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Apply electromagnetic approach to study saltwater intrusion in coastal aquifers, Crau delta plain, Southeastern France

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ABSTRACT

Coastal aquifers constitute an important high-quality freshwater resource exploited for agriculture, industry and human consumption. An increase in salinity occurs close to the sea, highlighting the need to investigate the water balance and groundwater behavior. Normally, this task could be solved by using monitoring data and groundwater modeling. The main difficulty is to parameterize and calibrate/validate the variable-density modeling. This requires adequate information on aquifer parameters and concentration distribution in groundwater. To solve this problem, we propose to use geophysical investigations to describe and image the transition zone of the freshwater/saltwater. Based on the apparent resistivity/conductivity values obtained from electromagnetic (EM) investigations, 3D saltwater distribution was characterized for study area. Saltwater were found from 4-5 m.asl close the southwest boundary to more than 20 m.asl near boreholes X34, X35 (about 1.7km from the boundary). In marsh area near the surface confirming the presence of a top clay layer and the salinity of surface water caused by evaporation. Such investigations can help to setup and validate the variable-density flow models. Electromagnetic method has been applied successful to determine saltwater intrusion in groundwater in Crau aquifer, southeastern France, where hydrological characteristics are similar to coastal aquifers in Vietnam.

1. Introduction

One of the most popular geophysical methods currently used to provide information about the spatial variation of soil properties is electromagnetic (EM) induction (Triantafilis and Monteiro Santos, 2013). EM methods were originally developed for mine exploration and have been widely used over the last decades for engineering purposes (McNeill, 1980) and for groundwater investigations (Fitterman and Deszcz-Pan, 2004) and its cost effective, reliable. These techniques have been described a number of in geophysical handbooks and scientific papers (McNeill, 1980; Stewart, 1982; Stewart and Gay, 1986; Borne, 1990; Triantafilis et al., 2003; Santos, 2004; Sirhan, 2013; Ramalho, 2013).

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Then, despite the qualitative nature of the provided information, this method is widely applied for hydrogeological and environmental investigations. Many applications of EM surveys have been applied for resources management in coastal aquifer (Stewart, 1982, Goldman et al., 1991, Frohlich et al., 1994, Triantafilis, 2013)

With the development of the EM31 and the EM34-3 (Geonics Ltd) it is possible to map terrain conductivity virtually as fast as the operators can walk and at low costs. The interpretation of EM data by using some modeling programs is qualitative even their inversion can be done for layered models.

2. Methodology

2.1. Principle of operation

In this study, we employed an EM34-3 of Geonics (Figure 1) to directly measure bulk conductivity. This equipment consists of two coils. One is the transmitter which is energized by an alternating current at a specific frequency and other is the receiver. The transmitter creates a magnetic field in the subsurface while the receiver detects and records the magnetic field. These two coils can be operated with different spacing of 10, 20 and 40m to vary the the conductivities range. The investigation depth depends on the frequency of the energising field, electrical structure of the earth and also the intercoil spacing and coil configuration (vertical dipole or horizontal dipole mode) (Santos, 2004). In the vertical dipole mode (VMD), the transmitter and receiver coils are located horizontally while in the horizontal dipole mode (HMD) these are placed vertically on the ground surface. Changing the orientation of transmitter/receiver loops from the vertical to the horizontal (Figure 2) also varies the depth of exploration by increasing the response from 0.75 to 1.5 times the intercoil spacing (McNeill, 1980). The use of different intercoil spacings with different frequencies (6400, 1600 and 400 Hz for 10m, 20m and 40m of intercoil spacing respectively) and different loops orientation vertical and horizontal allows to construct an image of subsurface electrical conductivity distribution from 7.5 meters to a maximum of 60 meters (Santos, 2004).

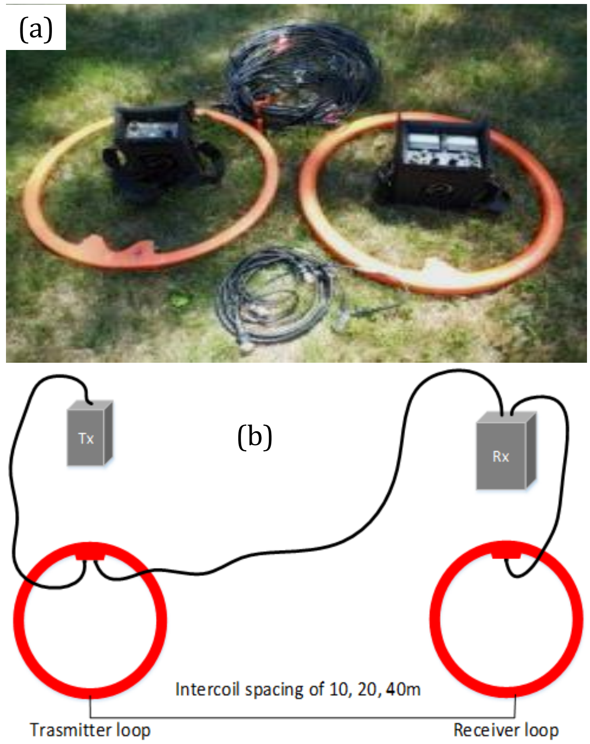

Figure 1. Geonics Electromagetic EM34-3 instrument applied in study area.

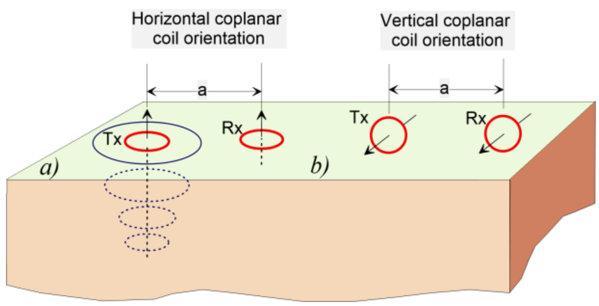

Figure 2. Relative response versus depth for (a) vertical dipoles and (b) horizontal dipoles.

The time-varying magnetic field arising from the alternating current in the transmitter coil induces very small currents in the earth which generates a secondary magnetic field H_s which is sensed, together with the primary field, H_p, by the receiver coil. In general, this secondary magnetic field is a complicated function of the intercoil spacing s, the operating frequency, f, and the ground conductivity σ. Under certain constraints, technically defined as "operation at low values of induction number", the secondary magnetic field is a very simple function of these variables. These constraints are incorporated in the design of the EM31 and EM34-3 whence the secondary magnetic field is shown in equation (1):

$$\frac{H_s}{H_p} \cong \frac{i\omega\mu_0\sigma s^2}{4} \quad (1)$$

Where: H_s: secondary magnetic field at the receiver coil; H_p: primary magnetic field at the receiver coil; $\omega = 2\pi f$; f = operating frequency (Hz); μ_o = permeability of free space; σ= ground conductivity (mho/m); s = intercoil spacing (m), $i = \sqrt{-1}$.

