EVOLUTION OF SEAWATER INTRUSION USING RESISTIVITY GEOPHYSICAL METHOD

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Abstract

Seawater intrusion is a severe contamination problem in the Tordera delta, in Northeast of Catalonia. Farmlands and tourist activities are considerable, thus the water consume is important. In 1969 electrical resistivity soundings were in this area. and control piezometers were installed since 1971. Starting from 1994, periodical electrical soundings have been carried out at almost the same locations. This study presents the evolution of the salinity plume obtained from these soundings during those 27 years.

Considering that electrical geophysical methods can be helpful in detecting saline intrusion, a contour maps have been generated from electrical resistivity data. The saline intrusion plume has been delineated as an area of low interpreted resistivity.

Introduction

This communication proposes to elucidate the contamination problem for seawater intrusion in a poor groundwater resource area, which suffers an important exploitation. The systematic hydrologic control of groundwater reservoir net have not been sufficiently effective to predict the intrusion problem, thus the problem continues increasing.

Vertical electrical resistivity surveys (VES) are sensitive to groundwater quality in a porous medium. Orellana (1966) and Bouwer (1978) among others point out that the water salinity plumes may be delineated as resistivity lows because of the increasing total dissolved salts in the water (sea effect). Since the apparent resistivity values collected in the field are affected by the thickness and fluid content of each of subsurface layers, interpreted resistivities should provide a much more accurate picture of resistivity as a function of depth.

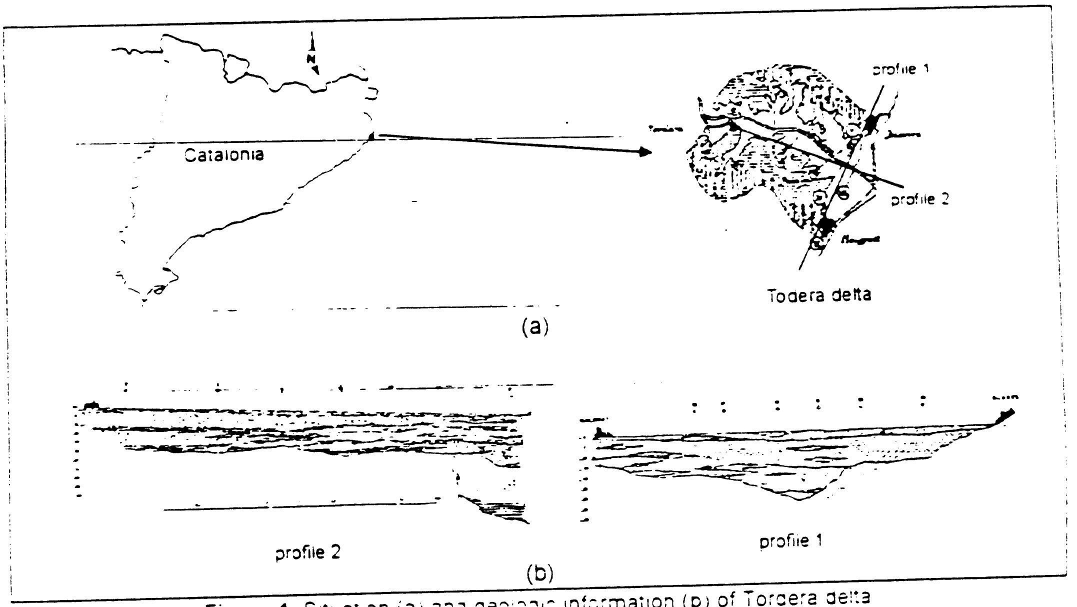

Figure 1 Situation (a) and geologic information (b) of Tordera delta

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Site Information

The Tordera delta is located in the Northeast of Catalonia (Figure 1a). Its subsurface geology mainly consist of unconsolidated to semi-consolidated alluvial deposits: gravel, sands, silts and clays (Figure 1b). These materials have a high to moderate permeability. Hydrologic features are described below, from top to bottom:

- Unconfined aquifer which totally covers Tordera alluvial plain. Its maximum thickness is about 20 m and it is characterised by a high permeability.

