Using Airborne Geophysical Survey for Exploring and Assessment of Groundwater Potentiality in Arid Regions

Mohamed A. Dawoud

Water Resources Department, Environment Agency - Abu Dhabi, P.O. Box 45553, UAE

Abstract. In arid regions, where no renewable surface water is available, groundwater is considered a vital resource. Exploration and assessment of groundwater resources and aquifer systems are very challenging tasks. Recently, airborne electromagnetic survey is used to provide a method for rapid monitoring of large areas and mapping subsurface hydrologic and geological features within 150 to 300 m of the surface. Airborne electromagnetic survey is used to provide information on aquifer thickness, depth to the top of the magnetic basement, location of major faults, dykes and sills. This information along with data from existing deep boreholes, can be used to characterize the water-bearing formations and develop a geological model for the area. In 2001, high-resolution TEMPEST airborne geophysical surveys were flown in Al Khazna area, some 80 km to the east of the city of Abu Dhabi in the UAE to acquire time-domain EM (TDEM) and magnetic field data. The survey, flown at 200-m line spacing over a 160 km² area, identified and assessed groundwater formation and salinity. This model defined the spatial and vertical extension of the aquifer formation and groundwater bearing types. A significant portion of the area is under cultivation. Hydrogeological control was provided by existing groundwater boreholes, both within and immediately outside the survey area. Changes in relief of approximately 50 m are caused by Aeolian sand dunes running ENE-WSW with the higher ground being in the east.

1. Airborne Geophysical Survey Technique

The development of three-dimensional hydrologic models requires information on the physical characteristics of the subsurface including the location and extent of geologic units, the hydrologic properties of
these units, and the quality of their water content. Traditionally, this information has been obtained from knowledge of subsurface geology, and ground-water observation and test wells. Relying only on wells can be highly uncertain because of the large inter-well spacing due to expenses. Also, access considerations may constrain well placement to locations less desirable from a ground-water model development standpoint. While wells provide detailed vertical information and allow sampling of geologic materials and groundwater, the distance from the well where information is valid is often unknown. The consequences of limited aquifer-property information on the resulting groundwater model is a complex issue (Peck, et al., 1988) that must be considered in the modeling process; consequently, using auxiliary means to obtain more detailed information is highly desirable.

Today’s airborne geophysical systems have the ability to make accurate, high-resolution measurements of subsurface ground conductivity in three dimensions. The capabilities of the airborne geophysical survey mainly depend on the method used as shown in Table 1. Airborne electromagnetic (AEM) surveys are used for shallow groundwater exploration by rapidly monitoring large areas and are capable of mapping subsurface hydrologic and geological features within 150 to 300 meters of the surface (Hammack, et al., 2002).

Table 1. Methods of Airborne Survey.

<table>
<thead>
<tr>
<th>Method</th>
<th>Explore Deep</th>
<th>Delimit Aquifer</th>
<th>Define Geology</th>
<th>Water Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>AEM</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Gravity</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Magnetic</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Radiometric</td>
<td>No</td>
<td>No</td>
<td>Yes (surface)</td>
<td></td>
</tr>
<tr>
<td>Hyper Spectral</td>
<td>No</td>
<td>No</td>
<td>Yes (Surface)</td>
<td>Yes (Surface)</td>
</tr>
<tr>
<td>Laser</td>
<td>No</td>
<td>No</td>
<td>Yes (Surface)</td>
<td>Yes (Surface)</td>
</tr>
<tr>
<td>Fluorescent</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Time-domain electromagnetic soundings provide detailed resistivity-depth information. The basis for this method is described in Kaufman and Keller (1983) and Fitterman and Stewart (1985). Dense spatial data obtained by flying the instruments at low altitude on a fine grid should allow subsurface changes in water quality and sediment type to be interpreted. The airborne geophysical data can be verified by (1) acquiring ground-based geophysical data at representative locations and comparing results, (2) comparing water well data with conductivity patterns evident in the airborne data set, and (3) incorporating existing
geological and hydrological information into the interpretation of the airborne geophysical data. AEM requires careful calibration to determine the relative contribution of conductive materials, but is the only geophysical technology that has the potential to map salt load directly in the sub-surface with good vertical resolution. These geophysical data help develop a better understanding of subsurface contaminants, contaminant flow, location of man-made buried metallic objects, surface water and groundwater location and quality. The ability to map the subsurface contributes to improved site management practices, and aids efficient targeting of costly follow-up ground surveys and location of drilling sites.

