DC geo-electrical and TD electromagnetic investigation of the Fresh Water Aquifer of Benjamin Aceval, Paraguay

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Summary

The lens shaped fresh water aquifer exploited by the township of Benjamin Aceval in the Paraguayan Chaco was investigated by 13 DC Geo-electrical Profiles and 24 Time Domain Electromagnetic Soundings. The 2D inversions of the DC resistivity sections delineate sharply the border line between the surrounding saline terrains and the fresh water. The TDEM soundings quantify the depth extent of the fresh water reservoir underlain by either highly conductive saline water and/or clay layers. The investigation provides quantitative information to the water management authorities showing clearly the 3D limitation of the water reservoir which appears split into several confined bodies separated by saltwater intrusions.

Introduction

The subtropical semi-arid climate of the Paraguayan Chaco, where the evaporation exceeds the precipitation during several months throughout the year, causes wide areas being characterized by very saline water in the near surface aquifers including rivers and streamlets. Small artificial ponds (*tajamares*) storing the rainwater are often the only source of drinking water and the basis for agriculture and stock farming. All the more important are rare occurrences of confined lenses of fresh water, which, under special conditions, are related to morphological elevations raising a few dozens of meters above the plains.

The city of Benjamin Aceval, situated some 40 km north of Asunción, Paraguay, and populated by more than 16.000 inhabitants, relies on such kind of valuable freshwater aquifer. The sustainable management of the limited resource, which is in danger of overexploitation in near future due to the increasing urban, agricultural and industrial development, requires the knowledge of the available reserves and a thorough understanding of the complex hydro-geological system. Besides the analysis of the water well monitoring, geophysical investigations are requested to provide the base line parameters for the modelling of the dynamical development of the aquifers balancing recharge, exploitation and progressive salinisation under changing climatic conditions.

Conceptual model

The starting point is a conceptual model of the hydro-geological situation (fig.1). Accordingly, the freshwater reservoir has the shape of a lens located below a hill consisting mainly of sandstones. It is completely surrounded by saltwater in unconsolidated sediments comprising sands and clays. Clay appears to form also the basis at a depth of some 90 m or more. The total extension of the system is about 5km from west to east and 10 km from south to north. A special lithological feature is a dyke-like basalt outcropping at the eastern border. During the investigations it became evident that similar basalts may also occur sub-outcropping at the western side of the hill. The basalt dykes are important as potential aquitards which limit the system. Moreover, the existence of the basalts are likely the reason for the existence of the hill as such, due to the thermal consolidation and partly silification of former sands into sandstone resisting the erosion.

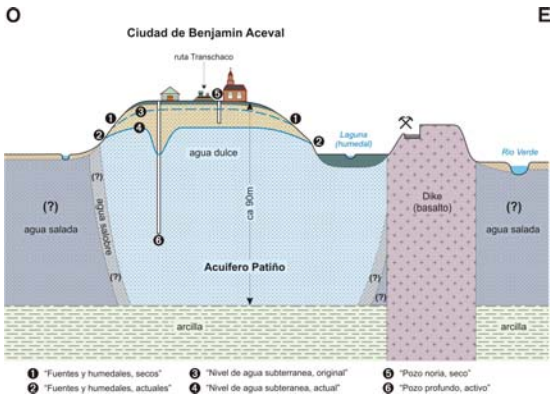

Fig. 1 Conceptual hydrogeological model

Given the morphological hill situation, the fresh water lens could have developed according to the classic Ghyben-Herzberg model in Fig.2 [2]), which is simply based on Archimed´s floating principle: The low density freshwater (ρ= 1,0) is floating on the denser saltwater (ρ = 1,015). The depth extent of the lens can be estimated by the formula

$$H = h * \rho f / (\rho s - \rho f).$$

With h = 3m and additional assumptions regarding the freshwater recharge a depth of some 120 m could be expected for the lens of Benjamin Aceval. With falling groundwater level due to exploitation the lens, however, can easily be destroyed, which underlines the importance of extremely careful water management.