The ratio of the secondary to the primary magnetic field is now linearly proportional to the terrain conductivity, a fact which makes it possible to construct a direct-reading, linear terrain conductivity meter by simply measuring this ratio. Given H_s/H_p the apparent conductivity indicated by the instrument is defined from equation as equation (2) below:

$$\sigma_s = \frac{4}{\omega\mu_0 s^2}\left(\frac{H_s}{H_p}\right) \quad (2)$$

2.2. Interpretation

Usually the interpretation of the EM34-3 data is qualitative. One-dimensional modeling or inversion is possible (Santos et al., 2002).

A mesh of prismatic blocks centered at each measurement point, as is usual in three-dimensional modeling, makes up the earth model. Measurements are inverted by the program, using the cumulative response (McNeill, 1980) approach at each site of the grid of measurements to calculate the forward response and derivatives. Spatial smoothness constraints are introduced during the inversion procedure in order to construct a conductivity model, which represents the main features contained in the data. Two inversion algorithms are given by Sasaki. The least square solution of such a non-linear smoothing problem as equation (3) (Sasaki, 1989):

$$\left[\left(J^T J+\lambda C^T C\right)\right]\delta p=J^T b \quad (3)$$

And in the second algorithm (Sasaki, 2001):

$$\left[\left(J^T J+\lambda C^T C\right)\right]\delta p=J^T b+\lambda C^T C\left(p-p_o\right) \quad (4)$$

Here δp is the vector containing the corrections applicable to the model parameters, p_o is a reference model, b is the vector of the differences between the logarithm of the observed and the calculated σ_a, J is the Jacobian matrix, the superscript T is the transpose operation and λ is a Lagrange multiplier that controls the amplitude of the parameter corrections and the elements of the matrix C are the coefficients of the values of the roughness in each parameter which is defined in term (Sasaki, 1989). Although the final result obtained applying such a method is only a rough approach of a three-dimensional model and, for this reason it is designated as quasi-three-dimensional model, it can be very useful in the global interpretation of surveys.

Therefore, we have some difference methods of interpretation:

i) Direct interpretation using multiple EM readings at selected locations apply (empirical) formulae and using EMIX34 computer software;

ii) Analysis of relative readings (shows area of saline water and fresher water);

iii) Correlation of results with other more direct techniques:

- Salinity profiles from boreholes on same island;
- Salinity profiles from islands with similar geology;
- Electrical resistivity soundings.

3. Research area

The Crau coastal plain is a paleo-delta of the Durance River, located in the Southeastern of France, East of the present delta of the Rhône River, which is also known under the name of Camargue. The Crau aquifer delimited by Alpilles mountains in the North and by the Mediterranean sea in the South, forming a triangular area of about 600 km^2 between Arles, Salon-de-Provence and Fos. The aquifer is mostly recharged by direct infiltration of rainfall, irrigation practices and lateral groundwater flows. The irrigation of about 15,000 ha of meadow is done using water from the Durance supplied by a dense network of channels (Nguyen, 2016; Olioso et al., 2013). Groundwater naturally discharges into the marshes and the Rhône River. Intensive withdrawal occurs from pumping wells. The Crau aquifer is the main resource of domestic water for more than 300,000 inhabitants. It is important to notice that there is no natural river over the Crau plain and that all the surface water transfers occur through artificial canals.

In this study, our approach was applied on an area of about 140 km^2, is situated in downstream part of the Crau coastal plain, what is now called "Study area" where located the salt/fresh water interface shown in Figure 3.

The study area was considered as a suitable case of study area because: (i) it is an important aquifer in the South of France, highly vulnerable to salinization due to its coarse nature; (ii) groundwater salinity problems have occurred due to a great number of groundwater extraction wells for irrigation and the changes in the water management; (iii) the groundwater abstraction for domestic/industrial use caused significant variation of water heads; (iv) a dataset over a 20 year period is available for the site (Nguyen, 2016). The Crau aquifer is globally unconfined, but becomes semi-confined to confined in the marsh area of Vigueirat and Landre ponds (Figure 4, Figure 5), due to the presence of semi-pervious material (Rhone River sediment and lacustrine deposits). This material has low hydraulic conductivity (between 3.7x10-5 and 8.7x10-3 m/s) and its thickness in the study area varies from 0m at the limit of Crau aquifer to more 7m near Arles-Fos canal. The specific yield of aquifer obtained from pumping tests is in the range of 0.01 to 0.18 attesting the unconfined to semi-confined (leaky) behavior of aquifer.

4. Results and discussion

Two campaigns of EM surveys have been conducted (Figure 5) in marsh area around the saltwater front which was defined by electrical conductivity measurements . Principle EM profile with regard to saltwater front is shown in Figure 7. The first campaign (Figure 6)have been carried out in four sectors northeastern side of the canal Colmatage (sectors 1-4) and the second campaign in eight sectors on the other side of canal (sectors 5-12). The transmitter-receiver separation was 10m (EM34-10) and 20m (EM34-20) with both

