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Use of D-C Resistivity to Map Saline Ground Water

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Abstract

It has been estimated in previous studies that 23 square miles of the Oxnard aquifer, a member of a multi-layered aquifer system beneath the Oxnard plain in Ventura County, California, has been contaminated as a result of seawater intrusion. To investigate this and other potential sources of saline water, a direct-current resistivity survey was made as an alternative to the costly and time-consuming method of well drilling in the part of the Oxnard plain where ground water is believed to be most affected by seawater. Findings from this survey and water-quality data collected from wells as part of this study suggest that the extent of seawater intrusion is much less than reported. A field inventory of the current monitoring-well network utilized by managing agencies suggests that the integrity of most of the well casings is questionable. Leakage of saline water from an unconfined 'perched zone' through these and other failed or corroded well casings is a possible source of increasing chloride concentration in the underlying Oxnard aquifer. Saline water also may be present in fine-grained deposits along the eastern limit of the Oxnard aquifer. Pumping near this area could induce the lateral migration of saline water from these deposits.

Introduction

A complex aquifer system beneath the Oxnard plain in Ventura County, California, has been the primary source for agricultural and domestic water supplies since the early 1900's (Fig. 1). On the basis of previous studies (California Department of Water Resources, 1965, and County of Ventura Public Works Agency, 1990), it has been estimated that 23 square miles of the upper-aquifer system beneath the Oxnard plain contains water considered unusable for water supply because of high chloride concentrations. The high chloride concentrations are considered a direct result of seawater intrusion, and the position of the seawater front currently is mapped on the basis of water from wells that exceeds 100 mg/L chloride. However, sources of saline ground water other than seawater intrusion could produce chloride concentrations greater than 100 mg/L. Water-quality data collected as part of this study indicate that chloride concentrations from some areas within the shallow unconfined aquifer or 'perched zone' are as high as 23,000 mg/L.

The objective of this study was to identify areas of the Oxnard aquifer that are intruded by seawater and to indicate additional sources of saline ground water that might be responsible for increasing chloride concentrations. The usual method to accomplish this--the installation and sampling of numerous wells--is expensive and time consuming. As an alternative, a direct-current resistivity survey was made by the U.S. Geological Survey in July 1990 in the part of the Oxnard plain believed to be most affected by seawater. The results of the direct-current resistivity survey were used to effectively locate test wells so that other sources of chloride to ground water, as well as seawater intrusion, could be investigated. The direct-current resistivity survey was funded as part of the U.S. Geological Survey's Southern California Regional Aquifer-System Analysis study.

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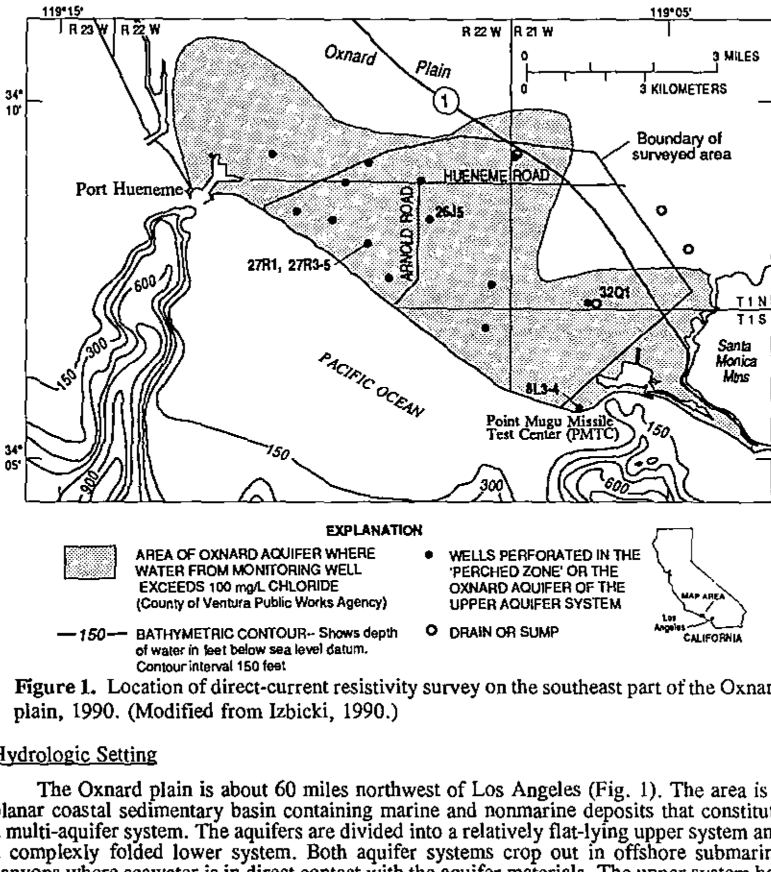

Figure 1. Location of direct-current resistivity survey on the southeast part of the Oxnard plain, 1990. (Modified from Izbicki, 1990.)