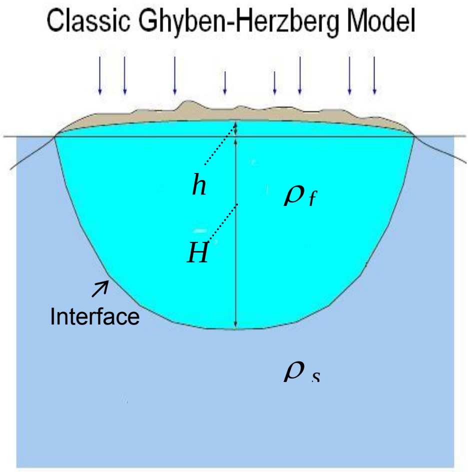

Fig 2: Sketch of fresh water lens floating on saline water according to Ghyben-Herzberg theory, (source [2]).

Methods

The geophysical investigation of aquifers in the Paraguayan Chaco has long tradition. DC Schlumberger soundings were the most often applied method. However, in particular for shallow aquifers, the method proved sometimes to give quite ambiguous results ([4]). The reason is the principle of equivalence which allows the same curve to be interpreted by quite different hydrogeological layer situations. This holds for both DC and EM methods. Additional hydrogeological input is therefore indispensable to reach realistic interpretations.

The methodology for the Benjamin Aceval investigation included 2D DC measurements along profiles and punctual 1D Time domain soundings.

The DC measurements used the multi-electrode instrumentation GEOTOM made by GEOLOG GmbH which allowed perfectly the quality of data acquisition to be checked visually and numerically during the measurements by observing on site the build-up of the pseudosections. The configuration was Wenner (n*a) with electrode spacing being a = 4m and the multiplication factor n = 1 to 20. The inversion of the data into 2D resistivity sections was carried out with the Finite Difference program DC2DInvRES provided by Günther [3].

The Time Domain Electromagnetic soundings used the TEM-FAST 48HPC instrumentation made by “Applied Electromagnetic Research” [5], including the 1D inversion software TEM-Researcher provided by the manufacturer. The transmitter loop sizes were usually 25m * 25 m or 50m*50 m, where local conditions permitted.

The aim of the geo-electrical profiles was mainly to determine the lateral contact or the lateral transition zone between the saline areas and the freshwater area of the lenses. Due to the large size of the investigation area of 5km * 10km the profiles had to be located at strategic zones of the fresh water lens, where the exact position of the borderline or the transition zone was not known at all or at least very unclear from the available boreholes. The minimum profile length using the full capacity of 100 electrodes was 400m, thus permitting an information depth in the center of the profile of approximately 45m. Several sections were added together, usually with an overlapping of 100m for continuity, forming profiles of up to 1400m total length.

The aim of the TDEM soundings was to increase the limited depth information of the DC soundings in order to reach the bottom of the fresh water lens and to investigate at least punctually its central parts.

The location of the profiles as well as the distribution of the sounding points is shown in fig. 3.

