Time Domain Electromagnetic Induction and High Resolution Electric Resistivity Soundings to Map Salt Water Intrusion in Coastal Sandy Aquifers, Los Angeles County, California

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ABSTRACT

Due to severe groundwater overdraft in the first half of the 20th century, salt water intruded into the coastal aquifers of the West Coast Basin in southern Los Angeles County, California. The intrusion contaminated fresh groundwater supplies resulting in the shutdown of wells or necessitating expensive reverse osmosis treatment. The extent of the intrusion is generally known, but the details are complicated due to 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/salt water interface.

A geophysical pilot test was performed in the basin using Time Domain Electromagnetic Induction (TDEM) and High Resolution Electric Resistivity (ER) to determine which method might be most suitable for full-scale intrusion mapping of the basin. Project challenges included the depth of the intrusion (200 to 800 feet), varying salinities (chloride concentrations ranging 100 mg/L to over 6,000 mg/L), multiple aquifers with different horizontal extents of intrusion, and a heavily urbanized area with abundant potential electrical interference. The ER soundings provided high resolution images of the upper 250 to 300 feet, but could not reach the greater depths due to the lack of an open corridor long enough for the survey. The TDEM using a 20m x 20m loop with four turns of the wire proved the most effective at measuring the brackish and salty water at depth with the smallest footprint and minimal noise. The results compared favorably to nearby monitoring wells. Due to the success, a full scale TDEM survey at 35 sites was performed in early 2008 and the results will be available at the conference proceedings.

INTRODUCTION

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 salt water to intrude into the coastal sandy aquifers that are used for potable, agricultural, and industrial supply (California Department of Water Resources, 1962). Groundwater provides a third of the water supply to the region, with the remainder being imported via aqueducts from the Colorado River and Northern California located hundreds of miles away from the Los Angeles region. Thus, 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 construction and operation of expensive reverse osmosis brackish groundwater desalination plants to make the 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. Lipshie and Larson (1995), CDWR (1957), and Johnson and Whitaker (2004) describe the barrier systems in detail.

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. Two desalination facilities have been constructed to remove relatively small amounts of this brackish groundwater (approximately 4,000 acre feet per year), but additional studies are being performed to evaluate the full extent of the plume so that an overall salt water management policy can be developed by local water managers. 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/salt water interface. Therefore, mapping of the intrusion using geophysical methods was pilot-tested to determine its three-dimensional extent.

METHODS

Under ideal conditions, several geophysical methods can easily detect zones of saline groundwater as highly conductive (low resistivity) volumes in the sub surface. This survey area was much less than ideal due to the dense residential and industrial land use and limited open space. These factors created severe restrictions on the survey area and types of geophysical methods that could be used.

Given the site conditions, the objectives of this study could be best accomplished through the use of two electrical methods; a high resolution electrical resistivity survey to map the lateral and vertical resistivity distribution of the upper 300 to 400 feet, and a time domain electromagnetic induction (TDEM) survey to map the electrical resistivity to depths of over 500 feet. 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. Sandy zones filled with air or fresh water generally have resistivity values of 30 to 50 Ohmm or higher depending on the silt content 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 1 to 10 Ohmm or less, depending on the degree of salinity in the groundwater.

Electrical resistivity measurements are made by passing weak electrical currents 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. 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 TDEM 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.

RESULTS

Resistivity profiles were conducted at two sites in the West Coast Basin on October 24th, 2006. The profiles at both sites detected high resistivity material (over 50 Ohmm) in the upper 50 to 100 feet. This layer represents sandy soils filled with air or fresh water. Beneath this layer lies a zone of lower resistivity material (40 Ohmm) that consists of silty sand. Resistivity values are generally above 10 to 20 Ohmm where the sand is saturated with relatively fresh water. Several pockets of very low resistivity below 10 Ohmm are also present. These zones indicate portions of the aquifer saturated with brackish or saline water with the more saline zones indicated by lower resistivity values of a few Ohmm. The distribution of low resistivity material suggests that the saline water is concentrated in pockets similar to coarser grained channel deposits that may have been preferential flow paths for sea water intrusion. The presence of the conductive zone prevented the current from penetrating deeper and the resistivity survey did not detect the bottom of this layer.

Four TDEM soundings were conducted at three locations in the survey area. Soundings 2 and 3 were conducted in the same location using two different transmitter loop configurations to optimize the depth of penetration while reducing noise from cultural features. A single turn 40m x 40m loop and a smaller 20m x 20m loop with four turns of the wire were used. The smaller loop using multiple turns was found to produce the best data at depth. The TDEM soundings detected three to four electrical layers. The upper layer has intermediate resistivity (41 to 121 ohmm) and is between 150 feet to over 300 feet thick. This layer appears to represent a combined average of the upper two layers seen on the resistivity data. The two middle layers are much more conductive (0.9 to 15 ohmm), with the lowest resistivity material present in the deeper portion of the two layers. The combined thickness of the two middle layers varies from 150 feet thick to about 200 feet thick. These layers represent sand filled with brackish to saline water. Soundings 2 and 4 detected a higher resistivity unit (50 to 100 ohmm) below the conductive unit that represents the base of the saline zone. Sounding 1 did not detect the lower unit, possibly due to the higher noise level in the larger transmitter loop.

DISCUSSION AND CONCLUSIONS

The geophysical survey appears to have detected a brackish to saline water in the aquifer at a depth of between 200 to 500 feet in the study area. An apparent fresh water sand zone may be present below the saline zone. The TDEM method achieved greater penetration given the limited space available and seems to have provided the most useful data. The resistivity method produced higher resolution data to depths of between 200 to 350 feet below the surface. It is likely that the depth of investigation of the resistivity method could be increased to about 400 to 500 feet if a longer electrode spread could be deployed. The geophysical results were compared to driller's logs and water quality data from adjacent wells. The well data confirmed the presence of saline to brackish aquifers at the depths mapped by the geophysical data. Due to the success of the pilot study, an additional 35 TDEM soundings were conducted in early 2008 to provide better resolution of the salt water intrusion. This information will be used to site additional monitoring wells and plan a water quality management program for the aquifer.

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