Groundwater Investigation by Combined Vertical Electrical Sounding and Magnetotelluric Sounding in Eastern Region of Mekong Delta, in the South of Vietnam

Khảo sát nước dưới đất bằng tổ hợp phương pháp đo sâu điện đối xứng (VES) và đo sâu từ tellua (MTS) ở miền Đông Nam Bộ (miền Nam Việt Nam)

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Abstract: In the Eastern Region of Mekong Delta (South Vietnam) may contain brackish or saline water from land surface to great depth, both superficial Quaternary and deep Tertiary Alluvium. The combination of two geophysical methods, the Vertical Electrical Sounding (VES) for shallow investigation, and the Magnetotelluric Sounding (MTS) for deep investigation, provides a complete electrical image of the sedimentary series from the surface to the deep crystalline basement. It turns out very efficient to delineate the groundwater contamination in both superficial and deep aquifers. The combined results reveal a close correlation of the extent of the contamination with the paleogeomorphology of laterites, and subsequently with the paleorelief during the Tertiary and Quaternary times. Because this study area is very complicated hydrogeological structure, it is necessary to survey the current status of deep-water storage floors with geophysical measurement technologies to prevent groundwater pollution when exploiting groundwater here.

Keywords: *Deep aquifers; Groundwater; Magnetotelluric Sounding; Mekong Delta; Vertical Electrical Sounding;*

Tóm tắt: Ở vùng miền Đông Nam Bộ có thể chứa nước lợ hoặc nước mặn từ mặt đất đến độ sâu lớn, kể cả ở các tầng trầm tích Đệ Tứ sát mặt đất đến các tầng trầm tích Đệ Tam ở dưới sâu. Sự kết hợp của hai phương pháp địa vật lý là đo sâu điện đối xứng (VES) đối với các cấu trúc tầng nông và đo sâu từ tellua (MTS) đối với các cấu trúc tầng sâu để khảo sát, đã cung cấp một hình ảnh địa điện hoàn chỉnh của loạt trầm tích từ bề mặt đến tầng đá móng nằm dưới sâu. Bằng cách này đã cho thấy rất hiệu quả trong việc phân định chất lượng của nước dưới đất ở cả tầng chứa nước gần mặt đất và tầng chứa nước ở dưới sâu. Kết quả kết hợp của hai phương pháp cho thấy một mối tương quan chặt chẽ trong phạm vi ô nhiễm với các ranh giới cổ của các trầm tích Đệ Tam và Đệ Tứ. Bởi vì vùng nghiên cứu này có cấu trúc địa chất thủy văn rất phức tạp, nên rất cần phải khảo sát tình trạng hiện tại của các tầng chứa nước dưới sâu bằng các công nghệ đo địa vật lý để ngăn ngừa ô nhiễm nước ngầm khi khai thác nước dưới đất ở đây.

Từ khóa: *Đo sâu điện đối xứng; Đo sâu từ tellua; Đồng bằng sông Cửu Long; Nước dưới đất; Tầng chứa nước dưới sâu*

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1. Introduction

The area of Eastern Region of Mekong Delta (South Vietnam) is 25,000 km^2 with 15 millions inhabitants [1]. Recently, this region is confronted with a dramatic problem of fresh water supply because of the contamination of several aquifers. By its location, in direct vicinity of the East Sea, superficial aquifers along the coastal area are contaminated by the seepage of sea water and by the inland incursion of salty tidal water, especially during the dry season (November-April). In the other areas, the contamination originates from the leaching of saline deposits during different Tertiary and Quaternary transgressions. The human activities contribute to the pollution of many rivers which run inside the regions [2,3,4,5].

For a long time, many wells were drilled in Saigon City by the French-Asian Hydraulic Company. Since 1959, the Americans began to concentrate groundwater investigation in the Mekong Delta [6,7]. After the end of the war in 1975, the demand of groundwater in use for domestic and industrial purposes and for new economic areas requires immediately attention. Some government agencies have been formed to investigate and exploit ground water. The results of many years of investigations gave possibility to localize fresh water aquifers in several favored areas. However, some deep aquifers as superficial ones, have brackish or salty water with variable Total Dissolved Solids (TDS). The chemical characteristics of groundwater varies with depth in a very complicated way and are known only in some localized deep wells. Therefore, it is very important to use efficient geophysical methodology in order to delineate the extent of groundwater contamination not only near the surface but also at great depth [2,5,8].