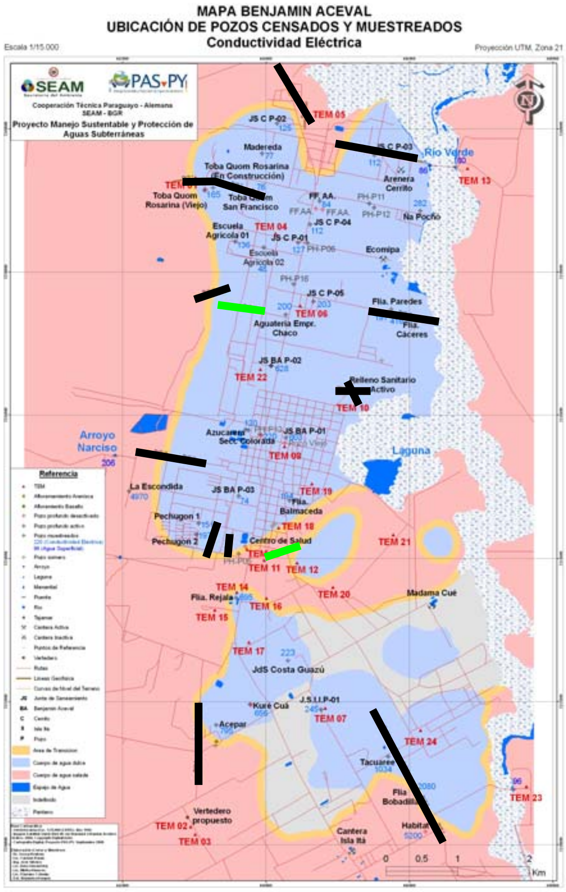

Fig. 3 Location of geo-electrical lines (black) and TDEM sounding points (red). Grid lines: 2km. Pink area: saline groundwater; Blue areas: Fresh water. Interpretation combining salinisation of borehole water samples and geophysical results.

Results

The total range of formation resistivities extends from less than 5 ohm.meters for positions within the saline aquifer up to more than 200 ohm.meters for the central parts of the fresh water lens(es). The numerical fitting errors of the inversions depend mostly on the data quality, which, in fact, was strongly determined by variable grounding conditions of the electrodes. Under good grounding conditions fitting of the 2D models is as good as ca. 3%, while worse conditions result in fitting errors up to ca. 22%.

The figures 4 to 6 show exemplarily three typical hydrogeological situations found by the interpretation of the resistivity profiles. Profile 13 in fig.4 crosses the western borderline of the freshwater lens at point 330 with a sharp contrast. In this particular case the contact turned out to be located far more to the east and much higher up on the hill than expected so far. The profile 17 in Fig. 5 crosses a side lobe of the freshwater lens at its northern border. This profile, with the broad resistive area under the morphologically highest ridge in the center and the conductive areas at the beginning and the end, reflects the main aspects of the conceptual model from Fig. 1. The narrow high resistivity anomaly at the eastern end is caused by a nearby outcropping basalt dyke. The profile in Fig. 6, situated at the southern border of the investigation area, runs along the transition zone between saltwater and freshwater. The hydrogeological situation is evident from three nearby boreholes in which the water salinity drops from 5200 µSiemens/cm at the southern end (profile meter 1) to 2080 µSiemens/cm at point 800 and eventually to 1034 µSiemens/cm shortly north of point 1400.

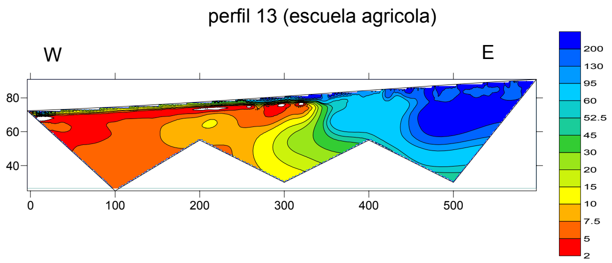

Fig. 4 DC profile example 1: sharp borderline between saltwater and freshwater at point 330.

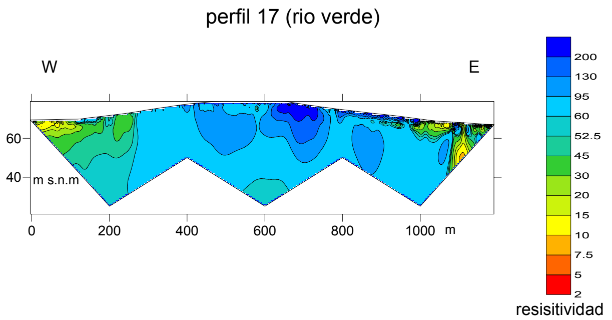

Fig. 5 DC profile example 2: crossing a branch of the fresh water lens. The steep high resistivity anomaly at the eastern end indicates a nearby outcropping basalt dyke.

