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Basement topography and fresh-water resources of the coastal aquifer at Acapetahua, Chiapas, Mexico

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RESUMEN

El acuífero costero de Acapetahua, Chiapas, en el sureste de México, consiste en una unidad hidroestratigráfica compuesta de sedimentos continentales con un basamento cristalino. Se realizaron veinticuatro sondeos de resistividad y se tomaron cincuenta y una muestras de agua con el fin de determinar las características básicas del acuífero, como son la geometría del acuífero y sus reservas de agua dulce. La topografía del basamento se caracteriza por cumbres y valles profundos. La profundidad al basamento varía entre unos pocos metros y varios cientos de metros. Los altos del basamento se encuentran a lo largo de la línea costera, a distancias entre 4 y 15 km de la costa, reduciendo considerablemente el espesor del acuífero. La zona de transición entre agua salada y agua dulce coincide en el espacio con los altos del basamento, que representan actualmente el límite del acuífero de agua dulce hacia la costa. Con base en la geometría del acuífero de Acapetahua determinada con los modelos de resistividad, y considerando los valores de sólidos totales disueltos de las muestras de agua, el volumen máximo de poros saturados de agua dulce fue estimado en 75 km^3.

PALABRAS CLAVE: Chiapas, acuífero costero, geometría del acuífero, interfase agua salada/agua dulce.

ABSTRACT

The coastal aquifer of Acapetahua, Chiapas, southeastern Mexico, consists of one hydrostratigraphic unit composed of continental sediments overlying a crystalline basement. Twenty-four resistivity soundings were conducted and fifty-one water samples were taken in order to determine basic aquifer characteristics such as aquifer geometry and fresh water reserves. The basement topography in the study area is characterized by hills and deep valleys with highly variable basement depths ranging from less than ten meters to several hundreds of meters below surface. Basements hills reduce the aquifer's thickness considerably along a zone at distances between 4 and 15 km from the coastline. The location of the transition zone between sea and fresh water coincides in space with the basement crests. These crests represent the limit of the fresh-water part of the aquifer in the near coastal region. Based on the aquifer's geometry determined from resistivity models, and total dissolved solids of the water samples, a maximum value for the pore volume saturated with fresh water in the aquifer of Acapetahua was estimated at 75 km^3.

KEY WORDS: Chiapas, coastal aquifer, aquifer geometry, salt/fresh-water interface.

INTRODUCTION

The southern part of the state of Chiapas consists of a coastal plain less than 35 km wide between the Sierra Madre de Chiapas and the Pacific ocean. Topography is smooth only on this narrow plain (INEGI, 1994a), while altitudes rise rapidly landwards from less than 100 m above mean sea level (amsl) to more than 3000 in the Sierra Madre de Chiapas. Climate is tropical, rainfall is intense during the hurricane season that lasts from May to November, and there is no well-defined winter season (Morán-Zenteno, 1994; Müllerried, 1957).

The coastal plain is used for limited agricultural activities (e.g. the cultivation of citrus fruit) and widespread stock breeding. Climate and topographic conditions favor an intensification of agricultural activities. Sustainable management of the coastal aquifer is the basis of such development. Despite the availability of surface water throughout the year, the use of ground water may be given priority since the dependence on precipitation rates disappear and a better correlation with other favorable conditions such as temperature or availability of manpower may optimize the yield.

However, there is little information available about the hydrogeology of the aquifer systems of the Pacific coast of Chiapas. Müllerried (1957) gave a description of the geology of the state of Chiapas. Based on this information, a unique hydrostratigraphic unit composed of continental sediments of Pliocene and Quaternary age overlaying the crystalline basement of Precambrian (Müllerried, 1957) and/or Paleozoic (López-Ramos, 1982) age, may be assumed for the coastal aquifer. There is no evidence of a confining layer (Müllerried, 1957; Morán-Zenteno, 1994), so the aquifer may be assumed unconfined. There is no information about the depth of the basement, and therefore no realistic estimate may be made about the aquifer's geometry and fresh water resources.

The location of the salt/fresh-water interface as a function of the exploitation of a coastal aquifer is a sensitive parameter for the impact of water extraction on the aquifer's water balance. Overexploitation has led to drawdown cones and to sea water intrusion in many coastal aquifers in the Mexican Republic and elsewhere (e.g. Andrews, 1981; Steinich *et al*., 1998; Steinich and Chavarría, in press; Chen *et al*., 1997). Sea water intrusion is often related to an advance of the fresh/salt-water interface landward and the replacement of fresh by brackish water in the pores. Secondary effects such as salinisation of soils may have specially high impact namely in areas with high evaporation indices, as is the case for the study area. Salinisation make soils unsuitable for agricultural activities and may lead to the desolation of vast areas along the coast (Steinich *et al*., 1998). A sustainable management of the ground water resources must consider this risk of desolation of cultivated land which may be a high percentage of the total available land in a narrow coastal band such as the study area.

