GEOPHYSICAL METHODS TO MAP BRACKISH AND SALINE WATER IN AQUIFERS

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Abstract. Many coastal aquifers around the world are experiencing some level of salinity encroachment. Increased development and the associated increases in groundwater withdrawals are expected to exacerbate the problem. Mapping migration and extent of salt water plumes is difficult and costly due to the three dimensional nature of the problem and the expense of drilling multiple level wells. Several surficial geophysical methods have been developed for measuring salinity levels in aquifers. These methods provide powerful tools to identify the position of saline or brackish water in an aquifer and can map the migration of a plume over time even in remote areas with little subsurface information.

The methods most commonly used geophysical techniques for salt water investigations are geo-electrical methods. Two primary methods are available, electrical resistivity (resistivity) and Time Domain Electromagnetic induction (TEM). Resistivity provides better resolution in the upper 200 to 500 feet than TEM but requires good electrical coupling with the surface soils and field operation is generally slower. TEM can generally cover more area in a given amount of time than resistivity and is used for target depths of about 50 to 2,000 feet.

All geophysical methods have limitations in terms of resolution and cultural interference that determine where a given method can be used and what level of detail can be obtained. This paper will present two case histories where surface geophysics has been used to identify saline and brackish water zones in aquifers. The case histories will describe using TEM and resistivity to map saline water zones in the coastal aquifer in urban areas of Los Angeles County and Orange County, California. Similar results have been obtained in the coastal plain aquifers of the eastern US.

INTRODUCTION

Salt water intrusion is a growing problem that affects the coastal aquifer in many places from Florida to Long Island. Increases in population density in coastal areas over the last 100 years has led to a dramatic increase in groundwater pumpage for water supply and industrial usage. In many areas the heavy pumpage has reversed the normal land to sea groundwater flow pattern and drawn salt water inland into the aquifers. The complex layering and variable hydraulic properties of the coastal aquifer causes the salt water to migrate to different extents both laterally and vertically creating a complex three dimensional distribution of salinity. Mapping the salt water plumes by traditional drilling is difficult and expensive. Long screen intervals in wells causes mixing of water from a long interval and smoothes the vertical distribution of salinity. Wells with short screen intervals provide better vertical resolution but an impractically large number of wells are needed to provide good vertical coverage. No matter what well design is used, the cost of drilling limits the number of wells or well nests that can be installed. As a result the shape and migration pattern of most saltwater plumes are not well understood. This makes it difficult to understand the nature of the problem or to formulate effective mitigation or management strategies.

Several geophysical methods can easily detect zones of saline groundwater as highly conductive (low resistivity) volumes in the subsurface; electrical resistivity (resistivity) and time domain electromagnetic induction (TEM). The application of both of these methods for salt water intrusion is described by many authors including Slater and Sandberg, 2000 and Land et al, 2004. The specific electrical property measured by these methods is electrical resistivity. Electrical resistivity is measured in units of ohm-meters (ohmm), and is the mathematical inverse of the more familiar property of electrical conductivity. Resistivity is a material property that can be used to determine the characteristics of the subsurface. Although resistivity values are determined by many variables, some typical ranges can be used to estimate the salinity of the groundwater. Sandy zones filled with air or fresh water generally have resistivity values of 30 to 50 Ohmm, or higher, depending on the silt content and mineralogy of the sand. Clay rich soils have resistivity values of about 20 to 30 Ohmm, or less. Sandy zones filled with brackish or saline water have low resistivity values, typically 10 Ohmm or less, depending on the degree of salinity in the groundwater. Aquifer with very saline water have resistivity values of a few Ohmm or less.

Resistivity Survey of Sunset Gap in Orange County, California. Electrical resistivity measurements are made by passing electrical current through the ground using a pair of electrodes (current electrodes) while measuring the resultant voltage field in the ground at another pair of electrodes (potential electrodes). The measured voltage is a function of the electrical resistivity of the soils beneath the electrodes. The subsurface penetration of the electrical current is a function of the current electrode separation. By making measurements with electrodes at different spacings, a resistivity survey can delineate vertical variations in resistivity with depth in the subsurface material. By making a series of soundings at different positions along a profile line, lateral changes in resistivity can also be measured. Multi-node resistivity systems use a cable system with multiple conductors to connect many electrodes to a switching box. The switching box selects pairs of current and potential electrodes to make resistivity measurements. The spacing between current and potential electrodes, the spacing between the electrode pairs, and the position of the center of the electrode arrays are changed to provide resistivity measurements to different depths and different positions along a profile line. These systems can make hundreds of measurements in a matter of a few hours or less. The data can be interpreted to produce a relatively high resolution two dimensional section that shows the lateral and vertical changes in resistivity along the profile line.

