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ORIGINAL ARTICLE

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Dynamic of the freshwater–saltwater interface in a karstic aquifer under extraordinary recharge action: the Merida Yucatan case study

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Abstract A hydraulic analysis of the interface between freshwater–saltwater behavior was done in the Merida Yucatan zone, two machines that constantly register the groundwater levels were installed, and three electric conductivity logs were taken from wells. When comparing the measured results with the ones obtained using theoretical equations developed to calculate the freshwater–saltwater interface position, it was proved that in some cases these equations can be applied, and in others not. Two effects that rule the behavior of karst aquifers in extraordinary conditions were found.

Keywords Salt water interface · Karst · Coastal aquifers · Groundwater · Yucatan · Mexico

Introduction

Back and Hanshaw (1974) observed that the water table was stable through long periods of time in sinkholes and water wells of the Yucatan Peninsula, which is why for a long time it was thought that by only taking some measurements of the static level it would be enough to know the behavior of the aquifer. Nevertheless, with the effects that hurricane Gilberto (Marin et al. 1990) brought to the area, the water table rose between 1 and 2 m in the Merida zone, indicating that it is necessary to perform detailed studies concerning the effects of additional recharge caused by an extraordinary event like a hurricanes and its impact on the position and extension of the freshwater–saltwater interface that underlines it for a proper management of the resource.

The karstic aquifer of Yucatan

The Yucatan Peninsula is a large platform in the eastern part of the Gulf Coastal Plain Province of Mexico. It has an area of approximately 350,000 km^2 that is bounded on the south by the Tierras Altas de Chiapas and the Guatemala Physiographic Province, to the north and west by the Gulf of Mexico (Fig. 1). The northern half of the Peninsula is a karstic surface with an average of 15 m above mean sea level bounded on the south by the Sierrita de Ticul range, a range of low hills with an elevation of about 150 m asl. The surface geology of Yucatan consists of sedimentary rocks from tertiary through quaternary.

Given the high permeability of the karstic aquifer (Back and Hanshaw 1974), the low depth of the water table, and the high precipitation rates that the Peninsula

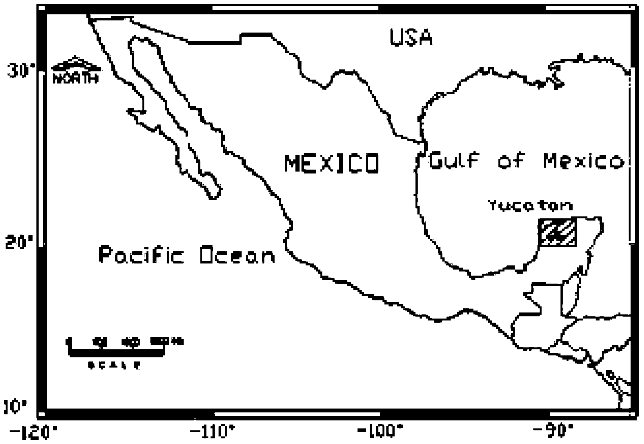

Fig. 1 Study area in the northwestern part of the Peninsula of Yucatán, México

has (CAN 2002), the aquifer recharge, due to its high hydraulic conductivity (Marin 1990; Graniel 2001), travels very rapidly into the coastal zones where submarine discharges of groundwater are presented (Perry et al. 1995). Due to its geographical location on the Caribbean, the Peninsula is subject to the presence of hurricanes that produce precipitations that generate extraordinary recharge.

Objectives

The objectives are to analyze the hydraulic behavior of the freshwater–saltwater interface in karst aquifers in extraordinary recharge conditions and to identify the processes that rule the hydraulic behavior of the aquifer with extraordinary recharge.

The extraordinary recharge

From September 22nd through September 24th 2002, hurricane Isidore passed through the Yucatan Peninsula. The National Water Commission (CNA 2002) estimated that the precipitation caused by the hurricane was 550 mm generated between September 14th, and September 25th. Measuring equipments that constantly register the piezometric levels were installed and field data were taken to measure the effect it had on groundwater.