- Low permeability levels constituted for silts, clay, fine sands and sludge. These levels reach its maximum thickness on the coastal line and disappears landwards.

- Deep aquifer located at right margin of the present Tordera river. It is a paleo-channel of about 500 m length made up by detritic materials (gravel and thickness sands) with high permeability. Its maximum thickness is about 20 m.

-The basement consist of a granite formation which is highly altered on its top.

In 1971 there were a total of 26 wells located in the delta, part of them were drilled to analyse water chemistry (Figure 2).

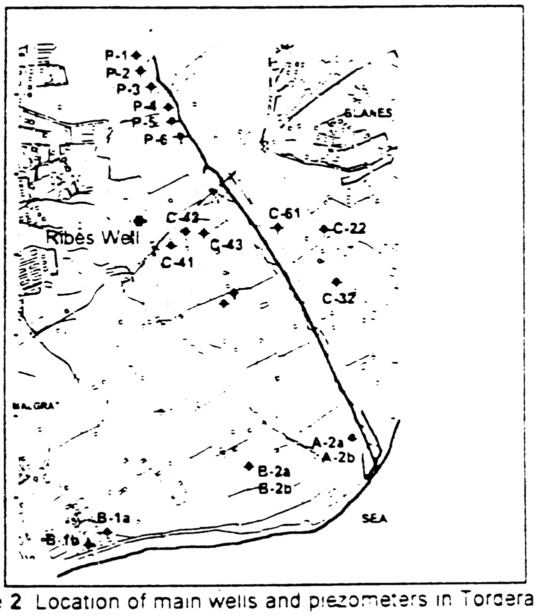

Figure 2 Location of main wells and piezometers in Tordera delta

Geo-Hydrologic features

a) Geo-hydrologic setting

The Tordera delta is located at the end of overflowing basin of 894 km^2. Water river inflows ranges from a maximum of 420 Hm^3/year to a minimum of 45 Hm^3/year and the average is sited in 178 Hm^3/year.

Considering the period 1967-1987, the average monthly river flowrates range from a maximum of 10 m^3/s in March to a minimum of 0.50 m^3/s in August. However in dry years the minimum average is reduced to 0 m^3/s in summer period.

Alluvial and delta surface is about 21 km^2 and total saturated volume for this materials is 390 Hm^3. Total reservoir subsurface capacity is 70 Hm^3 and the effective capacity is about 25 Hm^3. Geo-hydrologic parameters are summarised below (Table 1):

Unconfined aquifer		
	permeability effective porosity average saturated thickness	200 - 400 m/day 20% 8 - 10 m
silts levels (between)		
	drip factor hydrologic resistivity at vertical flow vertical permeability	390 - 1500 m 85 - 500 days 1 3 10^{-1} to 5.6 10^{-2}
deeper aquifer		
	permeability storage coefficient	50 - 200 m/day 1.5 10^{-3} to 6 5 10^{-4}

Table 1: Geo-hydrologic parameters for de Tordera basin.

b) Extraction and operating of underground reservoir

At present, a groundwater extraction greater than 40 Hm^3/year exists over this little area (≈21 km). Part of these water (20 Hm^3/year) is destined to supply urban zones of Alt Maresme and the South of the Costa Brava. Groundwater remain is for agriculture and industrial activities. This request is not homogeneously distributed along the year as between the 45-50 % is concentrated in de summer period (June-September). The flowrate in the month of maximum request is around 2.5 m^3/s. Major available resources (between 85-90 %) of the operating underground reservoir comes from superficial water of the bed river, and the remain comes from rains and surplus irrigated lands.