The objectives of this study are: (1) to describe the geometry of the coastal aquifer of Acapetahua, (2) to determine the location of the salt/fresh-water interface and (3) to estimate the fresh water resources of the aquifer of Acapetahua.

DESCRIPTION OF THE STUDY AREA

The study area is located at the Pacific coast of the state of Chiapas in southeastern Mexico. It consists of an area parallel to the coast line between 92°30' and 93°10' west and 15°00' and 15°30' north. It is 53 km long and between 23 and 32 km wide (Figure 1). The area is limited to the southwest by the coast of the Pacific ocean and to the northeast by the Sierra Madre de Chiapas. The rivers Novillero and Vado Ancho are located near its northwestern and southeastern limits, respectively (Figure 1). The topography is flat through-

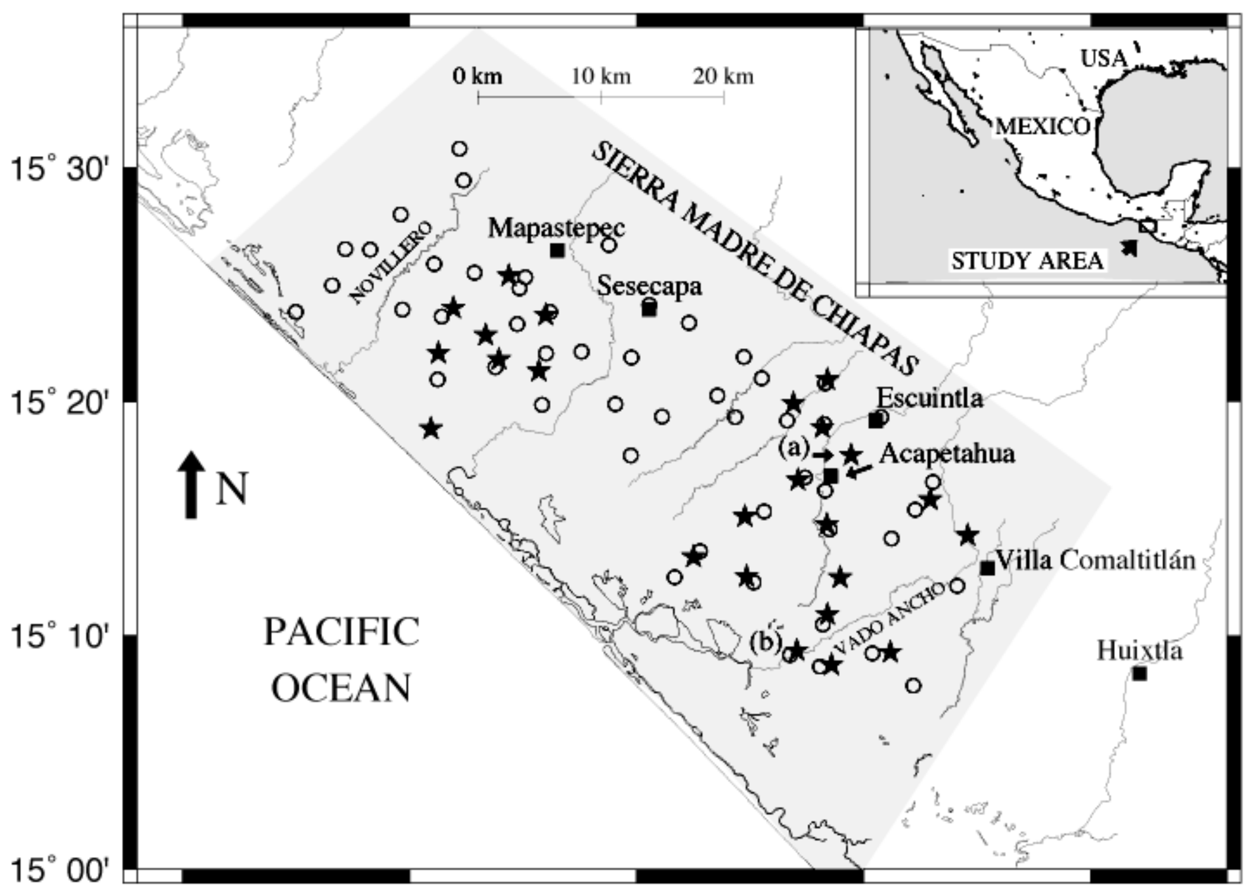

Fig. 1. Overview of the study area. Twenty-four Schlumberger soundings are shown as black stars (★), 51 water sample sites are shown as open circles (o). (a) and (b) are the locations of the resistivity soundings represented in Figure 2.

out the area with altitudes ranging from sea level at the coast line to 100 m above mean sea level (amsl) at its northeastern limit (INEGI, 1994b). While isolated hills are reported elsewhere within the coastal band, there are no such structures in this segment (INEGI, 1994a).

