Mapping Coastal Aquifers by Joint Inversion of DC and TEM Soundings—Three Case Histories

by Yves Albouy1, Pierre Andrieux2, Gérard Rakotondrasoa3, Michel Ritz4, Marc Descoëts1, Jean-Lambert Join5, and Eddy Rasolomanana6

Abstract

Electrical and electromagnetic methods are well suited for coastal aquifer studies because of the large contrast in resistivity between fresh water-bearing and salt water-bearing formations. Interpretation models for these aquifers typically contain four layers: a highly resistive unsaturated zone; a surficial fresh water aquifer of intermediate resistivity; an underlying conductive, salt water saturated aquifer; and resistive substratum. Additional layers may be added to allow for variations in lithology within the fresh water and salt water layers. Two methods are evaluated: direct current resistivity and time domain electromagnetic soundings. Use of each method alone produces nonunique solutions for resistivities and/or thicknesses of the different layers. We show that joint inversion of vertical electric and time domain electromagnetic soundings produces a more tightly constrained interpretation model at three test sites than is produced by inversion methods applied to each data set independently.

Introduction

Resistivity measurements are used to estimate the electrical properties of subsurface materials, which are highly dependent upon porosity, saturation, and fluid resistivity (Keller and Frischknecht 1966). Information about water content and water quality, including mapping of salt water intrusion, can thus be obtained in most coastal areas. The ground water system may be simplified as follows, from the surface downward: a high resistivity unsaturated zone above, then an intermediate resistivity fresh water lens, resting on a low resistivity salt water layer, which may be bounded by resistive bedrock at depth. This system is maintained in a dynamic equilibrium which is based on density contrast between fresh water and salt water (Kashef 1983). Although a transition zone may exist at the fresh water/salt water interface, a layered model is a reasonable approximation for a simple coastal hydrogeological environment.

Direct current (DC) resistivity methods have been successfully used for general investigations of aquifers (Van Overmeeren 1989), as well as for studying their hydrogeological characteristics (Urish 1981). On the other hand, electromagnetic (EM) methods which have a shorter history in ground water studies, are used for mapping the fresh water/salt water interface and, more generally, for studying conductive bodies of hydrogeological interest (Goldman et al. 1991). In general, EM surveys require shorter time and fewer personnel than DC resistivity methods for similar depths of investigation. One EM method that is used a great deal for ground water work is transient EM (TEM) sounding, sometimes called time domain electromagnetic sounding (TDEM).

The purpose of this study is to examine the relative merits of these two techniques, DC and TEM sounding, for coastal ground water exploration. Three data sets are considered: one in Biarritz (southwestern France) and two on La Reunion Island (Indian Ocean). This paper advocates joint inversion of VES and TEM data as a more efficient way of resolving the ambiguity of each single geophysical interpretation, especially in the absence of any additional information, such as well log data. The efficiency of joint inversion of VES and TEM data is discussed in detail by Raiche et al. (1985). The technique clearly has important applications in coastal hydrogeology, where conductive saline-water aquifers may lie between more resistive layers. We present two types of case histories related to different hydrogeological situations that fall within this general classification. Test site 1, in southwestern France near Seignosse, 30 km north of Biarritz, consists of an aquifer located within sands reworked by the ocean. Test site 2, located on Reunion, an island in the Indian Ocean, includes an aquifer located within basalt flows.

Methods and Techniques

Each method considered in this paper is described briefly; for a more complete and detailed presentation, the reader is referred to Kunetz (1966) and Nabighian (1991). The basic procedure of the DC resistivity method is to measure at the surface of the earth the resulting potential due to a known current flowing into the ground.
potential difference and resistivity in an infinite, homogenous medium. This value is different from the true resistivity of the subsurface, depending on the thickness of each layer and the geometry of the electrode array. The VES curve ($\rho_v$ versus $AB/2$) is interpreted by using one-dimensional (1-D) inversion programs. In our field work, resistivity data were acquired with an ABEM-Terrameter SAS 300 equipment; in some cases, the ABEM-2000 Booster was incorporated. Soundings were carried out with maximum $AB/2$ separations ranging from 80 to 500 m.