Considering the following aspects: a) the type of water-request and his seasonal distribution along the year, b) the effective capacity of underground reservoir (25 Hm^3) and c) the total available resources; it is easy to understand a massive marine water intrusion in the deep aquifer. As control measure only two piezometers are available between the main water catchments and coastal line. These piezometers give us a vague knowledge about the piezometric level in the reservoir, they hardly allow to evaluate the seawater contamination and its evolution.

c) Chemistry characteristics

The three next chemistry analyses show the seawater intrusion evolution in the deep aquifer in the left margin of Tordera delta.

- Water samples were collected from the Ribas well (Figure 2) on 24 November 1985. Results of the water analyses are listed in Table 2. In this area the deep aquifer is affected by the seawater plume, whereas the water in unconfined aquifer is continental.

Parameters		Unconfined aquifer	Deep Aquifer
Conductivity	µS/cm	741	9290
pH		7 06	6 83
TDS (total dissolved soils)	mg/l	270	2984
NH_3	mg/l	0 13	< 0 05
NO^{4-}	mg/l	< 0 02	< 0 02
NO^{3-}	mg/l	< 5	< 5
Ca^{++}	mg/l	63.4	792
Mg^{++}	mg/l	15 1	245 1
Na^{++}	mg/l	60 4	1395 1
Cl^{-}	mg/l	85 1	3755 1

Table 2 Results of Ribas well water analyses

- Next graphic (Figure 3) summarises chloride ion (Cl^-) evolution for deep aquifer from 1993 to 1994. This measures have been collected in C-41, C-42 and C-43 wells (Figure 2). It can be seen that the seawater intrusion does not occur in the major pumping period (July and August); whereas there are a time-delay response in the hydrologic system.

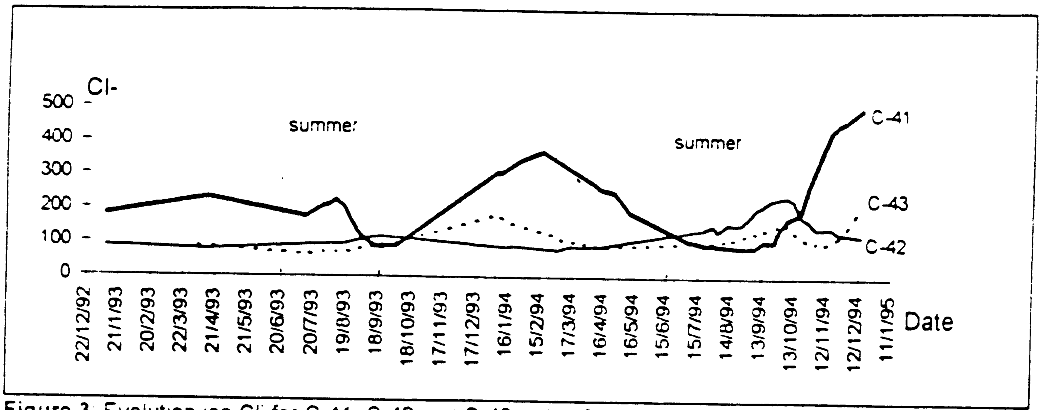

Figure 3 Evolution ion Cl⁻ for C-41, C-42 and C-43 wells. Concentrations are in mg/l.

Seawater intrusion plume can be indirectly evaluated from the lowering of piezometric levels. Table 3 shows water level evolution of the piezometer B-2b (Figure 2) during the 12 last years. Due to that B-2b piezometer is located far to the principal pumping area, the lost of water level can only be produced by a water density change. Considering that the density of continental water is 1 gr/cm^3 and the sea water is 1.025 gr/cm^3 and assuming that the descending level has a linear tendency, we conclude that the continental water has been substituted for sea water in this point about 50-60 %.