METHODOLOGY

Twenty-four Schlumberger resistivity soundings were conducted in November, 1997 and January, 1998. Maximum AB/2 spacings were 675 m in all cases. Locations are shown in Figure 1. All measurements were made with a SYSCAL R1 resistivity meter. Locations were determined with a GPS Garmin 47. Schlumberger soundings were interpreted using a FORTRAN code written by the senior author, based on digital linear filter theory (Koefoed, 1979) and on the automatic interpretation method presented by Zohdy (1989). The multilayer step-function model for each sounding was simplified using Dar Zarrouk functions (Zohdy, 1989). These equivalent models were interpreted for basement depth. Fifty-one water samples were taken in November, 1997 from domestic water supply wells; locations are shown in Figure 1. All samples were taken from the upper 5 meters of the aquifer. Samples were filtered to remove particles larger than 0.2 μm. Alkalinity was determined in the field by Gran titration (e.g. Stumm and Morgan, 1981) using a Hach kit and 1.6 N H_2SO_4. Samples were taken in four 10 ml vacutainers per site, two for the analysis of anions and two for cations. They were stored in a cooler and in a dark refrigerator at 4° C previous to analysis. Anions were analyzed using an ion chromatograph and cations by flame atomic absorption. All analyses were conducted at the Institute of Geology at the Autonomous National University of Mexico (UNAM). Detailed analyses are reported by Steinich and Sánchez-Ramírez (1998). For the purpose of this study, total dissolved solids were determined as the sum of the analyzed ions. All samples used in this study had a mass balance error of less than 5%. All figures except Figure 2 were generated with the Generic Mapping Tool (GMT) version 3 (Wessel and Smith, 1995).

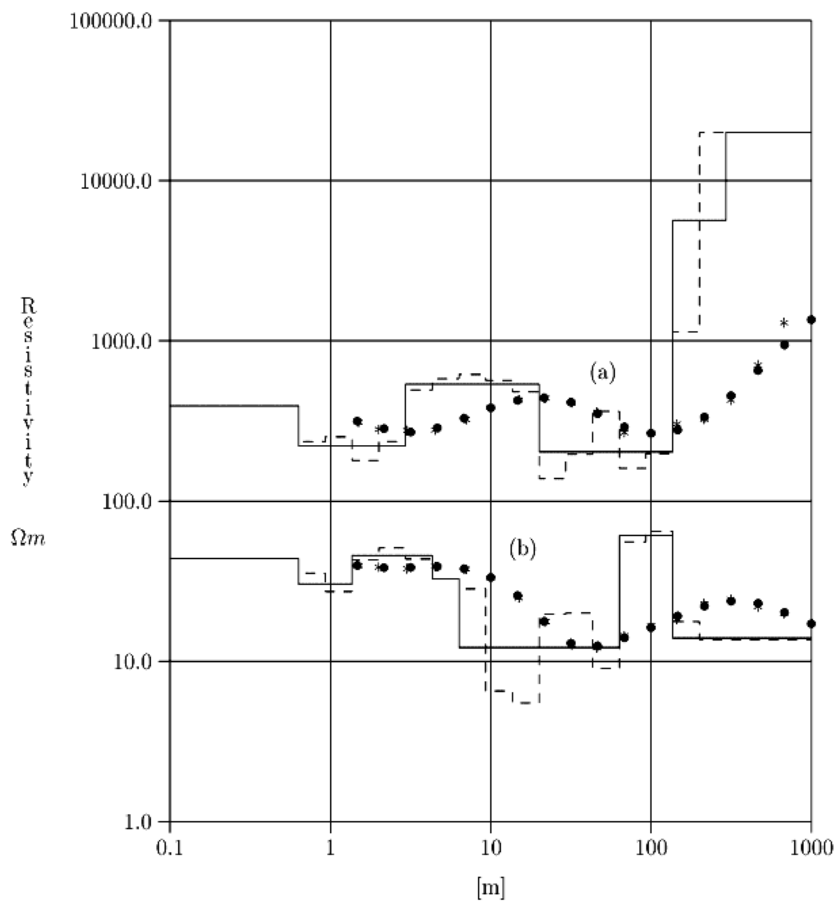

Fig. 2. Data and resistivity models of two soundings, (a) and (b). Field data is represented as solid circles (•) and apparent resistivities of the model curves as asterisks (∗). The dashed line represents the multilayer step-function models, the solid line is the interpreted simplified layer model. Locations are shown in Figure 1.

RESULTS AND DISCUSSION

Aquifer geometry

The aquifer of Acapetahua consists of porous material composed of continental sediments of Pliocene and Quaternary age. Rivers draining the Sierra Madre de Chiapas have been the transport agents of this material, so porosity in horizontal and vertical directions is variable. No evidence exists of any confining layer (Müllerried, 1957). On the regional scale, the aquifer of Acapetahua may be described as one hydrostratigraphic unit. One of the most important basic parameters is the depth to the crystalline basement in this area. The knowledge of this depth, together with the topography, allows an estimation of the aquifer's geometry and volume.