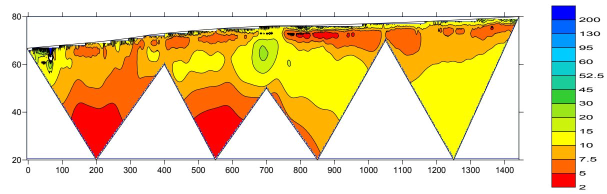

Fig. 6 DC profile example 3: Transition zone between saltwater in the south (at the left) towards less saline water in the north (at the right).

The special hydrogeophysical situation of a resistive layer (fresh water) on top of a very conductive layer (saltwater or clay) suites well the general capability of any electromagnetic method to determine better the depth of a good conductor compared to the opposite case. Fig. 7 shows the TDEM results from a typical sounding place. The data quality obtained with a 25*25 sqm transmitting loop is, in this case, good up to about 2000µsec, where noise begins to exceed the signal. Despite some differences in the equivalent models the bottom of the freshwater lens appears clearly at about 50m depth, where the resistivity drops below 10 ohm.meters and less.

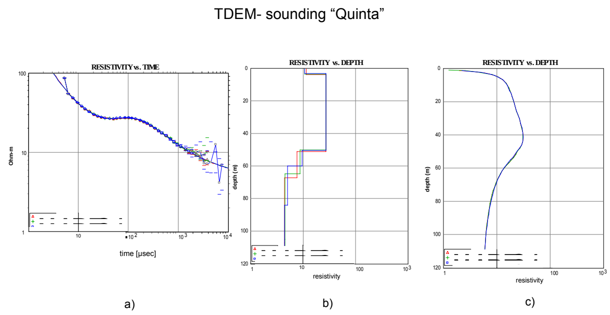

Fig. 7 Typical TDEM sounding curves: a) resistivity versus time: output data as provided by the Fast-Tem instrument. b) resistivity versus depth: 1D layer inversion c) resistivity versus depth: 1D smooth inversion.

The interpretation of all TDEM soundings give the following ranges of physical lens parameters: The thickness of the freshwater body varies from ca. 45 to 110 m, while its resistivity ranges from ca. 20 to 180 ohm.meters, ignoring a few apparent outliers probably caused by non 1D situations and /or low quality data.

Fig. 8 compiles into one resistivity map the resistivities of both methods applied. Though this map, created by SURFER, obviously still suffers from unsufficient data density, it improves the knowledge about the shape and the size of the freshwater reservoir. Dark green and blue colors in fig. 8 are interpreted to indicate the areas of fresh water resources. The information is taken into account for the revised hydrogeological as displayed in fig. 3.

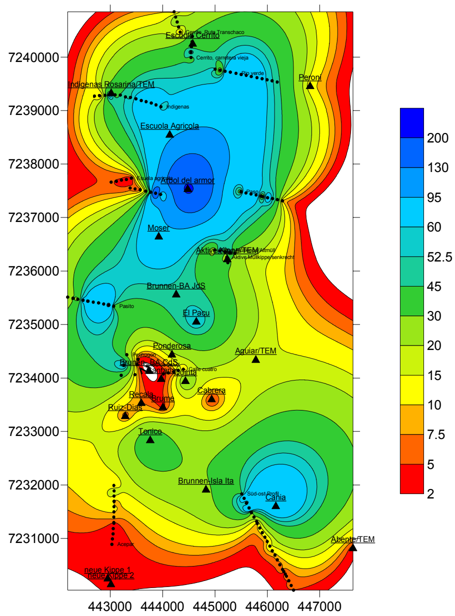

Fig. 8 : The resistivity distribution at the depth of 30 m below surface, combining DC and TDEM inversion results.

Conclusions

The geophysical investigation reveals some new features which are important for the calculation of fresh water reserves and the effective capture area for recharge after rainfalls:

- The border line is locally shifted towards the interior of the lens.
- The thickness of the lens is locally less than expected.
- The freshwater reservoir is split at least into two lenses, separated by a saltwater intrusion.

The coincidental detection of a sub-outcropping basalt dyke at the western side of the lens (on the occasion of drilling a new water borehole partly based on geophysical information) warrants a magnetic survey in order to improve the knowledge about the basalts and their role for the groundwater system.

Acknowledgments

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