YEAR	Maximum Level (m)	Difference (m)	Ratio Elevations (h/h')
1983	0.10	-	-
1984	0.15	0.05	1.0008
1985	0.25	0.15	1.0023
1986	0.50	0.40	1.0062
1987	0.50	0.40	1.0062
1988	0.35	0.25	1.0039
1989	0.65	0.55	1.0083
1990	0.78	0.68	1.0106
1991	0.84	0.74	1.0115
1992	0.81	0.71	1.0110
1993	0.73	0.63	1.0098
1994	0.98	0.88	1.0137
1995	1.01	0.91	1.0142

Table 3 Piezometer B-2b water level lost in last 12 years

Electrical Resistivity Results

In November 1969 vertical electrical soundings (VES) were carried out by GEFISA-PROHIDRO company in this region. A set of them were in our study zone. In September 1994 we started carrying out electrical soundings periodically near the old sites (Figure 4). Three data sets: November 1969, September 1994 and September 1996 are presented in order to compare de geo-electrical changes in a period of 27 years.

All data set were obtained using the same methodology: Schulmberger electrode arrays with spacing (AB) ranging from 0.5 m to 240 m on each point location. Sounding S (Figure 5) is a representative example from a contaminated area. The apparent resistivity data were modelled using the RESIX-P (V2) inversion modelling program (Interprex 1995).

a) Lines I-I' and II-II'

Figure 6 displays two vertical cross-sections produced from the interpreted resistivities along line I-I' and line II-II' (Figure 4), which are located from 300 and 800 m from the coastal line respectively. Comparing this sets, it can be seen the seawater intrusion in 1994 in the deep aquifer characterised by low resistivities.

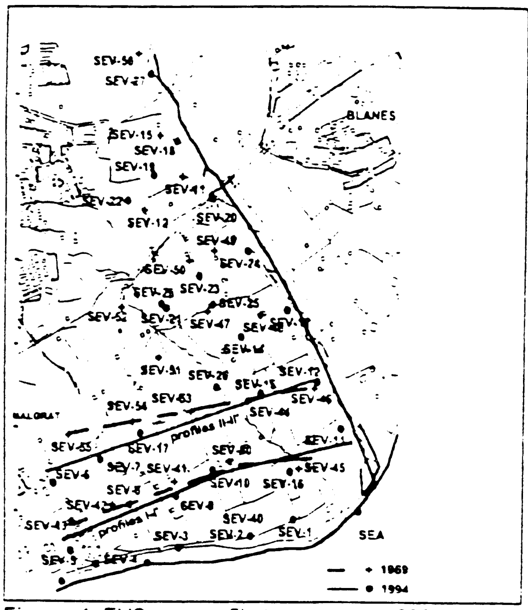

Figure 4 EVS and profile locations in 1996 and and 1994-1996

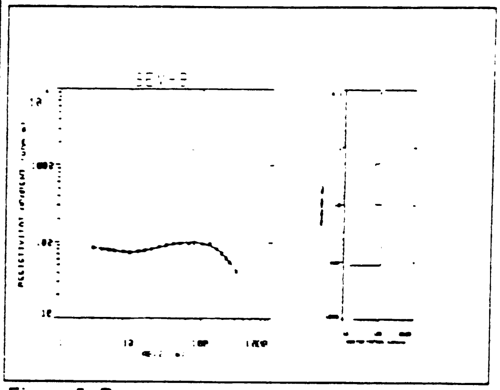

Figure5 Representative soundig interpreted (inverted) resistivities Sev-8 is in contaminated area Apparent resistivity sounding is to the left and interpreted resistivities are to the right

b) Contours maps of apparent resistivities

The contour maps of apparent resistivities for different AB lengths are plotting in figure 7. This graphs display a 2D surface distribution for apparent resistivities at determinate depth, which is directly related to AB electrodes aperture. Results of these figures are summarised below:

Iso-resistivities for AB= 20 m. For this electrode distance, values of resistivities characterise unconfined aquifer.