The resistivity method provides the highest vertical and lateral resolution but requires a relatively long surface electrode array relative to the depth of penetration. A general rule of thumb estimates that the depth of penetration is generally one third to one fifth the length of the electrode array. The actual depth of investigation is determined by the conductivity of the subsurface with greater penetration in resistive environments. Sites with large areas of relatively open land can be scarce in some areas limiting the use of the resistivity method. Modified electrode arrays with remote reference electrodes can be used to increase the depth of penetration of a given electrode array by between about 30 to 50% if sufficient area is available.

When site conditions are appropriate, the resistivity method can generally provide relatively high resolution images of the subsurface conditions to depths of 300 to 500 feet. Resistivity surveys can be used to map layered aquifer and aquitard systems, identify areas of salt water or brackish water, and find nearly vertical features such as faults that may influence the migration of groundwater. A resistivity survey completed in January of 2010 at the Seal Beach Naval Station in Orange County, California provides a good example of the results that can be expected under favorable conditions.

Preventing seawater intrusion into the Orange County groundwater basin is one of the primary goals of the Orange County Water District (OCWD). Seawater intrusion has affected the use of groundwater in the basin since the early 1900s. Permeable aquifer sediments occur within four erosional "gaps" along the western boundary of the basin. These sediments and are in contact with the shoreline and tidal inlets and act as a conduit for saline water to intrude inland into deeper aquifers. The Sunset Gap is a flat, 3-mile wide, low-lying topographic feature that is bounded by Landing Hill to the northwest and Bolsa Chica Mesa to the southeast. Landing Hill and Bolsa Chica Mesa are erosional remnants of Pleistocene-aged alluvial and marine sediments uplifted by the Newport-Inglewood Fault Zone (NIFZ). In general, offset along the NIFZ forms a significant impediment to seawater intrusion; however, the NIFZ is not a complete seawater barrier, as evidenced by increasing chloride concentrations in wells inland of the fault zone.

The focus of this study was to investigate the lateral and vertical extent of seawater intrusion beneath an approximate 5-square mile area in the Sunset Gap and evaluate the hydrogeologic controls that may affect the migration of seawater into the layered aquifer system in the area. The primary focus is on the Beta aquifer at a depth of about 260 to 300 feet. Identification of intrusion, if any, into the deeper sediments, to a nominal depth of 1,000 feet, was also of interest.

A total of 11 miles of resistivity data was collected using 20 resistivity stations along 4 profile lines. The data was collected using a pole-dipole array with a spread of 56 electrodes spaced 10 meter apart. Figure 1 shows a typical resistivity transect. The line covers approximately 2,000 feet horizontally and probed to a depth of just under 600 feet. Blue colors represent low resistivity values typical of salt water intruded aquifers. Green colors represent intermediate resistivity values typical of silt and clay confining units. Red and yellow colors indicate higher resistivity values typical of fresh water aquifers. The right side of the figure shows a layered system of three distinct aquifers, the upper aquifer appears to contain highly brackish or salt water. The lower two aquifers appear to contain fresh water. The aquifers are separated by low permeability confining layers that seem to be generally intact in this portion of the line. The middle of the line shows a nearly vertical conductive zone that truncates the layers on the right side of the line and separates these layers from an apparently more conductive aquifer system on the left side of the line. This feature is interpreted to be a fault that is preventing migration of salt water in the aquifers on the left side of the line into the lower two aquifers on the right side.

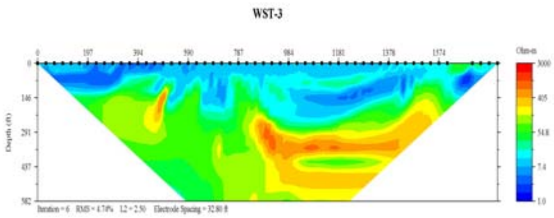

Figure 1: Typical Resistivity Transect

The results of the geophysical surveys conducted for this project provide a significant amount of information on the subsurface geology of the area and the distribution of saline and brackish water in the major aquifers. The results of this survey are being used to select the location and construction of monitoring wells, plan sea water intrusion mitigation efforts, and evaluate the applicability of geophysical methods to monitor the function of potential injection barrier well systems.

TEM Survey for the Water Replenishment District of Southern California. The TEM method uses a heavy gauge wire laid out as a square or rectangle to form a transmitter loop. A current of several amps is passed through the transmitter loop and switched off to create a broad band electromagnetic (EM) pulse of radio waves. The EM pulse measures the change in resistivity of the subsurface with depth as it propagates deeper into the ground. The TEM method can penetrate deeper into the subsurface for a given sized surface array but it has poorer vertical resolution and is more susceptible to interference from power lines, fences, or utilities than the resistivity method. Under favorable conditions the TEM method can usually measure subsurface conditions to depths of 1,000 to over 1,500 feet. The TEM method is more useful when greater depth of penetration is needed or when the size of available survey areas is limited. A TEM survey completed in 2008 for the Water Replenishment District of Southern California illustrates what can be accomplished by careful survey techniques even under less than ideal conditions.