The TEM method is based upon the diffusion of transient electromagnetic fields into the earth to determine its electrical conductivity as a function of depth. The TEM system consists of a large square transmitter loop with a multi-turn air coil receiver located in its center. The array is centered at each sounding location. The current waveform driven through the transmitter loop consists of equal periods of time-on and time-off (Figure 1b). The transient response of the ground is generated by abruptly turning off the current flowing into the transmitter loop. An apparent resistivity value is computed as a function of time after turning off the current. With increasing time, the induced currents reach further into the formation and are representative of greater depths. The relationship between time and depth depends on the distribution of electrical conductivities within the earth. Field measurements for these surveys were carried out with the TEM Geonics EM47 system using two or three base frequencies. An equipment configuration with the receiver coil located in the center of the transmitter loop was used because this geometry enhanced signal-to-noise ratio and has reduced sensitivity to lateral resistivity gradients (Eaton and Hohmann 1989). The data acquired in the field were then interpreted with layered models using the EINVRT4 (Sandberg 1990) interpretation package to obtain a solution for the resistivity stratification of the subsurface.

**Individual and Joint Inversion of VES and TEM Soundings**

When VES or TEM soundings are applied alone, either data set is interpreted in terms of horizontally layered models which lead to the best match with field data at a given station. Although the number of layers used in the model is arbitrary, the layers are usually kept to the minimum number needed to produce a reasonable fit between model and data. The solutions obtained in this way are known to be nonunique as follows.

When a layer of intermediate resistivity lies between two layers with different resistivities, then the sounding curves may be matched by a model with only two layers. This result suppresses the identity of the intermediate layer. Such a situation would correspond to a fresh water aquifer lying between a resistive unsaturated zone and an underlying salt water-saturated aquifer. If there is a thin layer of lower resistivity between two thicker layers, the geometry of this layer may not be uniquely defined by the model. This model equivalence effect means that soundings can be interpreted only in terms of the product of layer thickness and conductivity (inverse of resistivity) for such a relatively conductive layer. This situation corresponds to a salt water aquifer lying between an unsaturated or fresh water saturated aquifer, and resistive basement. This situation could also arise in the case of an electrically conductive clay aquitard separating two fresh water aquifers. Therefore, VES and TEM model inversions are often expressed in terms of longitudinal conductance, the product of layer conductivity and thickness.
Figure 2. Biarritz. Independent inversions of VES and TEM soundings from a three-layer model. Lines represent model derived data; squares represent observation data.

If there is a thin layer of higher resistivity between two thicker layers, the VES method can be interpreted only in transversal resistance, i.e., the product of layer resistivity and thickness for such a relative resistive layer, while TEM soundings can determine only the thickness of the resistive layer and not its resistivity.

Although VES and TEM soundings have important applications in the characterization of aquifers, the suppression and equivalence principles of DC and EM sounding interpretation clearly affect the ability to delineate certain classes of aquifers. The two techniques also have fundamental differences in the way they characterize subsurface structures. DC currents flow perpendicular to the layers' boundaries inside resistive layers and parallel inside conductive layers, while EM currents flow parallel for any resistive or conductive layers but are negligible in resistive layers. Raiche et al. (1985) demonstrated that joint inversion of VES and TEM soundings might yield results that could not be obtained with either method of inversion applied independently. Following Raiche et al. (1985), Hohmann and Raiche (1988), and Sandberg (1990, 1993), we use the Jupp-Vozof algorithm (Jupp and Vozof 1975) to iterate to the best fit between model and sounding data for the combined set of VES and TEM data. The model fitting procedure matches \( n \) observed apparent resistivity data \((d_1, d_2, \ldots, d_m)\) to \( m \) calculated apparent resistivity values \((y_1, y_2, \ldots, y_m)\) using \( n \) parameters (layer resistivities and thickness; \( p_1, p_2, \ldots, p_n \)). The quality of fit of the model to the data is given by

\[
\text{rcsq} = \frac{1}{(M - N)} \sum_{i=1}^{M} (d_i - y_i)^2
\]

An improved estimate of model parameters is given by a Taylor series expansion of the model:

\[
d = y + J \delta p
\]

This expression uses the Jacobian matrix, \( J \), representing the partial derivatives of the model with respect to each of the model parameters. Because the parameters may vary over many orders of magnitude, the model fitting uses the logarithm of the values of \( d_i, y_i, \) and \( p_i \) rather than the actual parameters. These equations are used to iterate to an improved estimate of model parameters: \( p_{\text{new}} = p_{\text{old}} + \delta p \)