November 1969: In N sector we detect a maximum of 600 Ωm, which quickly descends towards E direction forming a plate with resistivities from 60 to 80 Ωm. At SW (Malgrat zone) there are a maximum of resistivity (> 300 Ωm);

September 1996: The iso-resistivity lines present an important change in delta electrical distribution. Isoline of 60 Ωm is displaced to NW direction. A maximum resistivity zone (150-300 Ωm) is sited at NE (Blanes zone) and continues for the right margin of Tordera river.

Iso-resistivities for AB= 100 m. For this electrode distance, values of resistivities characterise materials sited from 40 to 60 m depth, thus representing the deep aquifer.

November 1969: iso-lines down to 60 Ωm are parallels to coastal line. Values from 80 to 100 Ωm reach delta centre, with a local maximum of 200 Ωm. At SW (Malgrat zone) we can see maximum resistivities (> 200 Ωm), which present the same tendency of AB=20 m

September 1996: Comparing to 1969 data set, resistivities values are very low for whole delta zone. They have been modified especially in area near Malgrat (SW). Iso-line 80 Ωm is sited paralle at right margin river up to 1km river mouth. Maximum of 170 Ωm is located at EVS 24

Iso-resistivities for AB= 200 m. This electrode distance characterises part of detritic sole materials and, probably, granite basement.

November 1969: Iso-lines are parallel to coastal line up to 500 m with values of 80-100 Ωm. In Malgrat zone (SW) two maximums are located in EVS 38 and EVS 31 with 200 and 130 Ωm respectively

September 1996: A great descends in resistivity values and an important change in electrical distribution are evidenced for this period. Values from 80 to 100 Ωm are located at NE (Blanes zone)