The electrical resistivity of the continental sediments is of the order of 10^1 to several 10^2 Ωm, whereas the resistivity of the crystalline basement is of the order of 10^3 Ωm or higher (e.g. Dobrin, 1981). An abrupt rise of the resistivity may be observed in several of the twenty-four Schlumberger soundings conducted in the study area: curve (a) in Figure 2 shows one example. The dashed line represents the resistivity model interpreted from the corrected field data, the solid line is the simplified layer model (Zohdy, 1989) used here for the interpretation of depth of basement. Resistivity values vary between 150 Ωm and 600 Ωm at depths down to 140 m below surface and rise rapidly to resistivity values higher than 1000 Ωm at this depth. A resistivity contrast like the one observed in curve (a) of Figure 2 was not detected in all soundings. Curve (b) in Figure 2 shows an example of a model where all resistivities are less than 100 Ωm and without a deeper abrupt rise. In this case, the depth to the basement is larger than the total thickness of the interpreted resistivity model of approximately 200 meters (above the infinity layer). On the base of the twenty-four resistivity models, a "depth-of-basement"-map was generated (Figure 3). In the southeastern and northwestern parts of the study area, where no depth of the basement could be determined from the resistivity soundings, interpolated depths using the values of the surrounding sites are reported (Figure 3). Depths of the basement vary between a few meters bmsl near the

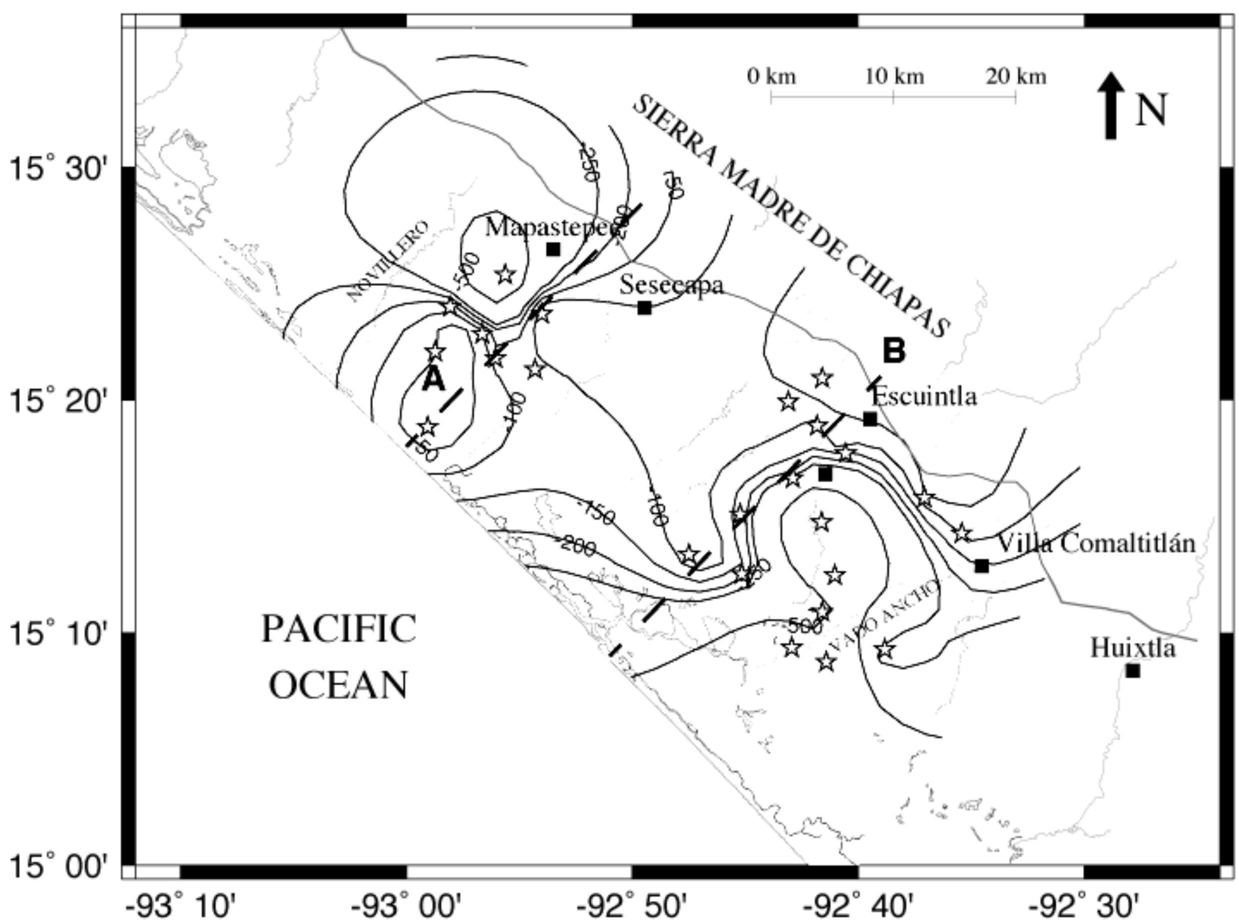

Fig. 3. Depth to the basement; values are in meters relative to mean sea level.

coast in the northwestern part of the study area and possibly several hundreds of meters in its southeastern and northwestern part.