Severe overdraft of the West Coast Groundwater Basin in southwestern Los Angeles County, California from the early 1900s to the late 1950s caused over 600,000 acre-feet of saltwater to intrude into the coastal sandy aquifers that are used for potable, agricultural, and industrial supply. The intrusion was a serious threat to the future usability of the local groundwater resource. The intrusion caused impacted wells to be shut off or necessitated the constructing and operation of expensive reverse osmosis desalination plants to make the brackish water potable.

In 1950s, the Los Angeles County Flood Control District undertook testing to evaluate the use of injection wells for seawater intrusion control. The tests were successful, so the West Coast Basin Barrier Project (WCBBP) was constructed consisting of a nine-mile stretch of 153 injection wells and 302 observation wells that currently inject approximately 13,600 acre feet per year of potable and advanced-treated recycled waste water into the multiple aquifers. Although the WCBBP currently protects the aquifers from further intrusion, approximately 250,000 acre feet of brackish groundwater was stranded on the landward side of the barrier after it was completed. This stranded brackish groundwater is known as the “saline plume”, and it is a continued threat to the groundwater resources in the West Coast Basin. The overall shape of the intrusion is generally well known, but the details are complicated due to the concentration and density differences of the saline water, the gradients and hydraulic properties of the multi-layered sandy aquifers, and the shape of the fresh water/saltwater interface. Therefore, mapping of the intrusion using geophysical methods was attempted as a means to cost effectively determine its three-dimensional extent.

A TEM survey consisting of 37 soundings along five profiles in southwestern Los Angeles County was completed in 2008. The survey area was much less than ideal due to the dense residential and industrial land use and limited open space. Typical survey sites were small parks, cemeteries, baseball fields, or school grounds. This required a modified survey design with a smaller transmitter loop footprint that consisted of 20 to 30 meter multi-turn square transmitter loop. This design provided the same depth of penetration as would be obtained from a 100 meter single turn square transmitter loop that is more typical for these exploration depths but fit onto smaller sites.

Figure 2 presents a sample of the results obtained. The profile line consists of four TEM soundings over approximately 3 miles near the coast in Los Angeles County, California. The soundings achieved approximately 700 feet of penetration. Several soundings on other profiles were able to achieve over 1,000 feet of penetration. Stratigraphic data from well logs were added to assist in delineating the aquifers. The green colors represent intermediate resistivity values interpreted as fresh water aquifers. The yellow zone represents low resistivity areas interpreted as brackish water zones. The red zones have very low resistivity values (below 3 Ohmm) that represent saline zones. The upper 200 to 300 feet contains fresh water. Below this layer the water on the western half of the line contains brackish to saline water. On the eastern half of the line the deeper aquifers contain a layered system of fresh and saline zones. The interpretation of a layered system of two saline zones sandwiched between fresh water zones near sounding TEM 2 was subsequently confirmed with a multilevel sampling well. The low conductivity zone below a depth of about 400 feet near sounding TEM 1 represents an apparent saline zone that was previously unknown but has yet to be confirmed by test drilling.

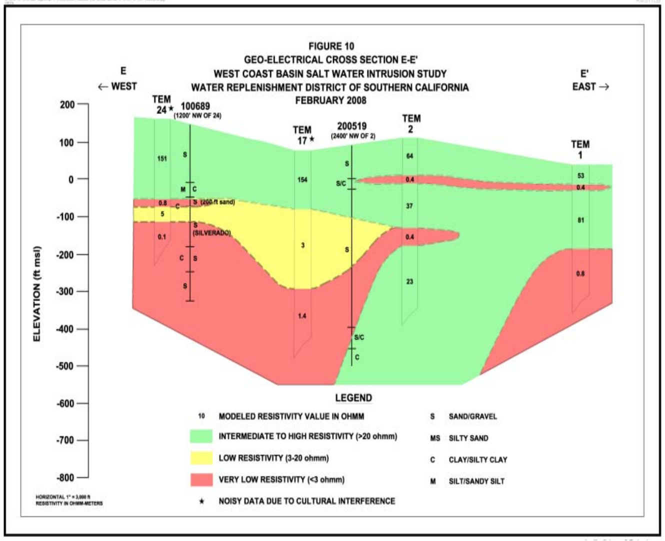

Figure 2: Typical Cross Section

CONCLUSIONS

Geophysical methods can map salt water plumes in three dimensions in the subsurface faster and for much less cost than by drilling alone. Suitable areas must be found to collect useable data, though the survey procedures can often be modified to accommodate less than ideal sites. The data can provide a degree of insight into the three dimensional distribution of electrical resistivity of the subsurface not obtainable by other methods. The property being measured is electrical resistivity which is related, but not perfectly correlated to, the salinity of the groundwater. Additional subsurface data, typically from drilling, is needed to calibrate the geophysical response and distinguish stratigraphic changes from variations in salinity. Data at a single location can usually be acquired in a few hours. The methods are fast enough and economic enough to be repeated over time to map changes in subsurface conditions related saltwater intrusion or the performance of barrier well systems.

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