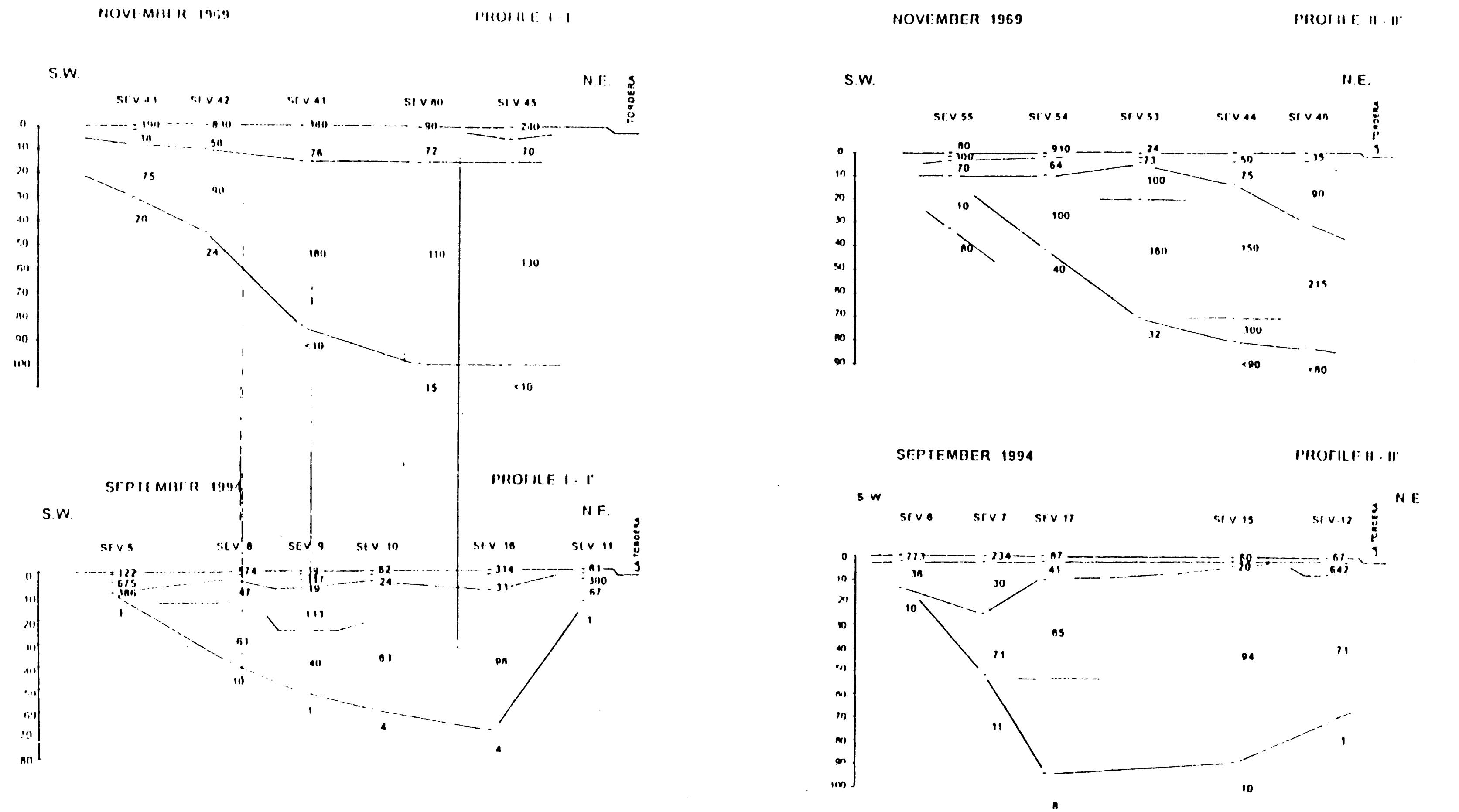

Figure 6: Vertical cross section produced from the interpreted resistivities along profile I-I' and profile II-II (Figure 6). Resistivity values are recorded in Ω m. Note the low resistivity layer (interpreted as seawater intrusion) below the higher resistivity layers (interpreted as uncontaminated materials)