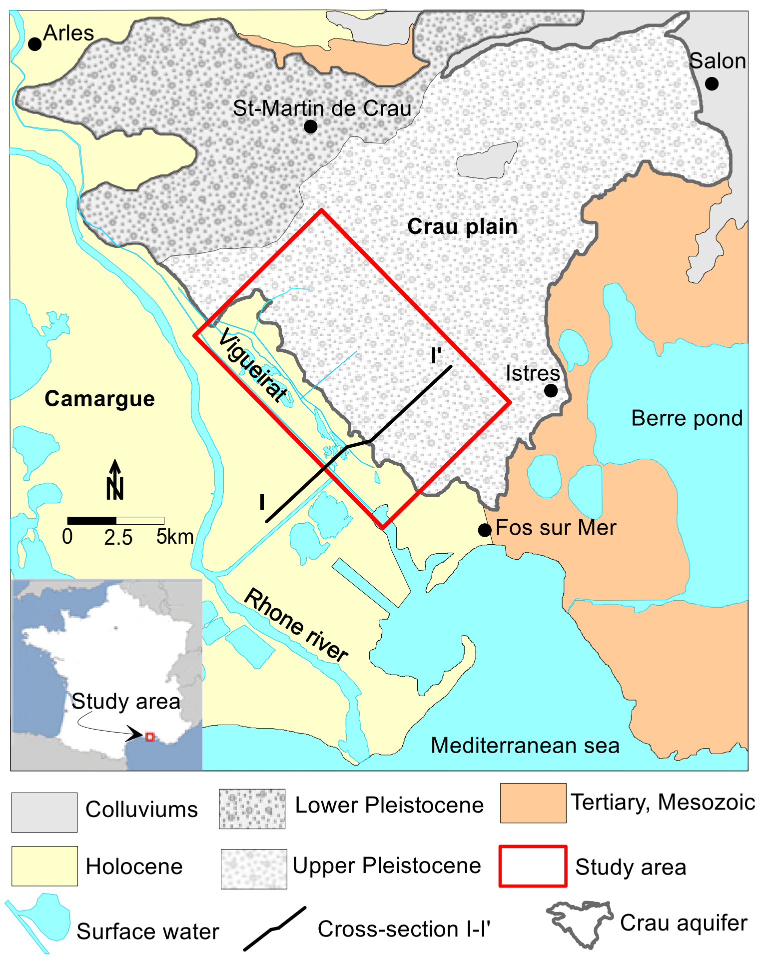

Figure 3. Location of Crau coastal plain and the study area.

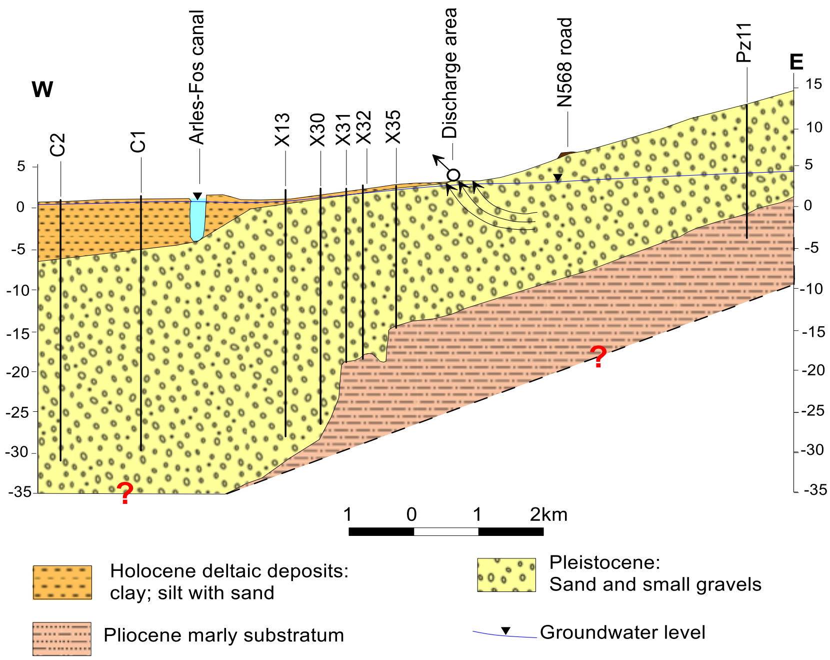

Figure 4. Schematic of hydrogeological cross section I-I' (BRGM, 1995).

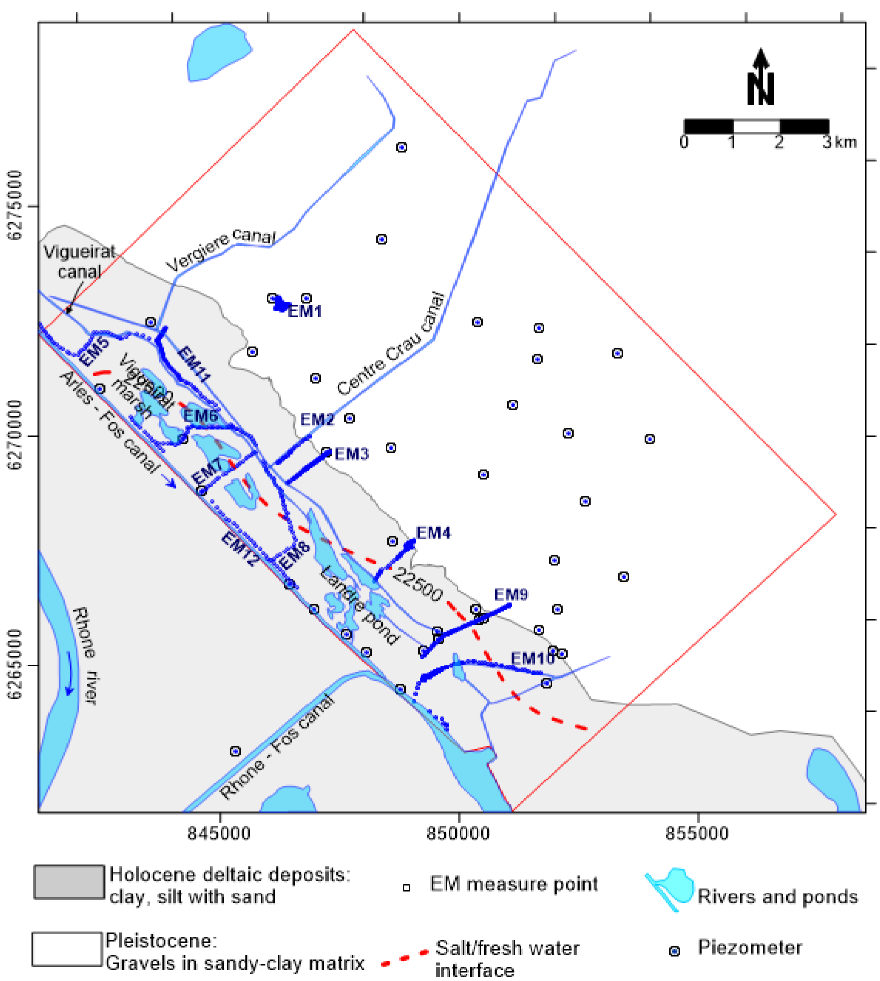

Figure 5. Position of electromagnetic (EM34) measurement points.

vertical dipole (VD) and horizontal dipole (HD). Distance between sectors varies from about 600 m to 11 km. 480 points where measured with EM34-10, 853 points with EM34-20 and 30 points with EM34-40 (Table 1). The topography in marsh area is flat at a level between 0-1 m.asl in the marsh zone and 2-3 m.asl in the sector 1-4. In several sectors, some measurements with an intercoil separation of 40m (EM34-40) have been added in order to image the apparent electrical conductivity distribution at the difference depths. These surveys have covered distances of more than 30km (Figure 5, Table 1). After two campaigns of EM survey, 12 profiles of EM34 have been done (Figure 5 and Table 1) in the marsh area, with 10 profiles perpendicular with salt-freshwater limit and two others along the canals. The spatial distribution of apparent soil electrical conductivity (σ_a - mS/m) of EM34-20 have been compared with a spatial distribution of electrical conductivity (EC) measurements from in pore water at 10 m depth.

