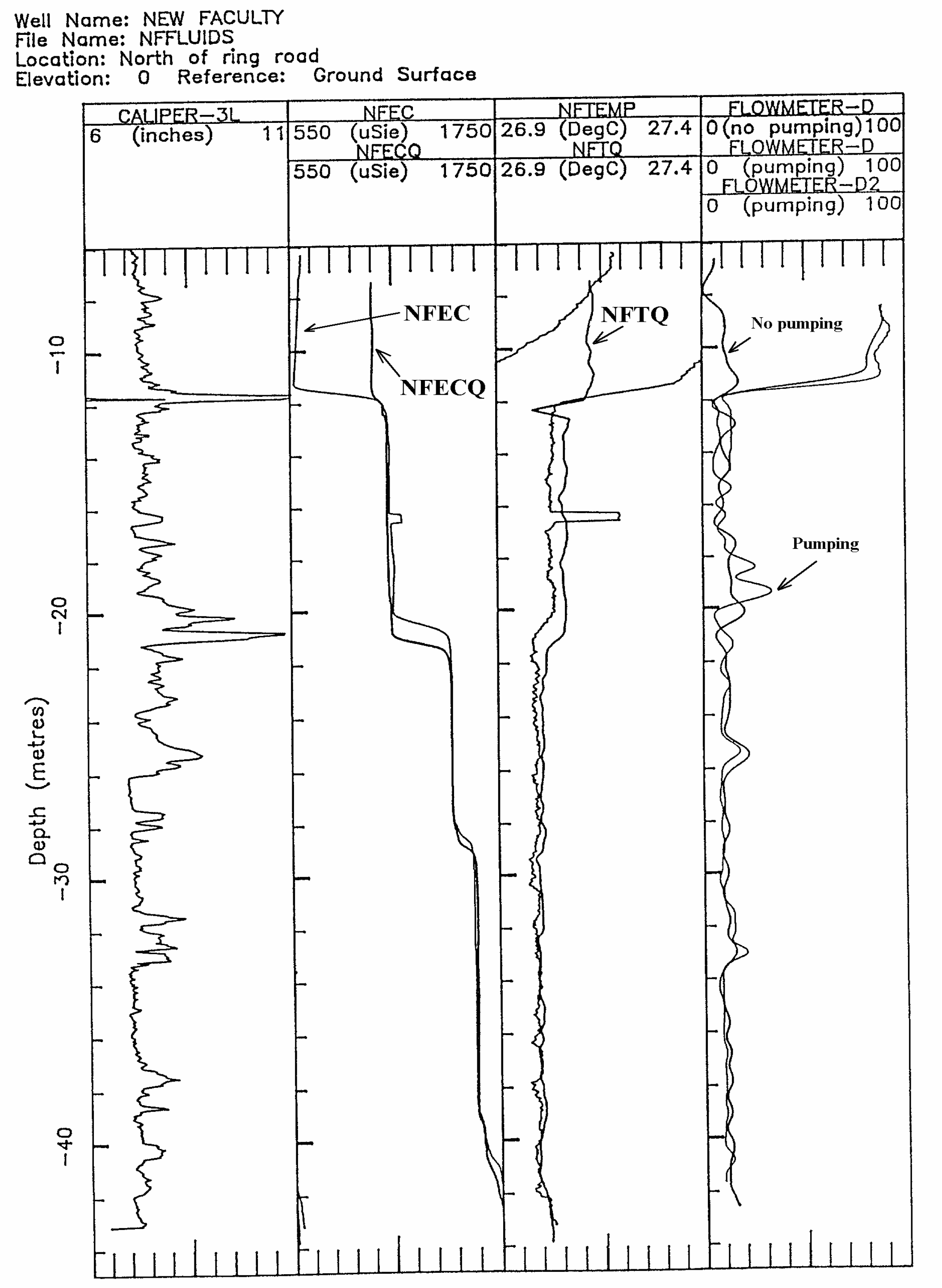
Marin (1990) measured hydraulic heads in the Yucatan aquifer and stated that the belt of cenotes works similar to a collecting pipe, because of its high hydraulic conductivity, conveying groundwater from the south to discharge points in the coastal intersections. This hydrogeologic conception of the Yucatan aquifer subsystem, suggests that preferential flow paths exist along some sections of the belt of cenotes.

Steinich (1996) presents a ground water divide in the belt of cenotes, implicit in the study carried out by Marin (1990), consisting of a low permeability thin belt located in the southernmost section of the belt of cenotes. However, hydraulic head contours indicate that groundwater flows through the SE segment of the belt of cenotes, crossing over it.

Hydrochemical evidence exists of preferential flows between the belt of cenotes and the Sierrita de Ticul. Velazquez (1986), using hydrogeochemical and geochemical methods, established that the Sierrita de Ticul represents a boundary between two aquifers called the Miocene – Pliocene aquifer and the Eocene aquifer; the first one is located to the northeast of the fault and the latter to the south. Along the Sierrita de Ticul, groundwater flow transports water with high sulfate content from Chichankanab lagoon and its surroundings, discharging it in the western segment of the belt of cenotes near a small town called Kopoma (Velazquez, 1995).

Well hydraulics in the Sierrita de Ticul area differs drastically when compared with the behavior of the inner plateau surrounded by the belt of cenotes. Pumping tests report up to 13 m drawdowns pumping from 12 to 38 l/s. Analyzing drawdown vs time curves obtained from some of these pumping tests, the hydrogeologic importance of fractures and dissolution cavities can be depicted given the system heterogeneous character and high hydraulic conductivity.