Traditionally, electrical method as Vertical Electrical Sounding (VES) is widely used and has played a significant role in investigation of ground water [9]. Owing to the strong contrast of the resistivity between fresh water aquifer (a few hundred Ωm) and saline water aquifer (a few Ωm), the strength of the VES method lies in the direct correlation of the interpretation data to groundwater quality [10,11,12,13]. Unfortunately, the investigation depth of this method is limited (about 100-150 m). Magnetotelluric Sounding (MTS) is more suitable method for deeper exploration [14]. In fact, these two methods are quite complementary, and the use of the combined VES/MTS methods can provide a complete electrical image of the sedimentary series from the surface to the deep basement [15,16].

Figure 1. Location of the 6 VES/MTS profiles in the Eastern Region of Mekong Delta

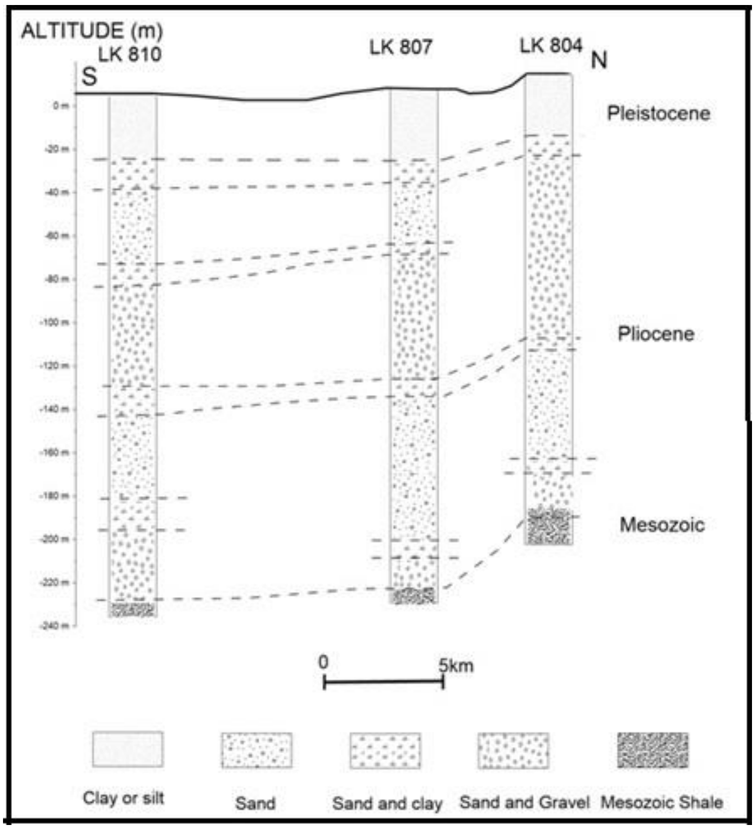


Figure 2. Geological and lithological section of 3 boreholes LK810, LK807 and LK804 in the study region

2. Geological Characteristics of the

Study Region

The vast alluvial plain of Eastern Region of Delta Mekong rises imperceptibly from sea level to about 5 m at delta borders. However, the hills and uplands bordering the deltaic plain towards the North and the East of HoChiMinh City rise to elevation of 100 to 900 m or more above sea level. As a result of the seasonal flooding and drying, the soils become saturated with aluminum and iron salts, which are toxic to the most crops. Moreover, a closely integrated man-made network of canals and inland waterways is subject to tidal incursions of brackish or salty water from the East Sea, which may extend far inland during the low water season [2,3,5].

The rocks of the studying region range from Precambrian to Holocene age. The oldest known rocks of the region are granite, gneiss, quartzite and other crystalline rocks considered to be of Precambrian to early Paleozoic age. From Permian to Eocene time, interbeded continental sediments were deposited in subsiding basins in South Vietnam. The northwest trending tectonic trough began to subside in late Tertiary time. During Plio-Pleistocene time, the Old Alluvium was deposited by the Mekong and its tributaries in a vast deltaic fill which extends laterally to the bedrock margins and seaward to the present coastline [17,18,19].