In situ determination of the interface position

Records of the electric conductivity in three wells were taken on October 25th, 2000, and on January 23rd, 2003, with the purpose to determine the freshwater–saltwater interface position and to determine the extent of the mixture between both fluids in the zone.

Piezometric level monitoring

Two machines equipped with a pressure transductor to take continual variation records of the piezometric level were installed. The first record was taken on October 21st, 2002, in the Observatory's well and on the following day in the Tamanche well, 27 days after hurricane Isidore; the registry ended on December 12th, 2002, for both cases. The equipment was programmed to take precise readings every hour; thus, 1,004 registries were taken from the Observatory's well and 984 registries were collected from the well in Tamanche (Fig. 2).

Freshwater–saltwater interface position

Analyzing the record behavior in Fig. 3, an abrupt change in the electric conductivity can be observed when it reaches 10,000 µS/cm. According to Appelo and Postma (1996), it implies a 15% seawater content. Further along, this will be taken as a reference value to indicate the freshwater–saltwater interface position. According to Appelo and Postma (1996), the present electric conductivity of seawater is in the order of 63,000 µS/cm, while in the well from the Observatory the value of 80,000 µS/cm was detected, which implies

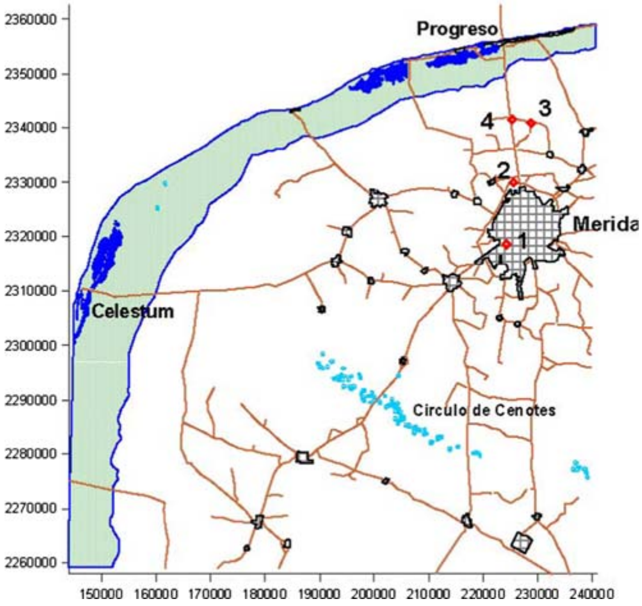

Fig. 2 Location of the measuring sites; *1* Observatory, *2* UADY, *3* Las Margaritas, and *4* Tamanche. The coordinates are in UTM

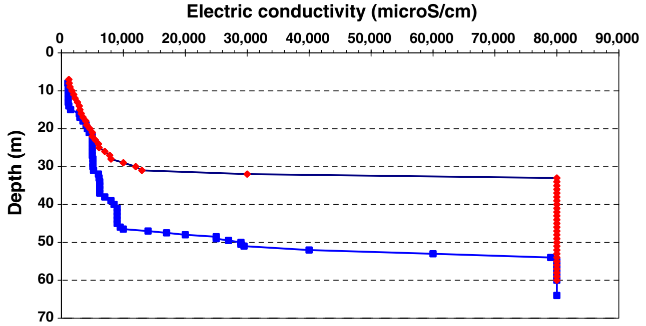

Fig. 3 Records taken from the Observatory's well; the curve with the *circle symbols* corresponds to the records taken on January 2003 and the curve with the *square symbols* represents the records taken on October 2000

that there is more ion concentration than in the present content of seawater.

With the results obtained from the electric conductivity records, shown in Figs. 3, 4, and 5, it can be seen that the Observatory's well is the only one where the freshwater–saltwater interface can be detected along with the zones where these fluids mix, since the electric conductivity reaches the values of 80,000 µS/cm. In the other two wells, even though an increase of electric conductivity can be seen, the highest values do not correspond to the presence of saltwater, but to the freshwater mixing zones with different salt concentrations, presenting values less than 5,000 µS/cm.