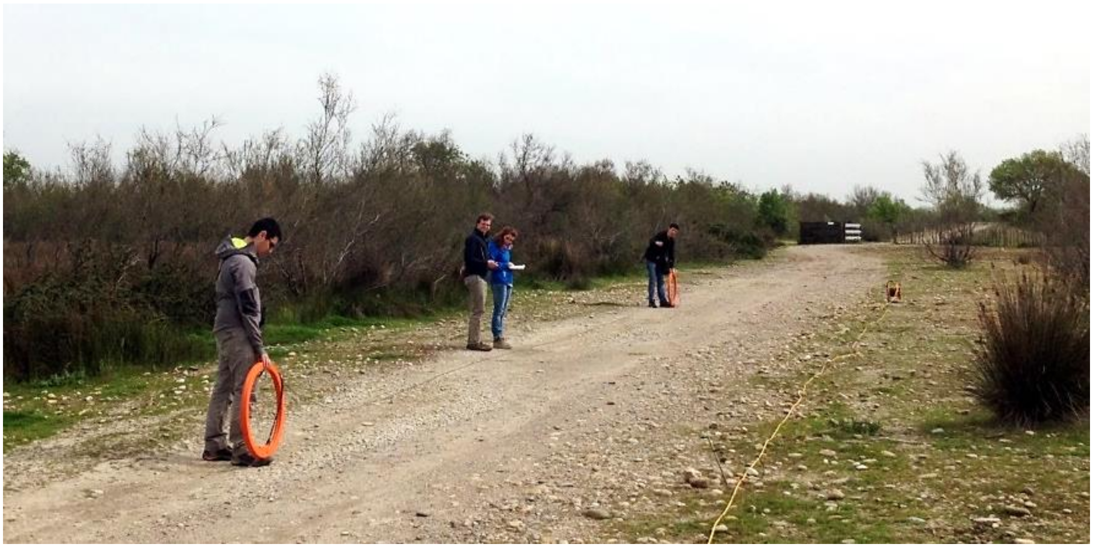

Figure 6. EM34 measurement in study area.

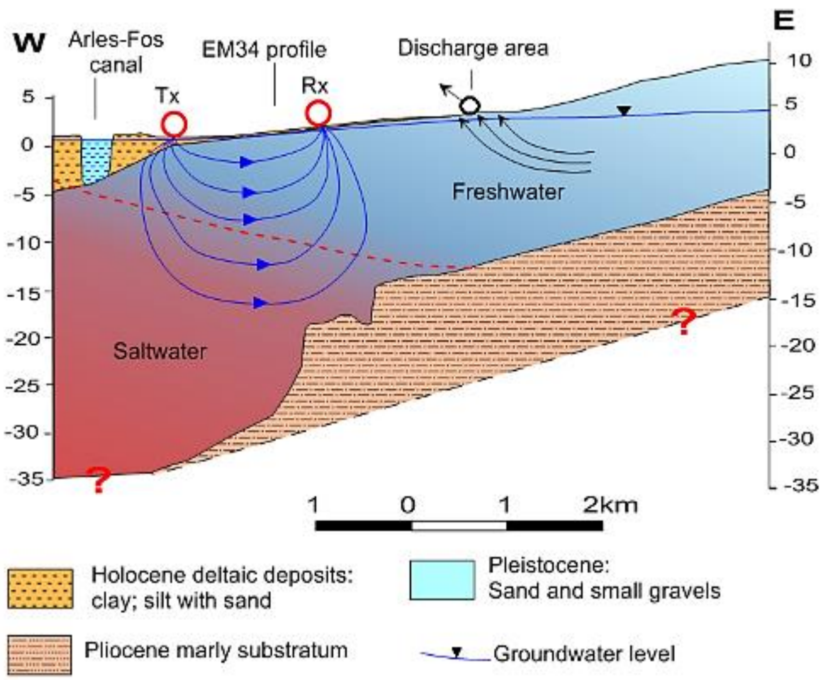

Figure 7. Principle of EM34 profile with regard to interface between fresh and salt water of cross section I-I'.

Table 1. EM34 profiles in research area.

Sector	Location	Distance	Measurements (point)	
		(m)	EM34-10	EM34-20
1	Center Crau (nearby P21, P21bis)	1,600	90	73
2	Along Center Crau canal	909		22
3	Nearby X20 piezometer	1,153		32
4	Nearby X26 piezometer	1,235	29	36
5	Northern of Vigueirat	1,977	57	57
6	Center of Vigueirat, nearby XB	2,028		40
7	Center of Vigueirat, nearby X19	1,426	33	33
8	Southern of Vigueirat	2,598		121
9	Sector Pissarotte, nearby X13, X31-X35	2,236	117	96
10	Sector Tonkin	2,599	28	83
11	Along Colmatage canal	5,849		107
12	Along canal Arles-Fos	6,800	126	153
	Total	30,410	480	853

The small σ_a (<30 mS/m) characterize the freshwater zone in the center and northeast of Crau. In the zone along the Colmatage canal in center of marsh area, σ_a varies from 30-80 mS/m characterize a saline intrusion zone, equivalent to EC from 6-18 mS/cm. In the southwest area, σ_a is very high (>100 mS/m) characterize the saltwater zone.

The EM34 data have been interpreted by using the software EM4Soil - a software package which was developed to enable the inversion of electromagnetic (EM) conductivity data σ_a acquired at low induction numbers (EMTOMO, 2015). The inversion algorithm is based upon the Occam regularization method (Sasaki, 1989, Sasaki, 2001) described and applied in several studies (Santos et al., 2010, Triantafilis and Monteiro Santos, 2013, Triantafilis et al., 2013). With the inverse model, EM34 apparent conductivity (σ_a) were inverted using a 1-D spatially constrained algorithm for quasi-3D conductivity imaging, then a map of spatial distribution of estimated electrical conductivity σ have been done would help to better understand in term of geology (structure, lithology,) and hydrogeology (saline groundwater interface, ...). To correlate geophysical survey results with model simulations a relation between bulk electrical resistivity and total dissolved solids contents (TDS, regional -chemical data) must be established (Figure 8). This relation has been found with R^2=0.9978 and y = $2.1983^{0.923}$.

The first campaign, studying the thickness and geometry of depositional systems, using intercoil spacing of 10 and 20 m, has been applied on 4 sectors in the NE of the Colmatage canal. This sector contains freshwater and is far from salt-freshwater limit as determined by electrical conductivity measured in piezometers. The second campaign have been developed around the salt intrusion zone described by previous studies (SAFEGE, 2006). This campaign was dedicated to understand the current distribution of salt and brackish water in this aquifer. The statistics of all measurements have shown in Table 2; Figure 9.