The benefits of airborne reconnaissance include minimal access issues and significant cost savings through fast data collection on large-scale surveys. Airborne systems are multi-sensor platforms from which various types of other data are collected concurrently. In addition to the collection of electromagnetic data for ground conductivity measurement, magnetic and radiometric (gamma) are collected, as well as digital video, digital terrain models and dual-frequency GPS.

The plane is equipped with a coil running from nose to wingtips to tail, through which an electrical current is pulsed as shown in Fig. 1.

---

Fig. 1. Airborne survey system setup.
This electrical current induces a magnetic field (an electromagnet works using the same principle), and provided the plane flies low enough, this magnetic field penetrates the ground to a significant depth (more than 100m). This magnetic field induces a secondary weaker electrical current to flow through the ground. As the electrical conductivity of the different materials that makes up the earth varies, the relative strength of this secondary, induced electrical current will also fluctuate. The secondary current moving through the ground induces a secondary magnetic field in the same way that the electrical current generated around the airplane induced the primary magnetic field. As the strength of this secondary current fluctuates, the secondary magnetic field induced by the current also fluctuates. Variations in this magnetic field are detected by a receiver towed behind the airplane, and it is the signal that is used to produce maps of the electrical conductivity of the landscape (Dunbar, et al., 2003). The effective depth of the exploration is a function of the height of the plane as shown in Fig. 2.

Figure 3 shows the schematic representation of airborne electromagnetic survey data collection.
Fig. 3. Airborne survey data collection and interpretation. A) Flight lines are flown along parallel lines spaced 200 m apart. B) The bird measures the inphase and quadrature electromagnetic response at several frequencies. C) The measured response is used to determine the resistivity-depth function by a process called inversion. D) The resistivity-depth functions are combined to produce an interpreted resistivity depth-slice map.

Time domain AEM data record changes in ground conductivity to depths of 100 to 300 m in most environments. Subsurface conductivity is affected by a number of hydrogeological factors that include water content, water quality, porosity, lithology, rock fracturing, and weathering as shown in Table 2. However, in many sedimentary environments water quantity and quality predominate. Generally, the resistivities/conductivities of saturated sediments lie in the following ranges:

- In hard rock terranes, aeromagnetic surveys are able to identify faults fractures and dykes that control groundwater flow as well as mapping palaeo-channels (old river systems).
- Where groundwater movement is controlled by faults, fractures and dykes, generally in hard rock terrains, EM usually identifies these features as linear conductors.

<table>
<thead>
<tr>
<th>Water Quality</th>
<th>Resistivity (ohm-m)</th>
<th>Conductivity (Siemens/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh</td>
<td>7 - 100</td>
<td>0.01 – 0.14</td>
</tr>
<tr>
<td>Brackish</td>
<td>0.7 - 7</td>
<td>0.14 – 1.4</td>
</tr>
<tr>
<td>Saline</td>
<td>0.1 - 0.7</td>
<td>1.4 - 10</td>
</tr>
</tbody>
</table>
2. Abu Dhabi Emirate Case Study

In 2002 a TEMPEST time domain electromagnetic (TEM) survey was flown at a 200-m line spacing in a north-south direction over an area of approximately 160 km$^2$ (16 km × 10 km), some 80 km to the east of the city of Abu Dhabi in the UAE. Total flying was 880 line and was flown in 2 days. A significant portion of the area is under cultivation. Hydrogeological control was provided by existing groundwater boreholes, both within and immediately outside the survey area. Changes in relief of approximately 50 m are caused by Aeolian sand dunes running ENE-WSW with the higher ground being in the east as shown in Fig. 4. TEMPEST is a broadband fixed-wing TEM system that has been developed primarily for soil salinity studies and mineral and groundwater exploration. A TEMPEST survey provides uniform coverage of an area and may be considered as equivalent to undertaking ‘EM depth soundings’ every 12 m along each flight line.

![Fig. 4. Location map of surveyed area showing flight lines.](image)

2.2 Hydrogeology

Boreholes in the area indicate a sequence of dry dune sand cover (0-30m), in places, resting on a 20m thick sandstone layer that overlies a sedimentary sequence comprising interbedded layers of conglomerate, caliche, and siltstone layers that overlie claystones at a depth of approximately 150 m. Where sand dunes are not present, the
water table occurs at depths of a few meters. Fresh water is moderately resistive and saline water is highly conductive. Generally the conglomerates form the main aquifer throughout the area whose resistivity is interpreted to be dependent on water quality/salinity.