The Holocene Alluvium contains relatively poor aquifers, mainly because of the fine texture of the deposits. Aquifers in Old Alluvium are the principal sources of fresh water supply. Generally, in this region several water bearing zones are present from Old Alluvium, especially in the Tertiary sediments, which have high yield and economical importance because they spread widely with large thickness and at great depth down to 200 m. However, the Tertiary aquifers have variable TDS and are also contaminated in some places.

The terrain of the studying region is generally flat, but to the North, East and Northwest, the elevation contours reach more than 10 m. The higher zone (>2.5 m) of the landscape corresponds approximately to the outcrops of Old Alluvium of Pleistocene age, and the lower zone (< 2.5 m) to the Holocene Alluvium [2,20].

3. The Principle of VES/MTS Methods

Numerous investigations have established the usefulness of surface electrical resistivity as a tool in the detection of groundwater contamination. Many contaminants contain an ionic concentration considerably higher than the native groundwater. Increased ionic concentration, or TDS, results in higher electrical conductivity (or lower resistivity) of the water. The VES method, well known as the direct current (DC) resistivity measurements, have an extensive history for use in groundwater studies and is described in details in many papers [21]. This method gives information about the presence of aquifers, its thickness and depth, quality of water (fresh or brackish) and the rock types buried at depth. There are a number of electrode arrangements for use in geoelectrical work, but the Schlumberger array is the most practical for the sounding technique. The variation of resistivity with depth is measured in VES. Usually the current electrodes A and B are the outer most electrodes. The potential electrodes M and N are the inner electrodes. Electrical current I from a battery is forced to flow into the ground through the current electrodes A and B and the resulting voltage drop produced by this current is measured by M and N. The resistivity is then calculated by formula:

$$\rho = K\frac{U_{MN}}{I} \quad [\Omega\text{m}] \tag{1}$$

Where K is geometrical constant.

The resistivity thus measured is attributed to the point "0". This value represents the resistivity of formations at depth which among other factors depends on the distance between the current electrodes.

The MTS method has more recent history in geophysical survey for structure study of the crust and for deep mining prospecting [14,15,16,22]. Therefore, the MTS method presents also an interesting potential for deep ground water investigation. The MT method is distinct from the other electromagnetic techniques, namely Frequency and Time Domains Electromagnetic Soundings [23,24,25], in using as a source the natural electromagnetic field with the period covering from 10^{-3} to 10^{3} sec. At a given station, along each direction x and for each period T, one defines an apparent resistivity ρ_a which is related to the amplitude of the natural electrical field (or telluric field) E_x and to the amplitude of the orthogonal magnetic field H_y by the formula [22]:

$$\rho_a = 0.2T\left[\frac{E_x}{H_y}\right]^2 \tag{2}$$

Where ρ_a in Ωm, T in sec, E_x in mV/km, H_y in nT.

The MT apparent resistivity represents somewhat of a mean of the resistivities in the portion of the subsurface energized by the circulation of telluric currents. Because these currents are continuously fluctuating in a random fashion, they exhibit the phenomenon of "skin effect", that is the exponential decrease of the uniform primary electromagnetic field with depth in a homogeneous and isotropic terrain, of resistivity. The decreasing constant is defined by the parameter p, called the " depth of penetration", given by:

$$p = \frac{1}{2\pi}\sqrt{10\rho T} \tag{3}$$

Where p in km, ρ in Ωm, T in sec.

From formula (3), p increases with the period and the terrain resistivity. For most rocks, the resistivity varies between 1 and 10000 Ωm. Consequently the penetration depth can vary between a few tens metres and several tens kilometres for periods varying from 10^{-3} to 10^3 sec.