The Jupp-Vozof method uses singular decomposition in representing the partial derivatives used in the inversion (Raiche et al. 1985). This method is used because the model predictions, \( y_p \), are much more sensitive to some of the parameters than they are to the rest. If all of the \( y_i \) are virtually independent of a parameter, \( p_i \), then the computed partial derivative with respect to that parameter will induce large variations in the model computations during the iteration. Singular decomposition addresses this problem by expressing parameters in terms of the eigenvectors of the Jacobian matrix. Very small eigenvalues in the expressions for the transformed \( J \) matrix...
Figure 3. Biarritz. Tentative joint inversion of VES and TEM from a three-layer model.

correspond to eigenvectors that have almost no effect on the model. Therefore, a damping factor is added to the values of the smallest eigenvalues to selectively suppress the oscillations in model iterations. The damping factors are then sequentially decreased until the model converges to a minimum residual error of fit.

At the end of each iteration, we calculate the standard error, using the logarithmic parameters

\[
\sigma = \left[ \frac{1}{M-N} \sum_{i=1}^{M} (D_i - Y_i)^2 \right]^{1/2}
\]

We estimate the confidence intervals in the parameters using \( \sigma \) and the Cramer-Rao multipliers (Bard 1974):

\[
p_{\text{max}} = p \exp(1.96B_j \sigma)
\]

\[
p_{\text{min}} = p \exp(-1.96B_j \sigma)
\]

where

\[
B_j = \left[ \sum_{k=1}^{K} \left( \frac{V_{jk}}{S_k} \right)^2 \right]^{1/2}
\]

These confidence limits and the inversion statistics proposed by Raiche et al. (1985) and Hohman and Raiche (1988) can be used to quantify the uniqueness of the joint inversion of VES and TEM soundings in comparison to the results obtained by separate inversion of the two data sets independently.

**Test Site 1—Coastal Sand Aquifer**

North of Biarritz, southwest of France, sand dunes run parallel to the shore of the Atlantic Ocean. They are made up of marine sands and pliocquaternary eolian formations. They rest on a thick marl substratum at an average depth of 50 m. Rainfall at this site is about 1200 mm/year, and fresh ground water flow is generally toward the coast. The hydrological situation is rather simple, and can be represented by the following model for a station located approximately 50 m inland from the shore:

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness</th>
<th>Resistivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry sands</td>
<td>15 m</td>
<td>2000 ohm-m</td>
</tr>
<tr>
<td>Fresh water sands</td>
<td>15 m</td>
<td>200 ohm-m</td>
</tr>
<tr>
<td>Salt water sands</td>
<td>12 m</td>
<td>2 ohm-m (Conductance = 12 m/</td>
</tr>
<tr>
<td>Maril substratum</td>
<td>50 ohm-m</td>
<td></td>
</tr>
</tbody>
</table>

Direct calculation of this four-layer model has been carried out in VES and TEM. Each curve has been sampled at depth stations corresponding to a sequence of surface sounding data. These samples are used to represent observation data for electromagnetic
soundings at this site. Model interpretations using this data set demonstrate the degree of uniqueness in the interpretation of sounding data obtained at this site.

Independent and Joint Inversions Using a Three-Layer Model

VES inversion (Figure 2). For the upper layer there is no equivalence: thickness and resistivity of dry sands are determined unambiguously. For the intermediate layer there is equivalence: any highly conductive layer with an equal conductance is acceptable. The resistive estimate for the substratum is reasonably constrained. The two alternate models in Figure 2 give almost the same residual error.

TEM inversion (Figure 2). For the upper layer, the thickness of resistive sands (dry + fresh-water saturated) is determined unambiguously, but there is large equivalence for the upper layer resistivity. There is equivalence for the intermediate layer: any highly conductive layer with a conductance of about 6.66 siemens is acceptable. With a smaller conductance of 6.5 the rcsq is higher. The conductance found by TEM is slightly above that given by the VES analysis (6.6 versus 5.6 siemens, or about 19%). Substratum resistivity is reasonably constrained.

Joint inversion. The calculated curves for a three-layer model are far from the data points and the standard error is high (Figure 3). The model fit is poor (rcsq = 0.011), the conductance of the intermediate layer is too high, and the basement resistivity is too small. Whatever the weighting between VES and TEM, correct simultaneous matches cannot be achieved. We conclude that the only way to achieve a correct joint inversion is to introduce one additional layer.