Figures 4 and 5 show the two sections A and B of the aquifer, respectively (see Figure 3 for location). It may be observed that the aquifer's geometry is characterized by a basement topography with hills and deep valleys which is a continuation of the similar topography of the Sierra Madre de Chiapas northeast of the study area. Crests that considerably reduce the aquifer thickness may be observed at a distance of 4 km from the coastline in the northwestern part (Figure 4) and a distance of 11 km from the coastline in its southeastern part (Figure 5). In the segment of the coastal band that corresponds to the study area, none of these crests reach the surface. However, northwest of the study area isolated hills may be observed within the coastal band (INEGI, 1994a).

Salt / fresh-water interface

The classification of ground water with respect to its quality is a function of the amount of its total dissolved solids (TDS). Water with less than 1000 ppm of TDS is considered fresh water (Freeze and Cherry, 1979). Water with TDS above this values may be classified as brackish (between 1000 and 10 000 ppm) or saline water (above 10 000 ppm). TDS of the ground water of the aquifer of Acapetahua varies between values less than 100 ppm near the Sierra Madre de Chiapas and approximately 10 000 ppm in its southeastern part (Figure 6). Figure 6 shows that the TDS gradient is high between 500 and 1000 ppm. This zone is named here the 'transition zone' between fresh and brackish water and is shown in Figure 6 as a gray shaded band. The part of the aquifer between this band and the coastal line is invaded by brackish or saline water, whereas water northeast of the transition zone may be considered fresh water.

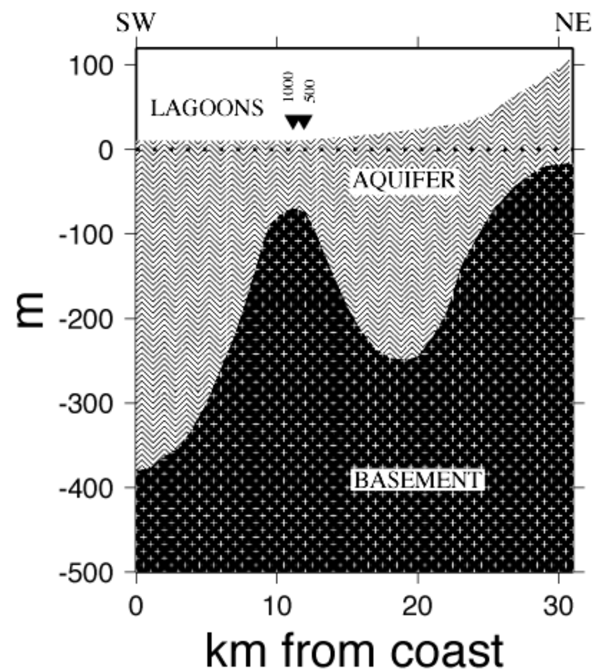

Fig. 5. Section B, see Fig. 3 for location. Vertical exaggeration is 60:1. Arrows show the limits of the transition zone, values above the arrows are in TDS.

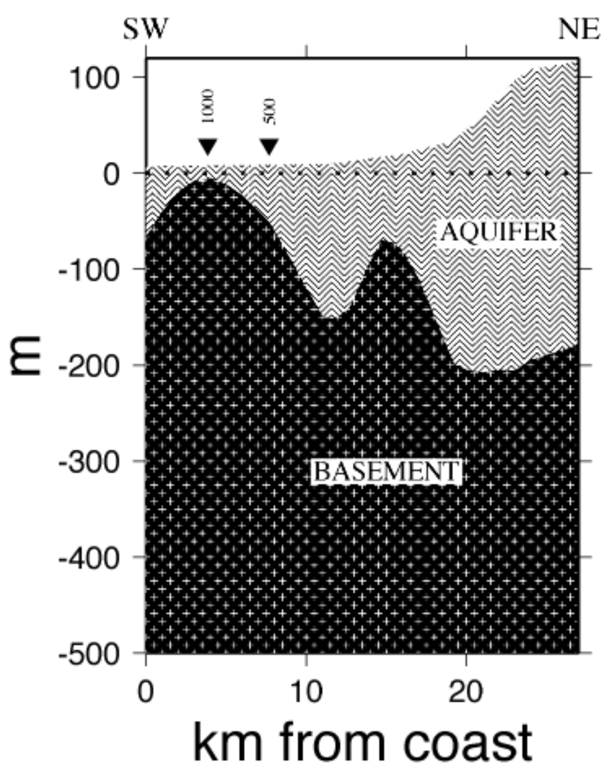

Fig. 4. Section A, see Fig. 3 for location. Vertical exaggeration is 60:1. Arrows show the limits of the transition zone, values above the arrows are in TDS.