The technique of MTS consists of studying the variation of apparent resistivity with period in order to contruct a MTS curve $\rho_a = f(T)$ from formula (2). In the case of a lateral and isotropic structure, the apparent resistivities do not depend on the direction of the measurement axis. The "scalar processing" of MTS data gives a unique MTS curve, the quantitative interpretation of this curve consists of a very simple direct calculation using one dimensional model [14,22]. In the specific situation where the geological formation has a two dimensional electric anisotropy, the "tensor processing" must be used [21] in order to obtain two MTS curves corresponding respectively to the parallel and perpendicular directions to the tectonic strike. In this case, the quantitative interpretation requires numerical two dimensional modelling [14].

4. Field Operation and Data Interpretation

In the studying region, 62 stations were carried out along 6 profiles, among these, two profiles with Northwestern-Southeastern direction and 4 profiles with Northeastern-Southwestern direction. At each station, the VES and MTS were used jointly. First a VES was carried out with Huntec M-4 instrument which was composed of a battery operated (36V) 160W transmitter with the output current automatically controlled to within 1%, and of a microprocessor receiver with a resolution of potential readings of 1μV for potential less than 2 mV. It is possible to obtain a very accurate VES curve with a maximum distance between the current electrodes AB = 1000 m using Schlumberger array by this light and portable instrument.

At the same station, the MTS was next carried out with a Telmag which consists essentially of an electronic amplifier-filter unit connected to a telluric line of 100 m long, and to an induction magnetometer with a resolution of 10^{-2} nT. It provides scalar processing of MT signal for 12 discrete frequencies in audiofrequency range: 3,5,8,13,21,34,80,170,380,680,1300 and 2500 Hz. Following formula (3), the penetration depth can reach several hundred metres for this frequency range.

The most important difficulty encountered in MT method is the very low level of natural electromagnetic signal, especially in audiofrequency range. Consequently, power line harmonics can pose a serious problem to data acquisition due to their strength compared to natural signals. Three notch filters are included in the electronic unit in order to eliminate industrial interferences, the 50 Hz, 100 Hz and 150 Hz harmonics. However, in some stations, near the domestic electrical lines, the high frequencies band greater then 50 Hz (80-2500 Hz) become impractical to use. Avalaible results can be obtained only for low frequencies band (3-34 Hz).

Nevertheless, these results can yield useful informations for deep structures down to a few hundred metres.

The pragmatic approach is used as modelling to interprete VES/MTS data in which a starting model of the electrical resistivity distribution is constructed and updated after comparison of its calculated response with the observations. For this approach, a sophisticated interactive software displays instantaneously on the microcomputer screen, not only the experimental results and theoretical curve but also the resistivities and thickness of every layer of the model. These resistivities or thickness can be modified also instantaneously by various steps from 0.1 to 1000 Ωm or metres. This procedure allows the interpreter to see directly on the screen the influence of each layer and to use our geological knowledge in order to choose the most suitable model for the hydrogeological problem. For example, Tab.1 presents the values of resistivities and thickness of curve VES for station HocMon from A-A' profile. The interpretation of this curve gives a model of 4 layers with a substratum at 43 m deep. Tab.1 presents also the values of resistivities and thickness of curve MTS for the same station HocMon. The interpretation of the MTS curve reveals the existence of a very resistive deep basement down to 423 m, using a model of six layers with three first superficial layers provided by VES result. Clearly, these results are quite complementary: VES results give more details about superficial layers and MTS results provide information about deeper layers.

Table 1. The results of interpretation VES and MTS curves for HocMon station from A-A' profile

V E S		**M T S**	
ρ_a (Ωm)	E(m)	ρ_a (Ωm)	E(m)
8.0	2.0	8.0	2.0
2.7	27.0	2.8	27.0
55.0	14.0	55.0	14.0
24.0		18.0	140.0
		23.0	240.0
		10000.0	