To interpret the spatial distribution of electrical conductivity σ within these sectors, one campaign of electrical conductivity ECe profiling in boreholes has been done at the same period of geophysical campaign. Two perpendicular sectors of ECe have been investigated, one along the road N286 (Figure 10) and the other along the canal from Arles-Fos (Figure 11). On both profiles, the spatial distribution of ECe is clear. Spatial maps of estimated σ from electromagnetic EM34 were compared the spatial maps of ECe. The spatial and vertical distribution of ECe measured in piezometers (Figure 11) shows that the saltwater comes from SW to NE. Saltwater (with ECe > 2250 mS/m) from -10 m in X4415, and from -14 m in X13 but in X33, ECe at -20 m is only 2030 mS/m. The spatial distribution map of σ (Figure 10) shows a similar pattern with higher conductivity

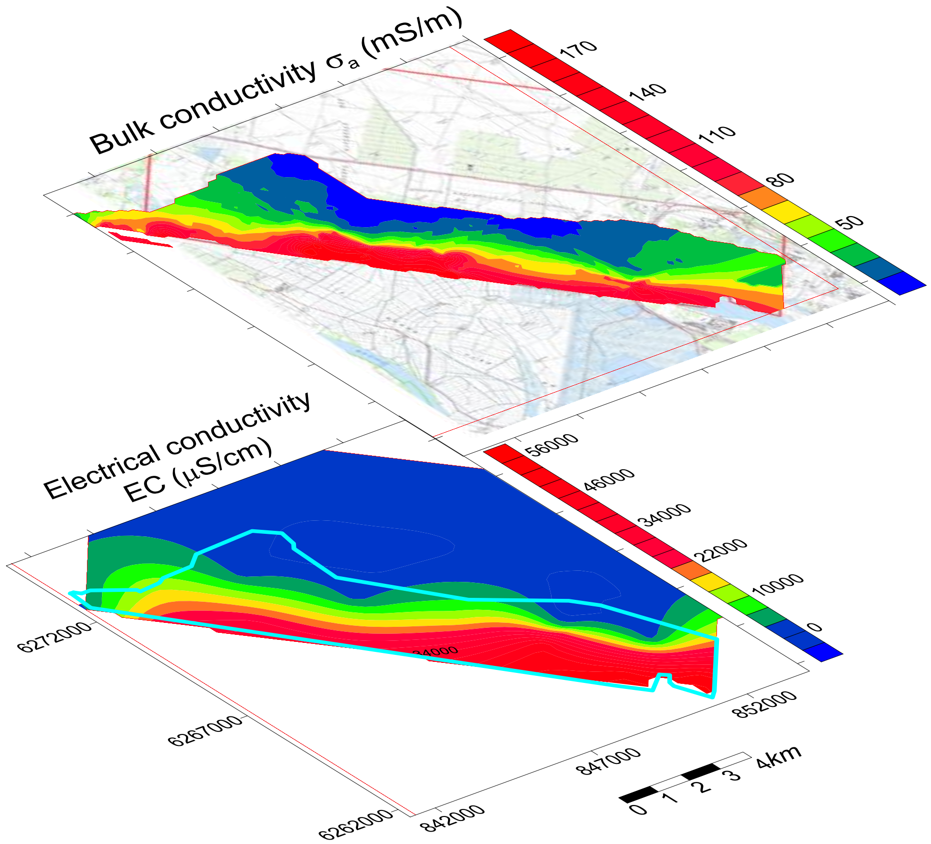

Figure 8. Spatial distribution of apparent electrical conductivity σ_a (mS/m) with EM34-20m HDM (upper) and electrical conductivity ECe (μS/cm) in groundwater at -10m depth from groundwater level in piezometers (lower), red and blue colors represent the conductive and resistive layers, respectively.

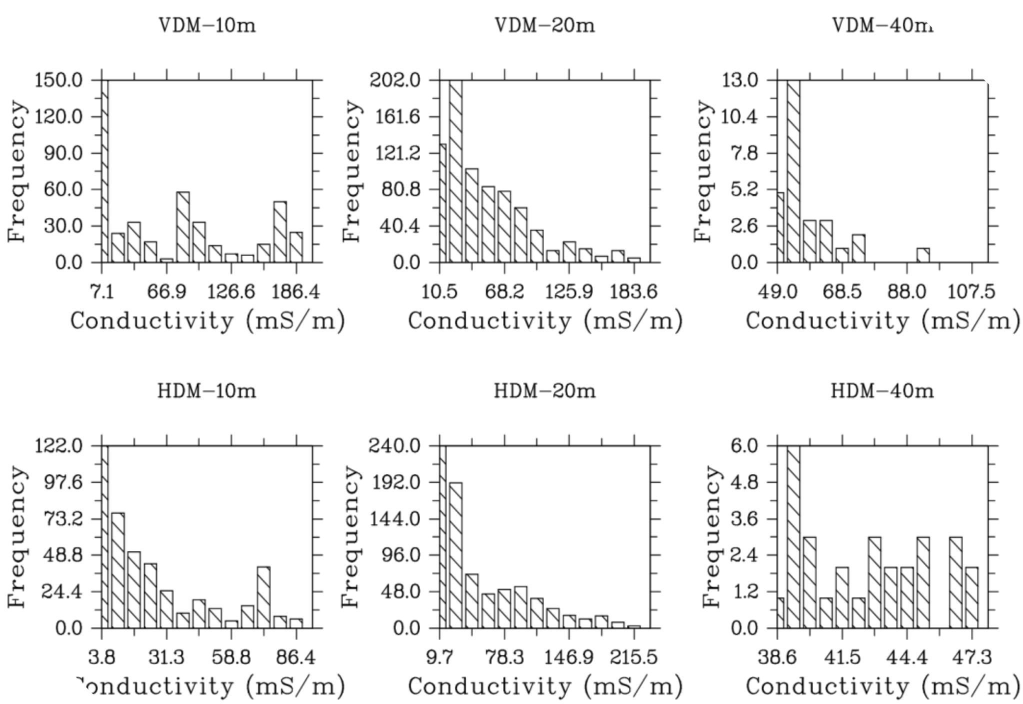

Figure 9. EM34 data statistic of all measurements.

Table 2. EM-34 survey measurement statistics.