Independent and Joint Inversions Using a Four-Layer Model

VES and TEM inversions (Figure 4). The two solutions are different, and the overall solutions are close to those obtained previously with three-layer models, with a thin fourth layer added just above the substratum. The interface between fresh and salt water and the resistivity of the fresh water are not well constrained by the inversion.

Joint inversion (Figure 5). A quasi unique solution is obtained, with most parameters well constrained. The final model is close to that represented by the original observation data. In particular, the thickness and resistivity of the fresh water aquifer are given correctly. This result could be achieved only by the joint inversion. On the other hand, the equivalence problem related to the salt water sand aquifer could not be solved; its conductance is given correctly while its thickness and resistivity cannot be determined uniquely.

Test Site 2—Island Basalt Aquifer

This is an example from the volcanic island La Reunion, where two sites are considered; the location of the soundings is shown in Figure 6. The two representative sites are located on the flanks of le Piton de la Fournaise. This volcanic feature was created by the superimposition of long and narrow basaltic flows with gentle seaward dips. The lava flows are the potential aquifer since high porosity and transmissivity lead to preferential water flows in
scoriaceous beds or lava tubes. On a regional scale, the electrical characteristics of the basaltic lava (SOGREAH 1990) can be synthesized from previous VES surveys. The resistivity of dry flows ranges from 1000 to 8000 ohm-m. Fresh water-saturated basalt resistivity ranges from 100 to 800 ohm-m. Salt water-saturated basalt resistivity is less than 10 ohm-m. Other low resistivity formations can be expected such as cinder layers or argillaceous detritals.

La Vierge Au Parasol

Independent inversions. VES and TEM soundings were obtained at a site (VP2, Figure 6) about 100 m from the coast. The independent 1-D interpretations for these soundings using a three-layer model are shown in Figure 7. The VES and TEM interpreted models are not highly different: two extremely resistive layers are sitting on top of a conductive substratum. Their total thickness seems to be somewhere between 39 and 44 m.

Joint inversion of VES and TEM soundings (Figure 8). A three-layer model is still adequate. The depth to the top of the brackish water saturated basalt is equal to 44 m (2.99 ± 40.9) as expected, since it is close to the depth determined by TEM. There is no fresh water at this site, since the base of dry basalt as determined by VES coincides with the top of brackish water as determined by TEM and with the mean sea level.

In this example, looking solely at the results of inversions as shown in Figures 7 and 8, one tends to think that the two techniques, VES and TEM, are almost equivalent and that joint inversion does not add much. By looking at the eigenvectors and the 95% confidence intervals, as shown in Table 1, the difference in sensitivity of each technique and the advantage of simultaneous inversions are clearly visible. This is demonstrated by the following.

A. For the VES data, the eigenvector matrix makes it clear that parameters are often correlated. For example, eigenvector 3
depends upon the logarithm of second layer resistivity minus the logarithms of the layer thicknesses; higher is the resistivity, smaller must be the thicknesses. Similarly, the eigenvalue for eigenvector 5 is equal to 0.0, indicating that there is no information about the resistivity of the substratum in the VES data set. The 95% undamped confidence intervals are also extremely large; they are all greater than 100% of the parameter estimates, except for the resistivity of the uppermost layer, which has a confidence limit of 29.4%.

B. For the TEM data, only two parameters are well resolved: the thickness of the intermediate layer and the resistivity of the substrate. Looking at the eigenvector matrix, it appears that these two parameters are not independent because they are correlated with opposite signs in the first two eigenvectors. On the other hand, the 95% confidence intervals are large for all parameters except for the resistivity of the substratum.

C. For the combined VES and TEM data sets, confidence limits indicate that the estimates of all parameters are better in the joint inversion. All the damping factors are equal to 1 and the confidence intervals vary respectively from 2.4% to 13.6%, except in the case of the thickness of the upper layer, which has a confidence limit of 93.4%. We also note that the estimate of the depth of the basement is 44 m (± 1 m). Accounting for the difference in elevation, the water table would be at 39 m and close to the combined surface layer minimum thickness in our inversion (41 m). The agreement is not excellent, but reasonably close. Unfortunately, it was impossible to verify the depth of the water table or the conductivity of the water at the time of our measurements because the borehole drilled in 1985 had been filled. We know only that the water sampled in the borehole in 1985 was brackish.