It may be observed in Figure 6 that the transition zone is not parallel to the coast line. The area of the aquifer invaded by sea water is less than 5 km wide in the northwestern part of the study area and more than 15 km wide in its southeastern segment. In the same Figure 6, it may be observed that the presence of lagoons, filled with saline water (Müllerried, 1957) represents a typical surface manifestation of the area between the transition zone and coastal line (INEGI, 1994b).

The limits of the transition zone are shown in the resistivity sections A and B (Figures 4 and 5) as arrows. It may be observed in these figures, that the 1000 ppm limit coincides in space with the crests of the basement. A comparison between these sections and the TDS-map (Figure 6) implies

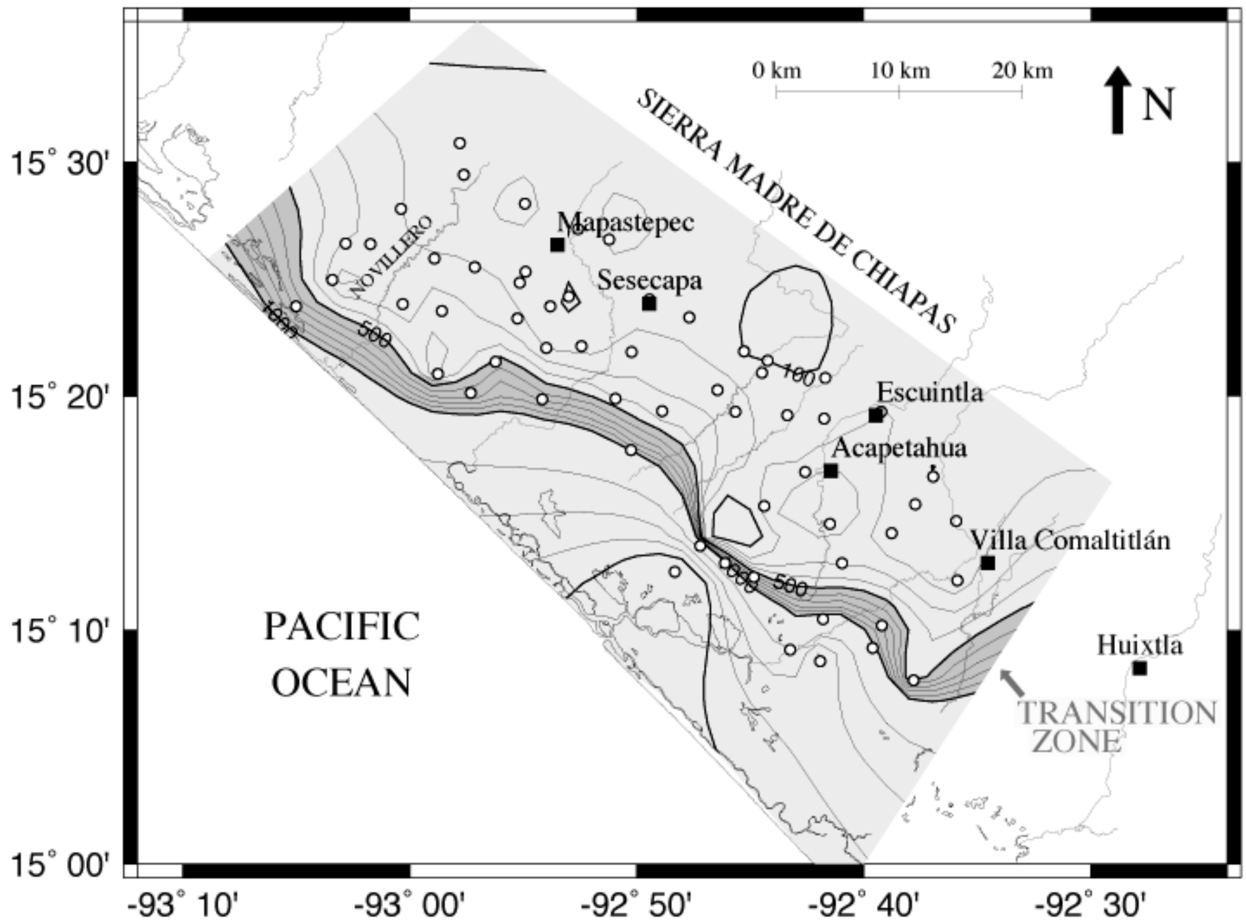

Fig. 6. Lines of equal Total Dissolved Solids (TDS). The gray shaded band is the transition zone, explanations in the text.

that the crests of the basement near the coast divides the aquifer in two parts. One from the crest towards the coast and another from the crest land inward. The former part is completely invaded by sea water and is characterized at the surface by the presence of saline water lagoons. The latter is the fresh water aquifer; only this part may be considered as the fresh water reserve of the study area. The high crest near the coast that may be observed in Figure 4, reduces the aquifer thickness to less than 10 m and may act as a protection barrier for the fresh water aquifer, preventing sea water from intruding further inland. The described configuration of the aquifer is that of its natural state, since almost no ground water extractions are occurring.