5. Results and Discussion

The quantitative interpretation of VES and MTS curves is hampered by the well known principle of equivalence which means that many different layered models may produce practically the same apparent resistivity curve. This ambiguity can be reduced by using the combination of methods. The combination of VES and MTS methods, its advantages and its complementarity are well discussed by K.Vozoff [21]. Nevertheless, some ambiguity may subsist and the best way to select the model that represents closely the true conditions of the subsurface, is to use additional geological informations, especially from drill holes near measurement stations. In the studied region distributed some geological and hydrogeological drill holes. For example, three boreholes are located near profile A-A' by Hydrogeological Division. Fig.2 presents the geological section of these boreholes which cross successively from the surface, the Pleistocene and Pliocene sediments, both correspond hydrogeologically to the Old Alluvium with a total thickness of about 200-250 m. Lithologically, the Old Alluvium is composed of interbeded clay and sand or gravel, but Pliocene sediments have thick sandy layers which constitute good potential reservoir for ground water. The boreholes are stopped when reaching Mesozoic bedrock with unknown thickness. This geological section shows also the lateral structure of studied area. Therefore, the assumption for the layered model in the quantitative interpretation has to be made to limit the ambiguity, as pointed out by Van Overmeeren [11]. The procedure of interpretation described above by using boreholes informations provides two geoelectrical cross sections along each profile, in which one corresponds to the superficial structure from VES results and the other to the deep structure from MTS results.

Two of 6 VES/MTS measurement geoelectrical profiles on the Eastern Region of Mekong Delta (South Vietnam) are presented below as the example.

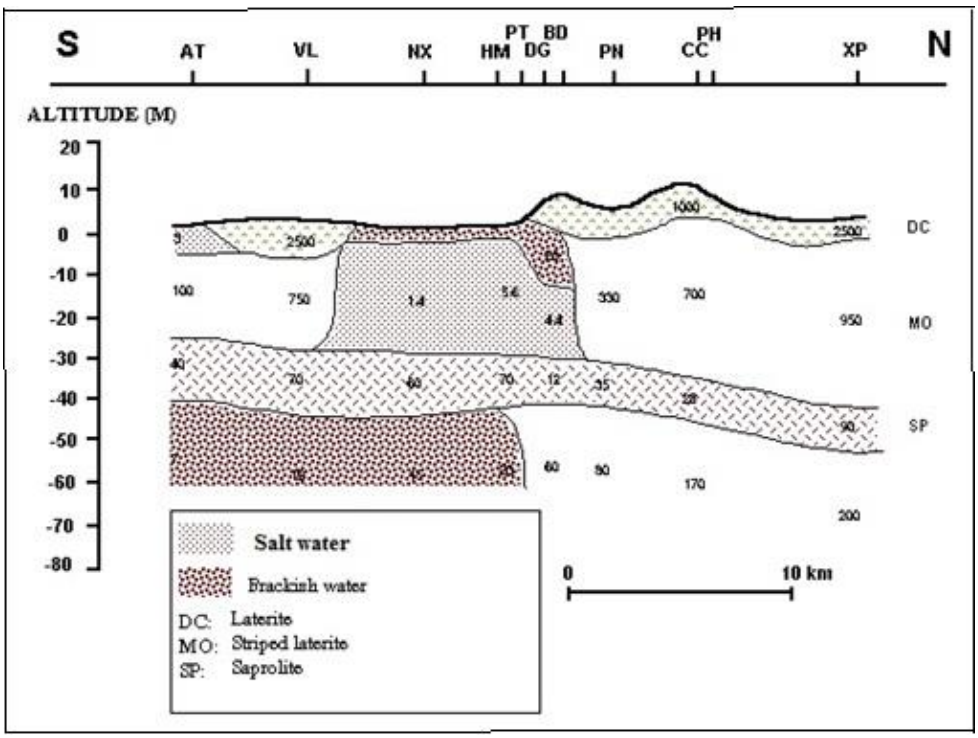
5.1. The A-A' Profile

The superficial geoelectrical cross section along the A-A' profile from VES results is shown in Fig.3. The most striking feature in this cross section is the strong variation of the resistivity values along the profile. In the northern half part, the resisivities are generally high. The layer surface with 5-10 m of thick and greater than 100 Ωm of resistivity is related to the presence of lateritic rocks which cover higher terrains bordering the delta. It is well known that, in tropical region, the chemical weathering process is accompanied by the lowering of the landscape, the increasing lost of mobile constituents and the enrichment of the resistant elements, like iron at the surface. On other hand, the northern half part of profile corresponds to the higher elevation zone (>2.5 m) of the landscape confirming the continuity of the weathering process during the Pleistocene time. The very conductive zone with resistivity below 10 Ωm is existent at the southern half part of profile which confirms the presence of a salty water nappe. This zone corresponds to the lower elevation zone in the region (< 2.5 m).