L’Etang Salé

Independent inversion of VES and TEM soundings with a five-layer model. The site (ES1, Figure 6) is located inland, approximately 1800 m from the coastline. The apparent resistivity curves and their interpretations are shown in Figure 9. In this example, there is an important discrepancy between VES and TEM for the interpreted thickness of layer 4, which represents the fresh water aquifer. It must be stressed that a minimum of five layers is required to obtain a reasonable fit for VES data. The intermediate resistive formation is thus divided into two layers: a thin highly resistive formation (1.8 m, 1300 ohm-m), representing unsaturated basalt and a thick moderately resistive formation corresponding to the fresh water aquifer (119 m, 169 ohm-m). This aquifer rests on a brackish salt water saturated zone with a resistivity equal to 8 ohm-m. A five-layer model is also compatible with the TEM data. After the first two resistive upper formations imposed by VES are introduced into the initial TEM model, the thickness of the main aquifer is found to be close to one half the value obtained from VES (68.3 m instead of 119 m).

Joint inversion of VES and TEM using five- and six-layer mod-
Figure 8. La Reunion: site VP2. Joint inversions of VES and TEM soundings from a three-layer model.

### Table 1
Vierge Au Parasol VP2

<table>
<thead>
<tr>
<th>Eigenvector</th>
<th>VES Eigenvector Matrix</th>
<th>TEM Eigenvector Matrix</th>
<th>VES+TEM Eigenvector Matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 2 3 4 5</td>
<td>1 2 3 4 5</td>
<td>1 2 3 4 5</td>
</tr>
<tr>
<td>log(p1)</td>
<td>-0.41 0.83 -0.32 0.16 0.00</td>
<td>0.00 0.01 -0.37 0.93 0.06</td>
<td>-0.01 0.44 0.35 0.58 0.20</td>
</tr>
<tr>
<td>log(p2)</td>
<td>-0.83 -0.29 0.43 0.22 0.00</td>
<td>-0.01 -0.01 0.90 0.34 0.28</td>
<td>-0.08 0.76 0.29 -0.57 0.08</td>
</tr>
<tr>
<td>log(p3)</td>
<td>0.00 0.00 -0.01 -0.01 0.99</td>
<td>-0.36 -0.93 -0.02 0.01 0.00</td>
<td>-0.31 -0.44 0.83 -0.12 0.00</td>
</tr>
<tr>
<td>log(e1)</td>
<td>0.14 -0.24 -0.35 0.89 0.00</td>
<td>-0.16 0.06 0.24 0.15 -0.94</td>
<td>-0.08 0.15 0.13 -0.11 0.97</td>
</tr>
<tr>
<td>log(e2)</td>
<td>-0.35 -0.40 -0.77 -0.35 -0.01</td>
<td>-0.92 0.35 -0.04 -0.03 0.16</td>
<td>-0.94 0.09 -0.29 0.09 -0.09</td>
</tr>
<tr>
<td>Damping Factor</td>
<td>1.00 1.00 1.00 0.99 0.00</td>
<td>1.00 1.00 0.85 0.02 0.00</td>
<td>1.00 1.00 1.00 1.00 1.00</td>
</tr>
</tbody>
</table>

Eigenvector Matrix:
1, 2, ..., 5: eigenparameter; p1, p2, p3: resistivity of layers 1, 2, 3; e1, e2 thickness of layers 1, 2
bold numbers correspond to values > 0.35; Damping Factor = 1.00 corresponds to undamped iterations.

undamped 95% confidence intervals
Par: parameter (resistivity or thickness); Max: maximum parameter; Min: minimum parameter
Dif: difference between Max and Min; D/P%: difference divided by parameter in %.
ETANG SALÉ

MODEL
\( \rho (\Omega \cdot m) \) \( \varepsilon (m) \)

| \hline
| 772.99 | 2.39 |
| 14.94  | 1.94 |
| 1300.32| 1.75 |
| 169.02 | 119.05|
| 7.8    | 10     |

\( rcsq = 0.00001 \)

MODEL
\( \rho (\Omega \cdot m) \) \( \varepsilon (m) \)

| \hline
| 458.48 | 1.32 |
| 20.01  | 2.61 |
| 2124.28| 1.75 |
| 143.32 | 68.29|
| 7.38   | 0     |

\( rcsq = 0.00026 \)

Figure 9. La Réunion: site ES1. Independent inversions of VES and TEM soundings from a five-layer model.

eels. The joint inversion using a five-layer model gives a rather poor fit as shown in Figure 10 (rcsq = 0.0027). However, a much better fit can be obtained using a six-layer model (Figure 11). The main conclusions reached in this example are that the top layers are highly resistive (773 and 1300 ohm-m) and represent dry or slightly wet basaltic flows. A thin conductive layer must be introduced within the resistive package to be consistent with the VES data. This layer is probably indicative of a lahar and/or tuffaceous interbed. The fresh water aquifer is 69 m thick (50.19 - 18.64) as determined by TEM, and it must be subdivided into two layers to be consistent with VES data. The top of these two fresh water layers is the thickest and probably has a higher porosity, while the lower one is tighter or has a lower clay content.