Fresh water resources

The knowledge about the aquifer geometry and the location of the salt /fresh - water interface may be used to estimate the fresh water resources of the aquifer of Acapetahua.

Due to the geology settings, the aquifer coincides with the continental sediment layer. The limit between this layer and the basement represents therefore the lower limit of the aquifer. The depth to the water level is less than 1 m across vast areas near the coast and descends to maximum values of 10 meters at the northeastern limit of the study area; for the purpose of this estimation, the totality of the continental sediments is assumed to be saturated. The upper limit of the aquifer coincides therefore with the topography levels within the study area. Figure 7 shows the thickness of the aquifer as derived from the depth-of-basement data presented in Figure 3 and the topography (INEGI, 1994b).

In the horizontal directions, aquifer limits are taken as follows. (1) The presence of fresh water is limited to the volume from the 1000 ppm isoline inland. There is no information about the curvature of the interface as a function of depth, so for this estimation the curvature is assumed to be zero. (2) The limit of the study area to the northeast coincides with the 100 m topography level and (3) the limits to the southeast and northwest coincide with the limits of the study area.

The projection of this fresh water portion of the aquifer described by these limits is presented in Figure 7 as a gray shaded area, including the transition zone. Topography, depth-of-basement and thickness values are gridded on a 1'x 1' grid. The average thickness of the fresh water part of the aquifer calculated based on the above assumptions has a value of 250 m, the corresponding volume is 300 km^3. Assuming a medium porosity of 25% (e.g. Steinich *et al*., 1997), there is about 75 km^3 pore volume saturated with fresh water in the aquifer of Acapetahua. It is important to stress that this amount is an optimistic estimate for the following reasons: (1) The top of the basement was not observed in all soundings. Aquifer thicknesses in the southeast and northwest parts of the study area may be smaller than interpolated. (2) Any realistic, non-zero value for the curvature of the salt/fresh-water interface tends to reduce the fresh water part of the aquifer, and (3) the water quality may decrease with depth. Sea water that intrudes beyond the basement barriers near the coastal line tends descend behind them by gravity and accumulate at the bottom of the basement depressions. The trend to lower values with depth before the abrupt rise of the resistivity as observed in various resistivity curves may be related to this phenomenon (Figure 2). However, all water samples were taken from the uppermost part of the saturated zone; no deep wells exist actually in the study area where the bottom of the aquifer could be monitored.

CONCLUSIONS

The aquifer of Acapetahua is a 53 km long segment of a system of aquifers along the Pacific coast of the state of Chiapas. Based on twenty-four resistivity soundings and fifty-one water samples, basic aquifer characteristics were investigated in this study.

The aquifer consists of one hydrostratigraphic unit of continental sediments overlaying a crystalline basement. There is no evidence for a confining layer, so the aquifer may assumed to be unconfined. The basement topography consists of hills and deep valleys as a continuation of the topography of the Sierra Madre de Chiapas at the northeast