The deep geoelectrical cross section of the A-A' profile obtained from MTS results is shown in fig.4. It brings out also a strong variation of the resistivity in the Pliocene sediment between 50-250 m altitude. The same situation as VES profile, the southern half part of profile is more conductive but less conductive than the upper Pleistocene salty water nappe. Nevertheless, the Tertiary aquifers could by partially contaminated in this part, and the water is brackish.

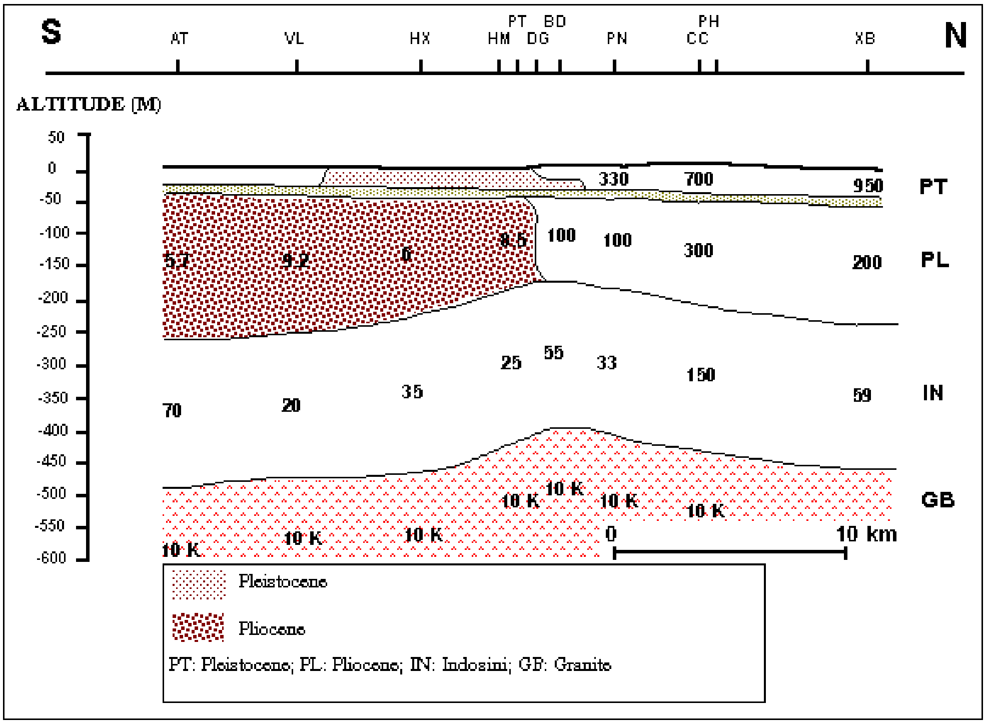
It may be concluded that the fresh water aquifers can be found only in the northern half part of the A-A' profile, both in superficial Pleistocene sediments and in deep Pliocene sandy horizons.

Finally, MTS results can achieve deep penetration, reaching a very resistive (the range about 10,000 Ωm) deep basement (below 400 m) which corresponds probably to the consolidated rocks of igneous origin (granite). Over in and under the Pleistocene sediments, lies a thick layer (at deep of 220 - 240 m) relatively conductive (the range of resistivity from 20 to 150 Ωm) of pre-Tertiary age. It corresponds possibly to the Indosinias shale found in a deep drill hole to the South of HoChiMinh City.