2.3 Presentation of Survey Data

Conductivity Depth Images (CDI) were produced for each flight line using EMFlow software. This data set was combined into a 3D conductivity grid that enabled selected isosurfaces (i.e. contour lines for a 3D surface) to be viewed in both plan and 3D as shown in Fig. 5.

The recorded variations in conductivity are interpreted to be more directly related to the salinity of the groundwater, rather than to differences in lithology. The all CDIs display highly resistive (dark blue) sand dunes as topographic highs at the surface. A thin conductive layer (red) occurs near the surface in the west. (e.g. evident on lines 160 and 230). Below this conductor, in some parts of the area, is “lies a shallow resistor” (light green), as identified by vertical arrows).

These are the target zones for fresh water with less than 500 ppm total dissolved solids, occurring at depths of 30 – 70 m and with typical resistivities of 9 ohm-m. In the west and the south “a deeper conductor” (red and yellow) is evident and contains the most saline water. In the east, the CDIs (lines 720 and 880) are generally much less conductive than in the west indicating less salinity. The interference caused by the power line is noticeable but not serious and most of its effects have been removed.

![Fig. 5. Conductivity depth images (CDI) of selected flight lines.](image)

2.4 Calibration

The raw data produced by the airborne survey can be presented as a series of maps of the uncalibrated ‘bulk’ electrical conductivity of the earth at a series of depth intervals from natural surface down to bedrock.
Because this electrical conductivity may be caused by a number of different factors including relative moisture, clay content or salt) the raw AEM data needs to be calibrated to transform the bulk conductivity into maps of landscape salt stores or groundwater quality (Hodges, et al., 2000).

A series of boreholes exist at sites around the survey area and a profile of the electrical conductivity from natural surface to bedrock at each of these sites is produced using a geophysical logging tool. As well as providing a series of calibration points, drilling also provides detailed information on the soil and regolith material, particularly its capacity to store or transmit water. Once the airborne survey data have been calibrated against the information from the drilling program, accurate three-dimensional maps can be produced, showing both where the salt is stored and the preferred conduits of groundwater movement (Hodges, 1999).

Figure 6 shows a plane view of the near surface 9 ohm-m resistive zone that is interpreted to contain the freshest water in the area consider that fresh water has TDS less than 1000 ppm. The shape of this resistive zone is generally in very good agreement with the 3,000ppm salinity contour in the central and southern parts of the area, as shown in Fig. 7. Figure 7 is a water quality contour map, supplied by the client, showing the total dissolved salts obtained by analyzing groundwater samples from boreholes. Figure 7 was produced over many years from fieldwork carried out on the groundwater. Figure 6 was produced entirely from an airborne TEM survey, which was flown in 2 days and subsequently processed and interpreted over a period of 3 to 4 weeks. It is important to study the similarities and differences between Fig. 6 and 7.

One of the most obvious differences between them is the extensive resistive zone in the north, extending from east to west across the area. Here there are noticeably fewer boreholes and the contour values on the salinity map have largely been interpolated. This suggests that greater confidence should be placed on the resistive zone as mapped by TEMPEST, rather than the contours depicting salinity values derived from sparse borehole data (McConnell, et al., 1998).
Fig. 6. TEM conductivity data showing interpreted freshwater.

Fig. 7. Hydrogeological data delineating groundwater quality.

Figure 8 is a 3D view from the WSW, looking ENE, where the surface topography is represented by the grey mesh at the top of the image. It shows the 9 ohm-m isosurface, which outlines that part of the aquifer likely to contain the freshest water. The arrow indicates where the fresh water aquifer is thickest. It should be noted that TEMPEST has a depth of investigation that is fully capable of identifying sources of potable water in this predominantly highly conductive subsurface environment. The results also suggest that the base of the sand dunes is not flat, as they appear to have a resistive “root zone”. The areas between the dunes are more conductive where sabkha conditions are more prevalent.
Figure 9 shows conductivities in the depth range 140 – 160 m, indicates the presence of a new hitherto unknown feature on the TEM data. An E-W trending basement ridge is evident, which suggests that there may be a palaeochannel containing fresh water on one side of it.

Figure 10 shows the magnetic data as a first vertical derivative image. Although it is mainly displaying cultural features (e.g. the powerline, fences and buried pipelines), the overall grain of the image reflects a response from the sand dunes, which is in an ENEWSW direction in the east and a more east-west, direction in the west.
Figure 11 shows the surface topography image derived from the GPS and radar altimeter measurements, which clearly show the position of the sand dunes.