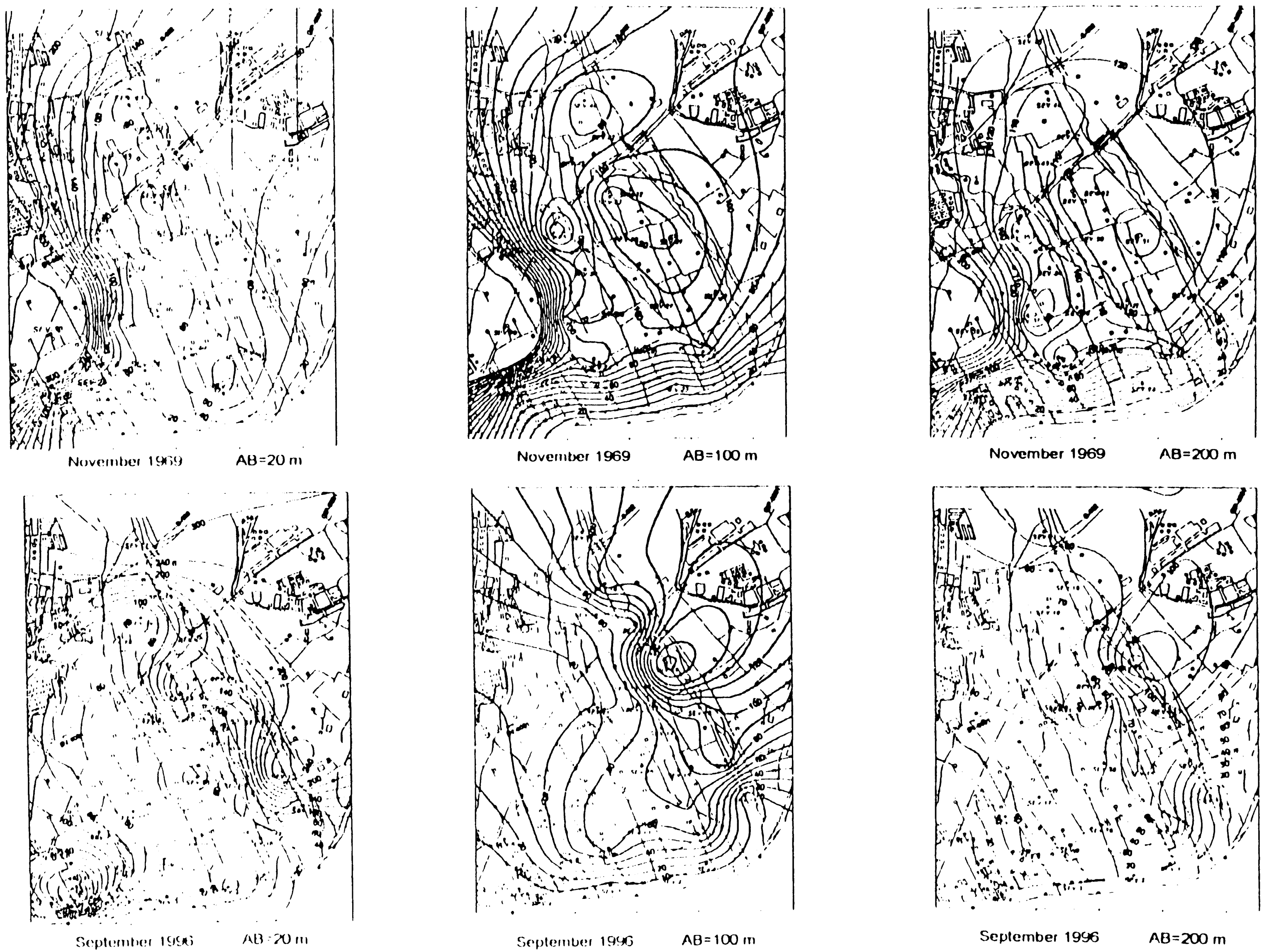

Figure 7 Contour maps of apparent resistivities for electrode distances AB=20 m and AB= 100 m
Note the evolution of seawater plume form 1969 to 1994 (interpreted as low resistivities).

- Iso-resistivities for AB= 240 m. In this case, the electrode distance characterises the granite basement. We can see the same morphology as for AB=200 m.

Conclusions

The total available resources are not sufficiently to guarantee the main request water for this region. The lack of water regulation for unconfined aquifer, the reduced effective capacity of underground reservoir and the request distribution have been produced a seawater intrusion in the deep aquifer of the Tordera Delta.

Globally, chemistry analyses of total dissolved solids in water offer the same characteristics in 1994 as in 1969. But the iso-resistivities at electrode distance AB=20 m present important differences for this two data sets. Trough this two results it can not be can conclude that unconfined aquifer is saline contaminated, only that in September 1996 a little infiltrated seawater is present, but the fast recharge from the water Tordera river reduces this salinity. It is concluded that the seawater plume intrusion can not be delineate for this unconfined aquifer.

Underground water in the deep aquifer (defined for AB=100 m and AB=200 m electrical levels) marks for this period a high tendency of total dissolved solids. Iso-restivity lines in 1996 are situate perpendicularly to the coastal line, while that same lines were parallels to the coastal line in1969 and the values of resistivity were higher. In this situation, it is concluded that the seawater plume intrusion can bee powerfully delineated for the groundwater reservoir.

Probably, the mainly front of seawater plume intrusion does not advance to the centre of de delta formation (where the control points are located); otherwise it advances from SW, trough the granite-deep aquifer contact, in direction to the main water catchements, which are pumping the main volume of water in the Tordera region.

Electrical resistivity surveys and contours maps of apparent resistivities were combined successfully to outline the contaminant plume produced by seawater intrusion. This geophysical method identifies the contaminant plume through low resistivity values as compared to the cleaner ground water.

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