Resistivities in Ωm or KΩm

Figure 3. Geoelectrical section for A-A' profile by VES data

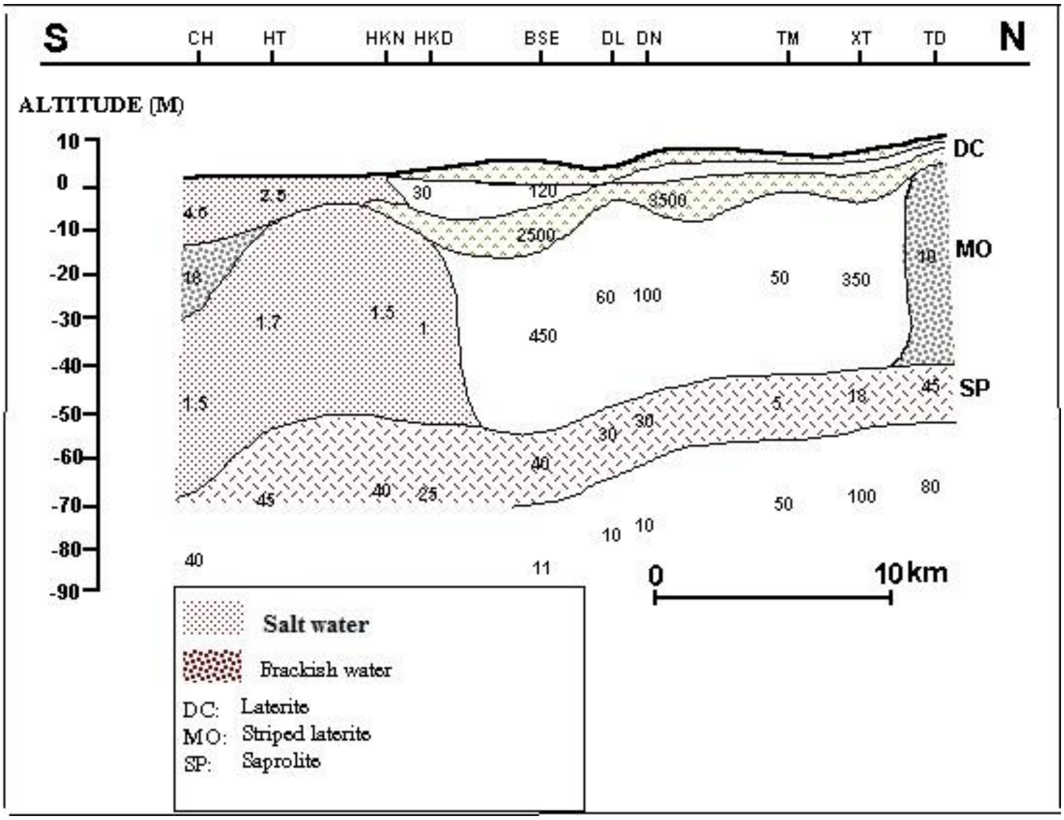


Resistivities in Ωm or KΩm

Figure 4. Geoelectrical section for A-A' profile by MTS data

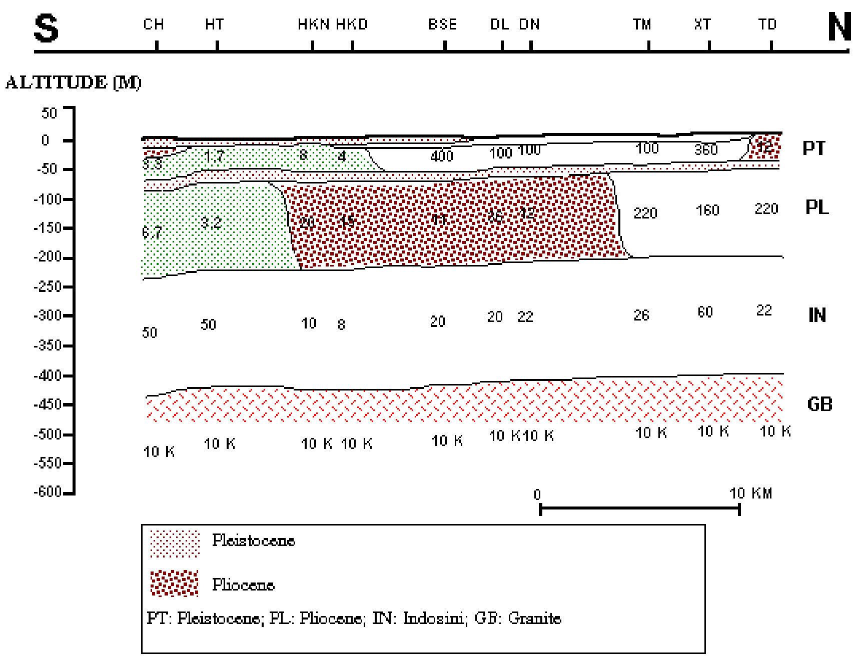
5.2. The B-B' Profile

The profile B-B' has the same geoelectrical characteristics as the profile A-A' in general. We will emphasize only some minor differences. Three zones in the Pliocene sediments can be distinguished on the deep geoelectrical cross section: A resistive zone related with fresh water at the north of profile; A conductive zone related with brackish water at the centre of profile; A very conductive zone related with salty water at the south of profile. Fig. 5 presents superficial geoelectrical cross section of the profile B-B' from VES results and Fig.6 presents deep geoelectrical cross section of the profile B-B' from MTS results.



Resistivities in Ωm or KΩm

Figure 5. Geoelectrical section for profile B-B' by VES data



Resistivities in Ωm or KΩm

Figure 6. Geoelectrical section for profile B-B’ by MTS data.

The rest 4 profiles with direction SW-NE namely: C-C’,D-D’,E-E’,F-F’are shown in Fig.1 which have generally electrical properties as the profile A-A’ and also have some different characteristics. The very conductive zone is presented from 10 m to 150 m deep at the south profile C-C’ which related with salty water. The variation of crystalline basement varies from 600 m at the south to 140 m at the centre and to 450 m deep at the north part of this profile. The geoelectrical cross section of D-D’ profile is the same to C-C’ profile in general. The conductive zone is also presented at the south part of profile with thickness about 180 m which related with brackish and salty water. On the geoelectrical cross section of E-E’ profile, we may distinguish the very conductive zone from surface to 60 m at the south and from 25 m to 170 m at the centre profile where are contaminated entirely by salty water. The crystalline basement lies at 150-200 m deep on south part and increases to 70-80 m deep on the north part of profile. The situation of structure of geoelectrical cross section of F-F’ profile is different. The south part of profile consists very conductive zone with the depth to 270-300 m and the crystalline basement here lies at 500 m of depth. But, the north part of profile, the crystalline basement is about 120 m of depth.