Color bars have been added to the resistivity log (above) using the same colour scale as the conductivity section. The match between the resistivity logs and the TEM conductivity data is remarkably good considering the difference in the scale of sampling, the time difference between measurements, and that the locations are not exactly coincident as shown in Fig. 12.

The analysis of the airborne electromagnetic survey indicated the following:

- The eastern half of the survey area is, in general, much less conductive (less saline) which is consistent with a system being recharged from the east;

- The water salinity interpreted from the TEM data is, in general, in excellent agreement with the salinity distribution derived from boreholes;

- The TEM data have the advantage of providing information on the variation of salinity with depth, whereas borehole data only provides average salinity values for the sampled aquifer;

- The agreement between the resistivity logs and the TEM conductivity data is good.
3. Conclusions and Recommendations

The results of this exploration program have demonstrated the usefulness of the aeromagnetic method for mapping the bedrock structure and the airborne EM method for determining water quality in the overlying sediments in a large area. The airborne EM provided the conductance variations within the Kalahai Beds that were related to fresh and saline water sediments. The regional coverage by airborne EM provided the delineation of the most promising areas for ground geophysics and ensured that no potential area was omitted. The TEM sounding method very precisely demarcated the zones bearing fresh, saline and brackish water in the exploration area. It was also better able to decipher the vertical distribution of resistivity than the airborne EM method.

In conclusion the Airborne EM survey provided an effective geophysical technique for delineating the lateral extent of shallow aquifers. Using this data in conjunction with ground TEM soundings accurately defined the lateral and vertical extent of fresh groundwater. The results provided the basis for definition of aquifer geometry and water quality for quantification of resources. Aeromagnetic data and deep TEM soundings were used to better understand the bedrock. For additional understanding of the bedrock, exploration methods such as seismic reflection and magnetotellurics are recommended.
References


استخدام المسح الجيوفيزيائي المحمول جَوًا لاستكشاف وتقييم
إمكانيات المياه الجوفية في المناطق الجافة

محمد داود
قسم الموارد المائية، هيئة البيئة – أبو ظبي، الإمارات العربية المتحدة

المستخلص. في المناطق الجافة، حيث لا تتوفر مياه سطحية متجددة،
تعد المياه الجوفية مورداً حيوياً. إن استكشاف وتقييم موارد المياه الجوفية
وشبكات المياه الجوفية هي مهام بالغة الصعوبة. وقد تم تغيير استخدام
المسح الكهرومغناطيسي المحمول جَوًا لتوفير وسيلة للرصد السريع
للمساحات الواسعة، ولرسم خرائط الخصائص الجيولوجية الهيدرولوجية
والجيولوجية ضمن 150 حتى 300 متراً من السطح. يكشف المسح
الكهرومغناطيسي المحمول جَوًا لتقدم معلومات عن سمك طبقة المياه
الجوفية، والعمق حتى سطح القاع للطبقات، وموقع الفوائد والحواجز
والعبئات. ويمكن استهداف هذه المعلومات مع البيانات من الأبار العميقة
القائمة لوصف التشكيلات الحاملة للمياه ووضع نموذج جيولوجي للمنطقة.

في عام 2001، تم التنقل جواً للمسح
جواً والعالمي الدقيق في منطقة الخلي Janeiro، لحوالي 80 كيلو متراً شرق مدينة
أبو ظبي في دولة الإمارات العربية المتحدة، وذلك للحصول على المجال
الزمني (TDEM)، وبيانات الحقل المغناطيسي. إن المسح، الذي تم
نقله جواً على خط 200 متراً مساحة 160 كيلو متراً مربع، قد
عدد وقيم تمكين ونسبة مثابة المياه الجوفية. يحذد هذا النموذج الامتداد
المكاني والرئيسي لتشكل طبقة المياه الجوفية ونوع المياه بها. ويجري زراعة
جزء كبير من المنطقة. تم توفير المراقبة الهيدرولوجية بواسطة أبار
المياه الجوفية القائمة، سواء داخل أو خارج منطقة المسح مباشرة.
والعوامل في تخفيض حوالي 50 متراً هي نتيجة لركبان رملية منقوطة بفعل
الرياح، والتي تتراوح شرق شمال شرق-غرب جنوب غرب ENE-WSW،
وبعى ارتفاع الأرض ناحية الشرق.