On the records of Fig. 3 the highest reachable value is 80,000 µS/cm. This value corresponds to the detectable capacity of the equipment used; it is assumable that at greater depths there may be values over 80,000 µS/cm.

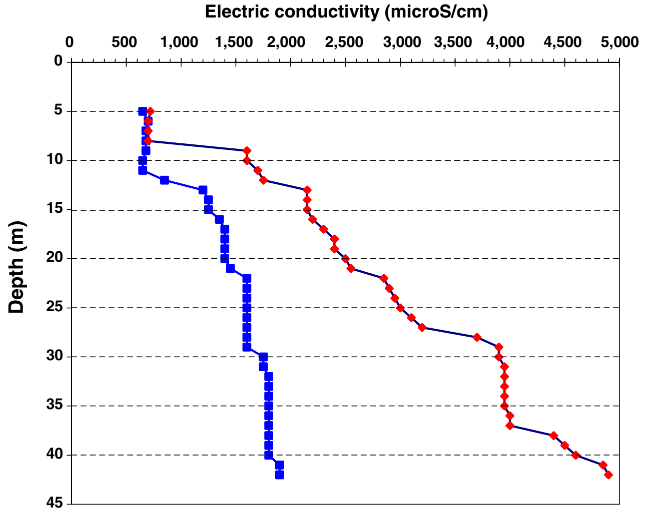

Fig. 4 Records taken from the UADY well; the curve with *circle symbols* corresponds to the records taken on January 2003 and the curve with *square symbols* corresponds to the record taken on October 2000

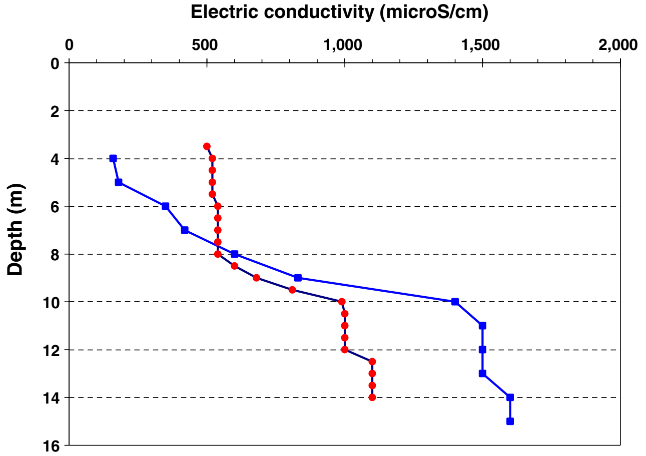

Fig. 5 Records taken from the well in Las Margaritas; the curve with *circle symbols* corresponds to the records taken on January 2003 and the curve with *square symbols* corresponds to the records taken on October 2000

With the measurements taken on October 2000 the interface position was determined in the Observatory's well located at a depth of 46.5 m. By taking the information from the Observatory's well, it was determined that the value of Z was 37.68 m. However, considering the same information from the Observatory's well and applying it to the Ghyben Herzberg equation, the value of Z becomes 36.4 m.

When applying the same procedure to the information taken on January 2003, the average Z value is 31 m. Calculated with the Ghyben Herzberg equation the value of Z results 78.4 m. If the freshwater–saltwater mixing zone derived from the Observatory's well records taken on October 2000 is assumed to be between the most superficial point with an electric conductivity of 10,000 µS/cm as the initiating zone and the most superficial point with an electric conductivity of 80,000 µS/cm as the end zone, then the mixing zone is between the depths of 45.6 and 54 m and it has a thickness of 7.5 m. For the records taken on January 2003, the mixing zone is between the depth of 29 and 33 m with a thickness of 4 m.

Interestingly, between the records of October 2000 and the records of January 2003, the mixing zone rose 17.5 m, although the static level is 1.05 m higher in January 2003. This is unexpected considering that in theory when the hydraulic head is greater in freshwater, saltwater is pushed down. Thus, the hydraulic behavior of the aquifer must be analyzed when referring to piezometric charges.