Conclusions

This study of the joint application of direct current and transient electromagnetic soundings to aquifer studies produces several conclusions. VES and TEM soundings are both reasonably well suited for delineating fresh water coastal aquifers, although they will generally lead to different quantitative results. These differences are primarily related to their intrinsic sensitivity to resistive beds; VES soundings are sensitive to the so-called transverse resistance (the product of thickness and resistivity) while (TEM) soundings are sensitive to their thickness only. For example, a thin highly resistive bed will greatly influence VES measurements but would be virtually invisible in TEM.

The first example from La Réunion Island demonstrates that when the model is simple (three layers) and when the second layer is thick—more than 10 times thicker than the top layer—both methods are equally suitable and will lead to similar results. In this example the second layer is unsaturated basalt; the same conclusion would still hold if it were a thick fresh water aquifer. The example from Biarritz, in contrast, demonstrates that when the second layer (the fresh water aquifer) is not thicker than the more resistive unsaturated top layer, VES will generally miss it. The fresh water aquifer will be suppressed because it is a thin intermediate layer. VES will only be able to determine unambiguously the depth to the base of the unsaturated formation. TEM in such a case will generally not identify the base of the unsaturated formation, but it will be able to determine unambiguously the depth to the base of the fresh water aquifer (the top of the highly conductive salt water-saturated aquifer underneath). The aquifer may be resolved completely when both methods are used and inverted simultaneously.

The second example from La Réunion Island demonstrates that when the fresh water aquifer is located between two conductive formations, VES cannot determine its thickness because its resistivity is unknown. In that situation, only the product of thickness and transverse resistance is determined unambiguously. In contrast, TEM soundings determine the thickness unambiguously. When both methods are used and inverted simultaneously, additional information about the aquifer is obtained. In accommodating the joint inversion, additional layers may have to be introduced. Two layers of different hydrologic quality were found in our example.

Y. Albouy et al. GROUND WATER 39, no. 1: 87–97
In a similar situation in Africa, for example, joint VES and TEM inversion disclosed interbedded sand and clay layers instead of a single isotropic aquifer of moderate quality as inferred from VES only. This interpretation has been confirmed by drilling (Bouvier et al. 1997). Such information is of real significance in the process of siting a well and forecasting its production.

Inversion statistical techniques introduced by many authors as early as 1985 provide an effective way to quantify the quality of individual and joint inversions as demonstrated for the first of the Reunion Island sites (La Vierge au Parasol). Comparison between VES and TEM soundings is important not only when it comes to quantitative interpretation, but also in regard to field conditions. The survey in La Reunion Island is a good example in that respect. A depth of investigation of the order of 75 m requires a linear array of 600 min DC resistivity soundings, and a square loop with a maximum side of 100 m (in some cases 50 m might be sufficient) for TEM soundings. This situation has three consequences:

1. Logistical considerations can be important because the TEM equipment is lighter and sometimes VES soundings cannot be carried out at a given site because there is not enough room for the larger electrode spacings.
2. Productivity is higher in TEM sounding because less than 15 minutes recording is required to obtain a complete sounding after the array is set up. In contrast, VES measurements have to be repeated at many different electrode spacings at each location.
3. TEM measurements are less sensitive than VES soundings to the presence of nonhorizontal interfaces in the vicinity of the site, or to local variations in site topography, which also introduce lateral variations in layer thickness.

The only significant disadvantage of TEM soundings in comparison with VES soundings is that the TEM equipment is rather sophisticated and expensive, so that only three or four companies are manufacturing it today worldwide. Thus, the hydrogeologist who wants to map coastal aquifers is in a better situation than 15 years ago, but it can be difficult to choose due to the increase in the numbers of resistivity techniques available. However, there is still a practical dilemma in selecting which of the two to use in an exploration program because each has specific advantages and drawbacks in a particular situation. Our analysis shows that the best results are obtained when both direct current and transient electromagnetic soundings are used to characterize coastal aquifers.