Then, every cross section profile consists several layers with different electrical conductivity which corresponds to typically deep structure of given zone. It is clearly demonstrated that the contamination is directly to the paleogeomorphology of the laterites and subsequently to the paleorelief in Tertiary and Quaternary times. In the case of the superficial Quaternary aquifers, the frontier between salty and fresh water is well delineated by VES results. For Tertiary aquifers, the contamination is , on the other hand, well delineated by MTS results. We know that the very conductive layers related with saline water or brackish water. After D.T.Hung [2] and V.C.Nghiep [3], the chemical contents of ground water for this region were formed by the process of leaching deposits. Atmosphere water penetrated into aquifers, leaching chemical contents of the soil and the deposits. Then, the Tertiary aquifers have essential and good potential ground water for this region. In fact, the three boreholes (Fig.2), already drilled and tested in the zone near A-A’ profile, confirm a good potential of fresh water in Pliocene aquifers with TDS <0.3 g/l.

6. Conclusion

Since Eastern Region of Mekong Delta has a variety of compositions, it created in this area with a complex hydrogeological structure. Deep detection and mapping of conductive fluids is a problem more and more encountered in groundwater investigations. Some examples are locating the salt water zone in thick aquifers, delineating saline zones in alluvial fills or determining the depth to the crystalline basement in sedimentary basins.

The VES method is easy and inexpensive to investigate for shallow structure. The MTS method is also easy to obtain data and refers to a few hundred metres or more of depth. Then, combination of VES and MTS methods constitutes an efficient geophysical methodology for deep hydrogeological investigation for Eastern region of Mekong Delta (South Vietnam). This is an area that is attracting more and more investment projects with a very fast speed in Vietnam, so it is necessary to regularly evaluate the current status of deep-aquifer water floors to prevent contamination in declaration Falls for sustainable development.

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