Sensor	Readings	Mean+-1std dev.	Std dev.	Min	Max
VDM-10m	435	77.38	64.83	7.13	201.30
HDM-10m	435	29.17	24.74	3.80	93.34
VDM-20m	774	58.99	38.30	10.50	198.07
HDM-20m	774	60.12	48.75	9.70	232.65
VDM-40m	30	62.32	13.65	49.00	112.60
HDM-40m	30	42.97	2.87	38.60	48.00

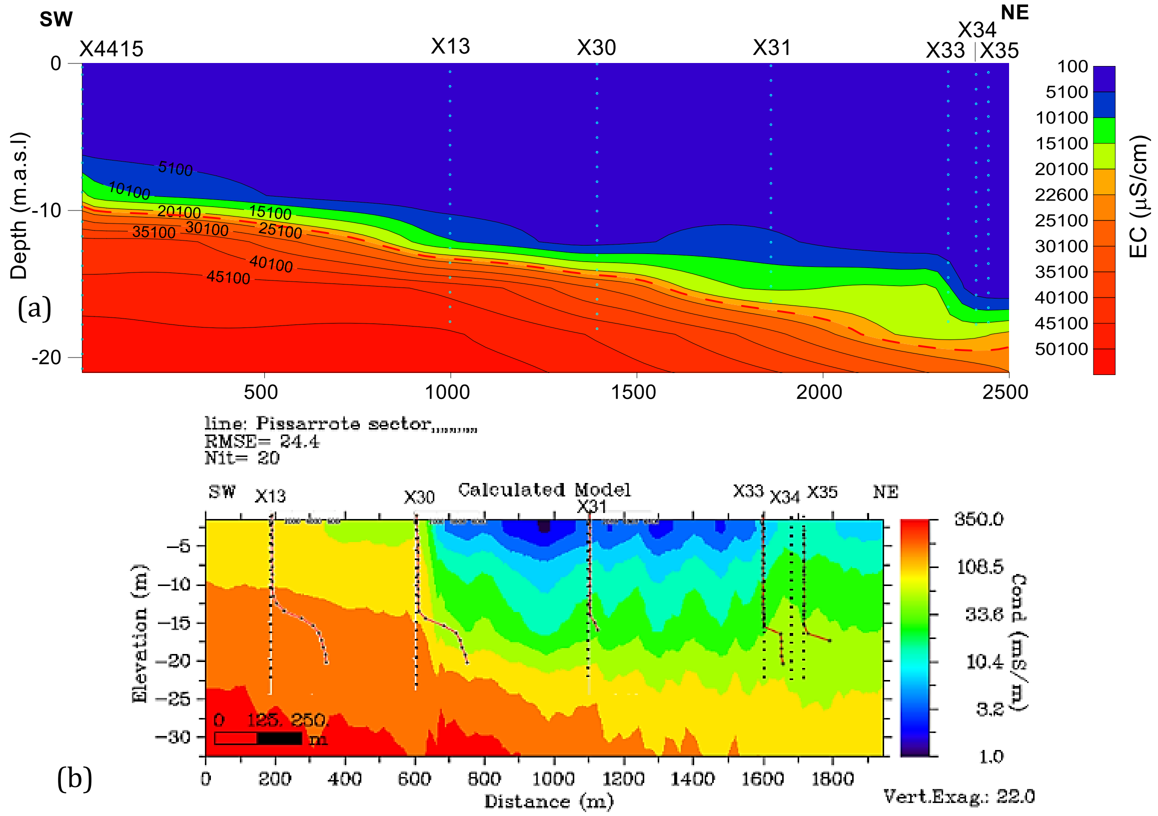

Figure 10. Spatial distribution of (a) electrical conductivity (EC) of water in piezometers (ECe - µS/cm) and (b) estimated electrical condutivity from EM34 apparent electrical conductivity (σ_a - mS/m) in cross section EM9 (Pissarote).

in the SW, and decrease to the NE. High value of electrical conductivity σ > 150 mS/m is observed at about 10 m depth in X13 but disappears even at -20 m depth in X31.

It is similar for the sector along the Arles-Fos Canal. A spatial distribution of σ was obtained from the apparent survey electricity with root mean square error (RMSE) of 28.0%. The 2-D estimated σ profile shows that the higher σ are distributed in SE and decrease to NW direction. It can be seen in Figure 11, the depth of saline groundwater with ECe > 2250 mS/m have been found at 14 m depth in L1 and are not present in X21 (at 18m). Comparing the pattern of two sectors, the saline groundwater zone from Figure 11 has the pattern of σ > 150 mS/m and fresh water zone with σ between 5 and 40 mS/m.

From the pattern of the distribution of the estimated electrical conductivity and electrical conductivity of water in piezometers from Figure 10 and Figure 11, the inverse models compared favorably with the electrical conductivity profiles obtained from piezometer measurements. It is obvious that the distribution of σ confirms the presence of saline groundwater