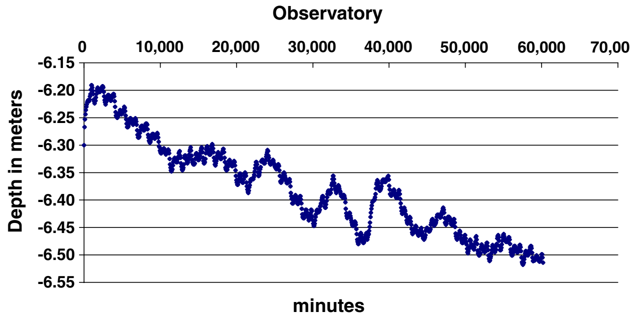

Fig. 6 Records taken with the minitroll equipment in the Observatory's well

Comparing the extraordinary recharge

With the records obtained from the minitroll equipment, the Temanche well decreased 43.3 cm in the same period of time, dropping at an average rate of 10.7 mm/day throughout the whole record.

From the analysis of the records shown in Figs. 6 and 7, several sections with different drop rates of the static level were determined. These are greater during the first sections. In the first section in the Observatory's well, the average dropping rate of the water level was of 20.9 mm/day. In the Temanche well the average drop rate was 32.7 mm/day.

In Figs. 6 and 7, there four peaks that have static level increments in a very short period of time (40–60 h). It is possible that they are associated with extraordinary rainfall making recharge waves travel throughout the aquifer, considering that the rainfall that made this extraordinary recharge was concentrated in 10 days. When analyzing the data presented in Figs. 6 and 7, it is clear that the peaks appeared at the same time in both wells located 23 km apart and that the peaks arrived with a regularity of every 5 days.

Discussion

The entry of the extraordinary recharge mass was so fast that there was not any time for it to mix with the water that was already in the first layers. From this behavior, it can be concluded that in the cases with extraordinary recharge, the flow is preferably vertical and it works as a piston moving layers of water down. This hypothesis is backed up with the results from the records taken with the minitroll equipment, where the peaks arrived at the same time in wells located 23 km apart and no horizontal movement is detected with respect to time.

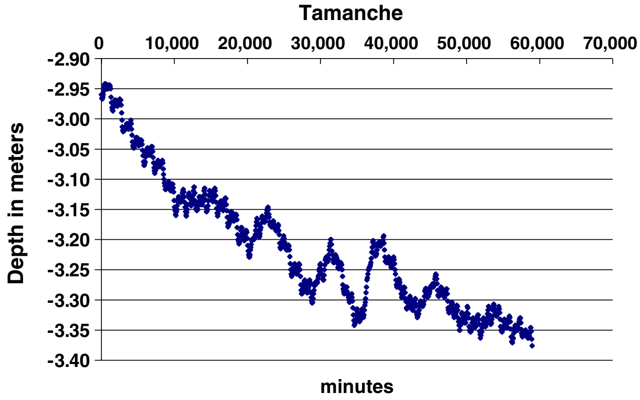

Fig. 7 Records taken with the minitroll equipment in the Temanche well

This behavior suggests that the system works like a coiled spring when the layers of freshwater are moved down due to the extraordinary recharge. First there is the piston effect, then later water layers bounce back and move up and down, until the energy dissipates and the system returns to its original position. This hypothesis is backed up with the behavior taken from the minitroll equipment records where peaks every 5 days and at the same time are observed, and with the mixing zone amplitude variations. This implies that the system rebound wavelength takes 5 days, and that the effect diminishes, gradually reducing amplitude (Figs. 6, 7).

Conclusions

In karst aquifers with great permeability and superficial static levels, when there is extraordinary recharge due to the speed and volume of water entering the system, the flow is preferably vertical and works like a piston effect, pushing the layers of water down. In the cases with extraordinary recharge in karst aquifers, the system (rock and water) works like a coiled spring, moving the layer of freshwater down with a piston-like effect due to the extraordinary recharge; then later, freshwater bounces back to the top and once again back down until the energy dissipates and the system returns to its original position.

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