Fig. 4. Caliper, groundwater electric conductivity, temperature and flow velocity logs recorded in a borehole in Merida, Mexico.



DISCUSSION

Electronic devices and loggers are invaluable tools in groundwater monitoring. Precisions, of the order of millimeters, in these instruments allow recording tide effects on the groundwater level, in some cases up to 20 km inland, covering huge aquifer volumes where secondary heterogeneities in karstic systems can be considered. Estimating hydraulic conductivity by means of seawater and aquifer hydrodynamic studies is an important resource to obtain representative hydrogeologic parameter values in the Yucatan regional aquifer.

Reeve and Perry (1990), using limited data of tide influence on groundwater level fluctuations and assuming a specific storage in the range of 10^{-3} and 5×10^{-7} m^{-1} (Freeze and Cherry, 1979), estimated the hydraulic conductivity on the coast, north of Merida, between 22 and 45,000 m/d. The highest estimated value represent the order of magnitude of hydraulic conductivities used when calibrating numerical models applied to simulate the Yucatan aquifer. This suggests that estimating K by means of phenomena whose effect on the water table propagates extensively is the best alternative to obtain representative hydrogeologic parameter values in highly transmissive aquifers.

As far as the inner plateau, surrounded by the belt of cenotes (Fig. 1), is concerned, groundwater flow as well as aquifer trasmissive capacity, at least in the top 30 metres, are strongly controlled by the C / K subsystem. Groundwater flow in this region occurs diffusively or as preferential flow. In the diffuse flow, groundwater moves trough grains, while in preferential flows, water circulates trough fractures or via dissolution cavities and conduits, like karstic strata in the C / K subsystem.

The importance of these preferential flows at depth is manifested when contaminant transport studies are carried out or when tracers are used in the system for many purposes; therefore, these zones must be carefully monitored in future groundwater contamination and transport studies because they represent preferential paths where water circulates. Buckley et al., (1994), used video logs to identify almost vertical fractures which probably enhance hydraulic communication between these systems. Therefore, contamination entering from the top of the aquifer could easily move down to deeper layers promoted by the hydraulic head difference existent between the C / K subsystem at 12 m and the one at 30 m depth. On the other hand, these subsystems are a natural media to study the influence of the porous media and the karstified strata on the hydraulic conductivity.

Analogous to the caliche distribution on the surface of the state of Yucatan, as well as the presence of the karstic stratum underlying it, it is likely that C / K subsystems in the saturated zone to be highly distributed in a discontinuous way in the whole peninsula of Yucatan. Sea transgressions and recessions in the geologic past covered and exposed, respectively, huge extensions of land parallel to the old coastline in the Yucatan peninsula.

Caliche originates when dissolved calcium carbonate precipitates in the sediment on the surface exposed to atmospheric conditions when sea moved away. Therefore, it is likely that at different times when the sea moved down below 12, 20 and 30 meters, marine sediments deposited and exposed each time, were extensive land sections parallel to the coastline, where caliche could develop. Furthermore, groundwater at water table level has some acidity which could dissolve the limestone rock at that depth, allowing the development of karstified strata, parallel to the water table. During seawater fluctuations, the water table varied simultaneously with the sea. Those zones where water table was near the ground surface, were probably the best ones where both the karstification process and the caliche formation took place simultaneously, given origin to C / K subsystems.

When hydraulic heads are measured in an aquifer, to determine groundwater flow direction, it is advisable to investigate on its hydrodynamic behavior because high water table elevations, due to direct infiltration of rainwater in some wells, result in singular contour configurations of equipotential lines that distort groundwater flow direction. In the plateau surrounded by the belt of cenotes, groundwater at water table level moves on certain direction; however, groundwater circulating through C / K subsystems could travel to other directions. Hydraulic head differences between these systems also suggest this fact.

The high transmissivity of the Yucatan aquifer, together with the limitations of loggers, as far as their precision is concerned, and their difficulty in measuring the dynamic level, make pumping tests inefficient to evaluate the hydraulic conductivity. Thus, precision of electronic equipment as well as their capability to record continuously the water table dynamic level opens an optimistic possibility of using them in pumping tests carried out in highly transmissive systems.

Apparently, the preferential flow nature between the Sierrita de Ticul and the belt of cenotes is controlled by the fracture systems associated to regional geologic structures. However, Gonzalez (1992) showed that a flow pattern similar to the one occurring in this zone could be obtained via numerical simulations assuming that certain lithologic heterogeneity exist, a difference of two orders of magnitude in the hydraulic conductivity, between the Sierrita de Ticul and the plateau surrounded by the belt of cenotes. A systematic study of different ground water geophysical logs in this zone could contribute to the quantitative knowledge on the flow movement and could help in understanding the hydrodynamic interaction between the belt of cenotes and its surrounded inner plateau.

CONCLUSIONS

The study of certain aspects of the Yucatan aquifer hydrodynamics is a recourse that must be considered in order to obtain representative hydrogeologic parameter values. Hydraulic conductivity in a belt, some kilometers wide, parallel to the coast, could be estimated by means of studying the hydrodynamic relation between groundwater and tides. Important relations could also be established between the limestone hydraulic conductivity and the karstified strata in the inner plateau region surrounded by the belt of cenotes. C / K regional subsystems are very important in the aquifer transmissive capacity and also are an efficient means of contaminant transport. Karstic strata in this plateau seem to be the main zones through which preferential flow occur, while in the belt of cenotes and the Sierrita de Ticul the fracture systems associated to the developed karst are probably the main mechanisms controlling the flow system. Regional hydrogeologic characteristics should be considered in the different groundwater studies to be carried out, where groundwater movement is considered as an important factor.

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