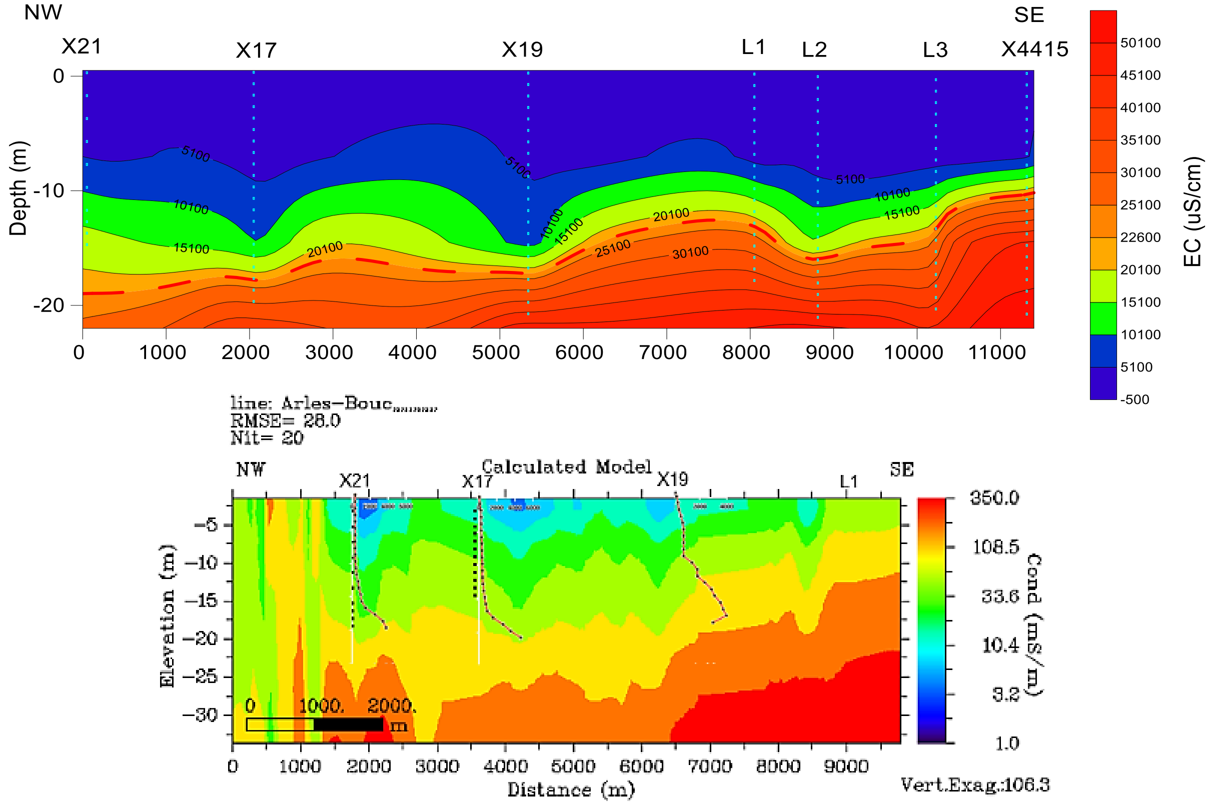

Figure 11. Spatial distribution of a. electrical conductivity water in piezometers (ECe - µS/cm) and b. estimated electrical condutivity from EM34 apparent electrical conductivity (σ_a - mS/m) in sector EM12 along the canal from Arles-Fos.

In sector 1, the small σ (less than 2 mS/m) have been found from top to about 4 m depth. One can distinguish the water table in the aquifer (water table in Pz21 is 3.15 m). In some sectors, σ of the top soil (few meters depth) is high (σ> 150 mS/m) and compares to the values of ECe smaller than 20 mS/m (fresh water). These zones coincide with the clay layer described in piezometers XB, X19, L1. The electrical conductivity is high in some places because: 1) water table is very low about 0.3 m to 0.7 m from the surface; 2) saltwater table is shallow (less than 10 m); 3) surface water is not connected to pond or canals and 4) effect of evapo-transpiration that concentrates salt in water. In comparison, the saturated sand and gravels layer with fresh water (ECe < 200 mS/m) is characterized by σ ranging between 5 and 40 mS/m.

In sector EM12 along the Arles to Fos canal, the value of RMSE is 28% and could be due to the low resolution of σ_a along this sector. The sector is too long (>10km), and data of EM34 is discontinue in some parts because of the security regulation of Vigueirat (cows and bulls grazing).

Despite these comparisons and validations, electrical conductivity σ shows the presence of saltwater and the difference of lithology. Therefore, distribution of σ from quasi 3-D imaging have been used to validate and calibrate at difference depths the saltwater model. Figure 12 shows the spatial pattern of estimated electrical conductivity from EM34 data at difference depths. All distributions show a high conductivity zone in the southwestern part of the area. These conductive zones can potentially present saltwater intrusion. With 2-D cross sections (Figure 10, Figure 11), interpretation for the different depth has been done. With the respect to soil type and conductivity, the depth of clay layer and the interface of salt-fresh water have been determined.

Resistivity distributions from EM method show four different layers. i) A superficial unsaturated layer made of coarse sand and gravel (thickness of about 6 m) in the northeastern part of marsh area (center of research area) with very

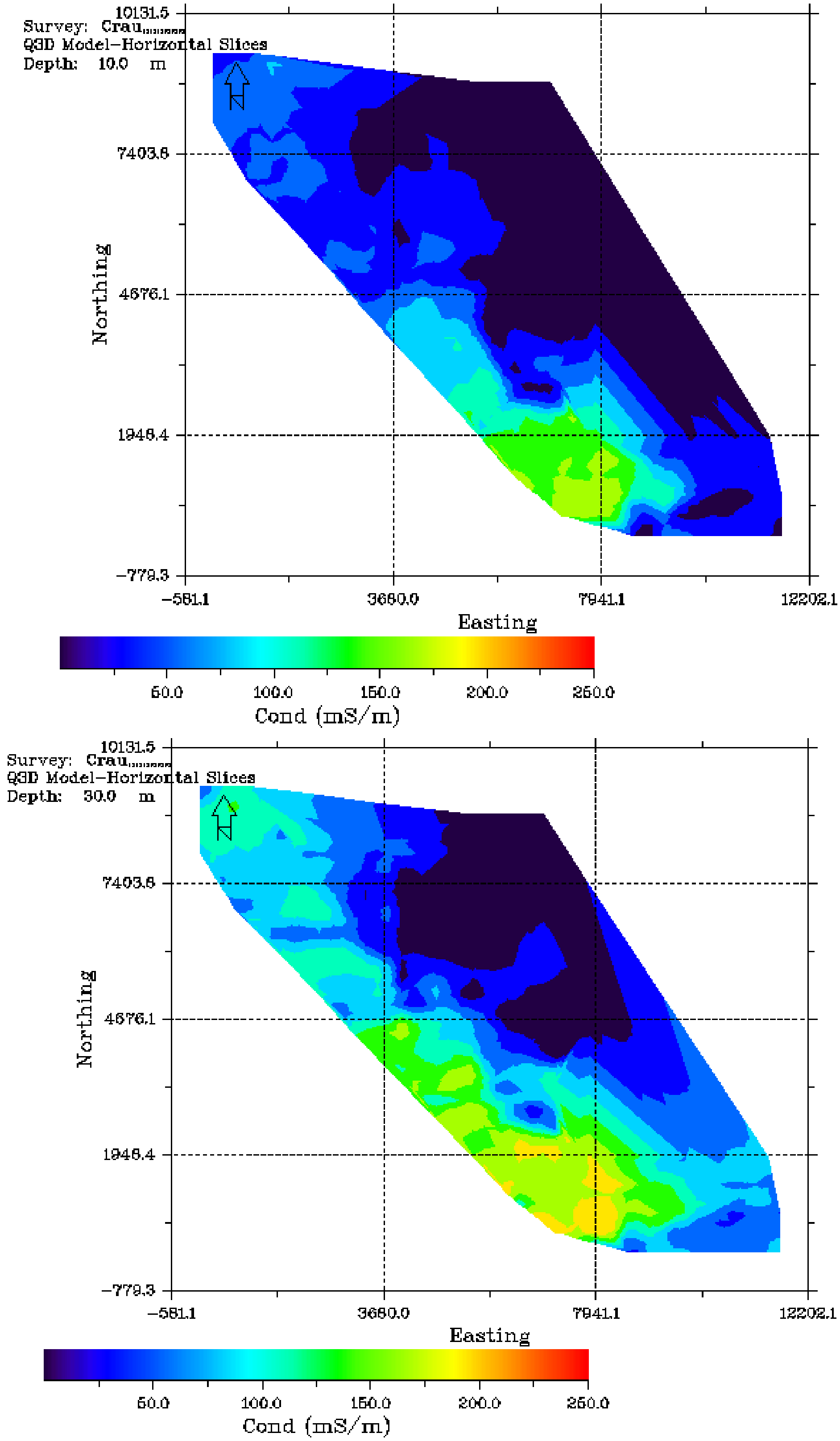

Figure 12. Spatial distribution of estimated EC (ms/m) at 10m and 30m depth from a joint inversion of EM34-10, EM34-20 and EM34-40 data using a 1-D laterally contrained algorithm for quasi-3D conductiviy imaging.