Acknowledgments
We would like to address special thanks to Dr. Fred Paillet, associate editor, who was kind enough to correct our manuscript, greatly improving its quality.

References
Figure 11. La Reunion: site ES1. Joint inversion of VES and TEM soundings from a six-layer model.
Geochemical Evolution of Ground Water in the Great Plains (Dakota) Aquifer of Nebraska: Implications for the Management of a Regional Aquifer System

by David C. Gosselin¹, F. Edwin Harvey¹, and Carol D. Frost²

Abstract

The Great Plains (Dakota) aquifer system is one of the most extensive in North America extending from the Arctic Circle to New Mexico, and underlies approximately 94% of Nebraska. In Nebraska, we do not have the physical ground water monitoring data at the scale that is necessary to manage ground water flow systems. However, first-order management strategies for this regional aquifer can be developed by understanding the geochemical evolution of the ground water. Using major-ion water chemistry data from 203 wells in 19 counties in eastern Nebraska, reconnaissance δ¹⁸O, δD, and δ⁶⁷Sr data, and two geochemical models, PHREEQC and SNORM, we determine that modern meteoric water, NaCl brines from underlying formations, and cold glacial melt water are the primary sources for the water in the Dakota Aquifer. Based on these three water sources and the geochemical evolution of the various water types, the following first-order management strategies are suggested. In areas where CaSO₄ and Ca-Na SO₄ type water occur, Pleistocene-age glacial meltwater is the source. This water supply is not easily renewable. It is recommended that detailed water resource evaluation be conducted before extensive development occurs. The source of Ca(±Mg) HCO₃ type water is from recharge by local precipitation and should be managed to maintain them as a renewable resource. In mixed ground water type areas, the ground water chemistry reflects the interaction of two distinct water types, one of which is meteoric water and the other is either CaSO₄ and Ca-Na SO₄-type water or NaCl-type water. If the relatively fresh ground water is extracted at a rate that changes the location of the interface between the endmembers, then monitoring changes in water chemistry in a well over time could be used as an early warning system for the onset of potential problems related to overpumping.

Introduction

The Great Plains aquifer system (GPAS) is one of the most extensive in North America, extending from the Arctic Circle in Canada to New Mexico (Figure 1) (Heggholm et al. 1982; Jorgenson et al. 1993). In a stratigraphic context, the Dakota Formation, Dakota Group, Dakota Sandstone have all been used to refer to the Lower Cretaceous sandstones that comprise the GPAS in the western glaciated plains. Hence, the term Dakota aquifer system has also been used in reference to the GPAS. In this paper, we will refer to this system as the Dakota Aquifer because the name has local, as well as regional, name recognition and the GPAS terminology has not been generally adopted. The Dakota Aquifer includes stratigraphic units beyond the limits of the Dakota Formation. In addition to the Dakota Group, the system includes the Swan River Formation of Manitoba and eastern Saskatchewan, the Inyan Kara Formation and the Omadi Sandstone of the Plains states, and the Mannville Group of south-central Alberta and Saskatchewan.

The Dakota has generally been considered to be a classic example of an artesian aquifer system (Lennox et al. 1988). Upman (1895) and Darton (1905) proposed the analogy of pipe flow for ground water movement in the Dakota in which recharge enters sandstone beds in mountains to the west and discharges in the east where the sandstones outcrop or subcrop beneath the glacial drift. Current thinking about the source of ground water in and movement through the Dakota Aquifer indicates that the flow in the aquifer is far more complex (e.g., Jorgenson and Signor 1984). The complexities in the flow system are directly reflected in the natural spatial variations in ground water chemistry, in which extreme differences in water quality can occur on local scales (Rutulis 1984; Lawton et al. 1984). As a result, water quality strongly influences the use of the Dakota as a source of potable water.

The Dakota Aquifer underlies 94% of Nebraska (Ellis 1984) and is utilized in two areas. In western Nebraska, oil, natural gas, and saline ground water are produced from the D and J sandstones in the upper parts of the Dakota Group (Figure 2). These oil producing zones extend to depths greater than 2130 m (7000 feet). In eastern and northeastern Nebraska, the sandstones within the Dakota Formation are used as a source of ground water where shallow Quaternary deposits cannot provide an adequate water