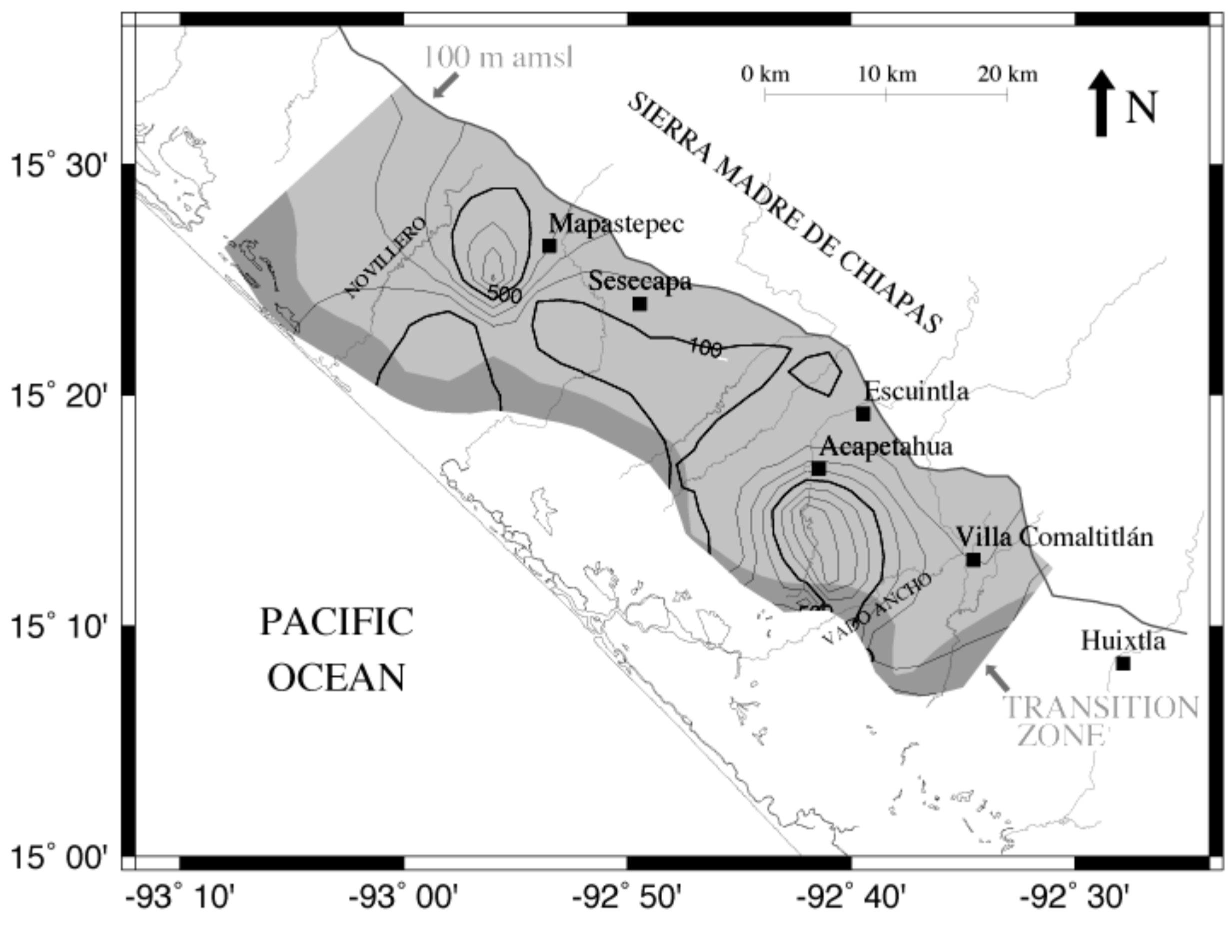

Fig. 7. Thickness of the continental sediments that host the aquifer of Acapetahua. Values are in meters.

of the study area. Aquifer thickness varies between less than 10 m and several hundreds of meters. Basement crests near the coast reduce the thickness of the aquifer to such an extent that they may act as protection barrier against intruding sea water at some places. Based on the classification of natural water presented by Freeze and Cherry (1979), the 1000 ppm TDS-isoline was taken as representive for the salt/fresh - water interface in this study. This 1000 ppm TDS-isoline coincides with the basement crests in the aquifer of Acapetahua. Therefore, the alignment of crests near the coast line acts as the limit of fresh-water bearing part of the aquifer towards the sea. The distance between the coastal line and the interface is then related to the location of basement crests and is less than 5 km in the northwestern part of the study area and more than 15 km in the southeastern part of the aquifer. The part of the continental sediments between the crests and the coast is completely invaded by sea water.

Basement hills and deep valleys are probably the decisive characteristic for the flow system within the aquifer. One consequence is the spatial coincidence of the salt/fresh - water interface with the location of basement crests in the near coast region. On some aquifer segments, these crests reduce the aquifer thickness to such an extent that they may protect the aquifer from intruding sea water. On other segments, sea water may intrude and descend behind the crests by gravity, filling up the basement depressions without triggering a substantial displacement of the salt/fresh - water interface. This type of sea water intrusion may not be monitored with shallow wells and may occur unnoticed during a long period.

The volume of the fresh-water bearing part of the aquifer was estimated based on the aquifer thicknesses and the location of the salt/fresh - water interface and is approximately 300 km^3. There is no information about the medium porosity of the aquifer of Acapetahua, however, taking the typical value for continental delta deposits of 25%, a total of 75 km^3 of fresh-water filled pore volume may be estimated for the aquifer of Acapetahua.

The study area represents 19% of the coastal band of the state of Chiapas. Since there is no evidence for a substantial change in overall conditions of the remaining part of this coastal band relative to the aquifer of Acapetahua, it may be assumed that the aquifer characteristics proposed in this investigation are representive for the whole Pacific coast of the state of Chiapas. Any planning of ground water management and the location of exploitation wells may be undertaken on the basis of this type of unconfined coastal aquifer that consists of only one hydrostratigraphic unit and a highly variable depth to basement.

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