low σ(< 2 mS/m); ii) a saturated coarse sand and gravel layer with fresh water where σranges from 2 to 30 mS/m; iii) a superficial fine sand and clay layer found in marsh area where σ varies from 100 to more than 300 mS/m and iv) a conductive (σ > 80mS/m) coarse sand and gravel layer saturated by brackish or saltwater observed between 3-7 and 30 m depth in sector Pissarotte and between 15-20 and 30 m depth in Vigueirat area (Figure 10 and Figure 11).

The electrical conductivity of aquifer increases with depth and towards SW due to saltwater. The most conductive area is found in sector Pissarotte (Figure 10) and in sector along the Arles-Fos canal (Figure 11) with σ > 150 mS/m at a depth less than 10 m. This characteristic is observed for all other sectors in the marsh area.

The variation of electrical conductivity also corresponds to the variation of lithology. The thickness of superficial fine sand and clay layer increases to SW from 0 m in center to 5-7 m along the Arles-Fos canal. On the other hand, water level decreases to SW from 2-3 m in the NE of marsh area to 0.3-0.7 m SW of marsh. Therefore the thickness of high conductive (low resistivity) superficial layer also increases to SW due to two factors such as: i) influence of clay content and ii) increase of dissolved salt due to evaporation.

5. Conclusion

Geophysical methods are very useful techniques to inform on the hydrogeological characteristics and calibrate models. Inversed 2D and 3D geophysical models provide high resolution datasets of subsurface structure at a low cost and in a short time. However, this technique still faces difficulty while different resistivity models may produce the same apparent geophysical effect. Therefore, to reduce the errors and uncertainties in geoelectrical models, it is necessary to compare these models with geological and hydrogeological data.

In the study area, the saltwater front is located around the marsh area where it is distributed in a dense network of ponds, canals and the bulls grazing fields of the bull husbandry industry. Because space of EM measurements is very constrained, electromagnetic methods appear useful and need little measurement space. An electromagnetic method using a EM34 device have been applied for mapping the saltwater intrusion with a total investigation length of more than 30km. This method is very simple and rapidly operated at a low cost and on a restrained surface. In order to reduce the errors and uncertainties and to validate results of EM method, a combination of difference geophysics techniques is strongly recommended. The EM34 data have been interpreted using the software EM4Soil.

Based on the apparent resistivity/ conductivity values obtained from EM investigations, 3D saltwater distribution was characterized (Figure 13). The low resistivity area is located in the southwest of the study area. Low resistivities were found from 4-5 m.asl close the southwest boundary to more than 20 m.asl near X34, X35 (about 1.7km from the boundary). Observations of water in wells and boreholes also indicate brackish water. In marsh area, low resistivity was found near the surface confirming the presence of a top clay layer and the salinity of surface water caused by evaporation. Outside this area no indication of saltwater or saltwater intrusion has been found.

Acknowledgements

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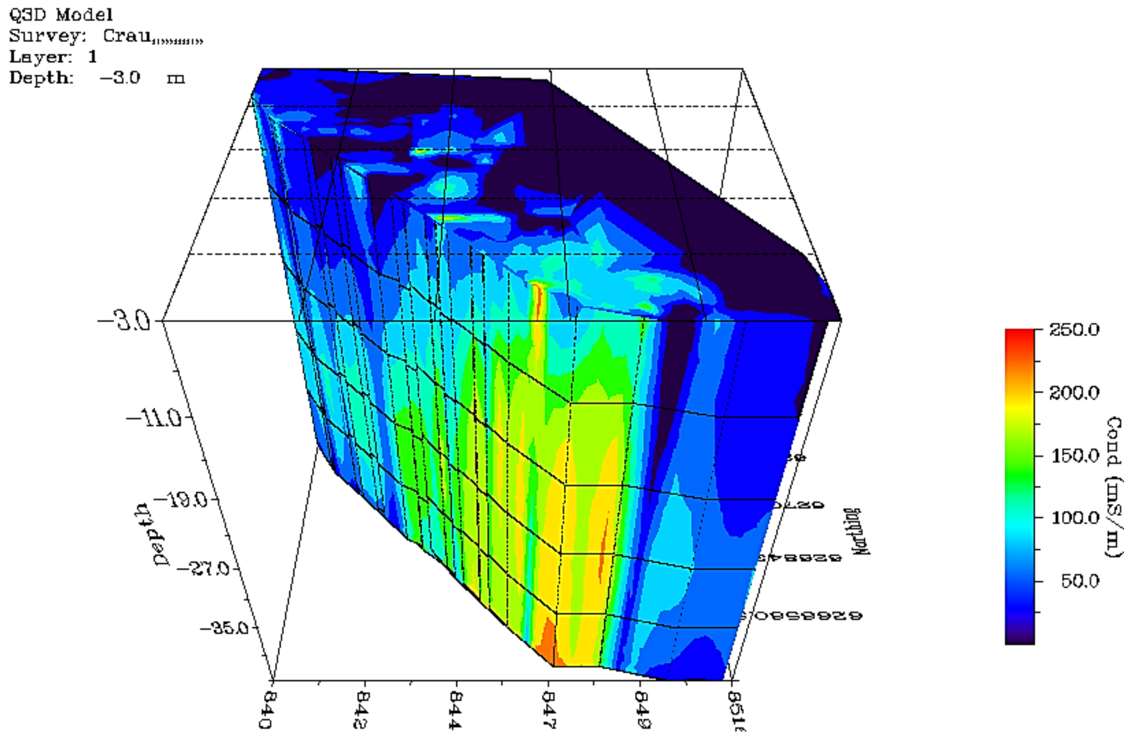

Figure 13. 3D distribution of estimated EC (σ- ms/m) from a joint inversion of EM34-10, EM34-20 and EM34-40 data using a 1-D laterally contrained algorithm for quasi-3D EC imaging.

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