Hydrologic Setting

The Oxnard plain is about 60 miles northwest of Los Angeles (Fig. 1). The area is a planar coastal sedimentary basin containing marine and nonmarine deposits that constitute a multi-aquifer system. The aquifers are divided into a relatively flat-lying upper system and a complexly folded lower system. Both aquifer systems crop out in offshore submarine canyons where seawater is in direct contact with the aquifer materials. The upper system has a total thickness of approximately 400 feet and consists of three aquifers: (1) A shallow unconfined aquifer, known locally as the 'perched zone,' extends 90 to 105 feet below land surface. It consists mainly of fine-grained sands that are interbedded with lagoonal silt and clay deposits. Test drilling shows a clay layer with a thickness of 10 to 20 feet separating the 'perched zone' from the underlying Oxnard aquifer throughout most of the study area. (2) The underlying Oxnard aquifer has an average thickness of 110 feet and consists of flood-plain gravel deposits that yield copious amounts of water to wells. These coarse sand and gravel deposits grade to finer materials along the eastern part of the study area, toward the eastern extent of the Oxnard aquifer. (3) Directly underlying the Oxnard aquifer are the sands, gravels, and interbedded silt deposits of the Mugu aquifer. These deposits range in thickness from about 200 to 250 feet and unconformably overlie the sediments of the lower aquifer system. The complexly folded and faulted sediments of the lower aquifer system, where present, have a total thickness of more than 1,000 feet; these sediments are discontinuous or absent beneath the southeastern part of the Oxnard plain.

Available data indicate that prior to the expansion of irrigated agriculture, potentiometric levels in the upper and lower aquifer systems were above land surface, and hydraulic head increased with depth (California Department of Water Resources, 1965). Ground water then moved upward from the lower aquifer system to the upper aquifer system during nonpumping conditions. Discharging ground water on the Oxnard plain resulted in marshland conditions along the coast, and soluble salts accumulated, as a result of evaporation, in the soils and fine-grained deposits of the 'perched zone.' This natural-discharge area also was fed by canals and sloughs carrying water from irrigated fields.

Soon after the expansion of irrigated agriculture, increased pumping caused water levels to decline below sea level and caused the normal seaward flow of ground water in parts of the upper and lower aquifer systems to reverse. This resulted in the migration of seawater into aquifers beneath the Oxnard plain. However, water levels in the shallow 'perched-zone' have remained above sea level during pumping conditions, providing the potential for saline water in the 'perched zone' to move downward, through failed well casings and leaking sanitary seals around wells, and thereby contaminate underlying aquifers.

Approach

A direct-current resistivity survey was made to delineate variations in water quality in materials beneath the Oxnard plain. The survey included the area between Point Mugu Missile Test Center (PMTC) and Port Hueneme along the coast, and extended inland about 4 miles (Fig. 1). Ninety-four resistivity soundings were made using the Schlumberger electrode configuration. Maximum current-electrode spacings (AB/2), which by definition were equal to or greater than five times the potential electrode spacing (MN/2), ranged from 1,000 to 8,000 feet. Probing depths are estimated to have reached 1,500 feet below land surface.

In this paper, interpreted-resistivity data are related to geologic, hydrologic, and water-quality data collected as part of this study from aquifers underlying the Oxnard plain. Water-quality data were obtained from 39 wells perforated in the upper aquifer system, as well as from agricultural sumps and tile drains. Historical hydrologic information was obtained from the California Department of Water Resources (1965) and the County of Ventura Public Works Agency (1990).

Distribution of Interpreted Resistivity and Saline Ground Water

Apparent-resistivity data are a function of several variables, including electrical conductivity of interstitial fluids within the aquifer materials (Zohdy and others, 1974). In

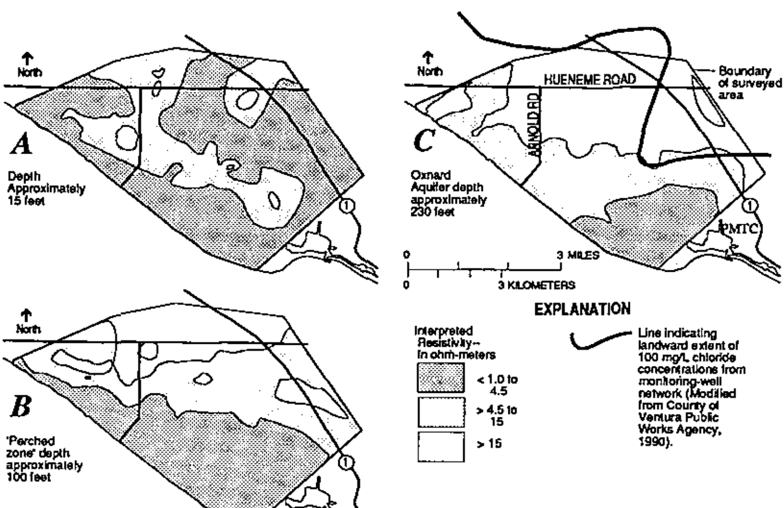

Figure 2. Interpreted resistivity at about 15,100, and 230 feet below land surface.

unconsolidated sediments, apparent-resistivity data can be controlled more by the water quality of the interstitial fluids than by the resistivities of the rock matrix. Therefore, sediments that contain saline ground water will have lower apparent resistivities than those containing non-saline ground water. Clay minerals also are capable of conducting electricity, and the presence of clays and other conductive minerals can reduce resistivities. Therefore, on the basis of resistivity methods alone, it is impossible to distinguish one cause of low resistivity from another. However, knowledge of the rock type and salinity of the ground water can be used in conjunction with the resistivity distribution to help define the causes of the observed resistivity.

The Schlumberger sounding data were interpreted to produce maps that show areal variations in the subsurface resistivity at depths of about 15, 100, and 230 feet below land surface (Fig. 2). Generally, interpreted resistivities of the upper aquifer system at depths of about 15, 100, and 230 feet below land surface were lowest along the coast at shallow depths and became higher in a landward direction and with increasing depth.

The interpreted-resistivity map at a depth of approximately 15 feet revealed that most resistivities were low (<1 to 4.5 ohm-meters) in the lagoonal areas at PMTC, in the northwestern parts near the coast, and in some inland areas (Fig. 2*A*). Ground water from shallow wells and effluent from agricultural drains were moderately to extremely saline. Average chloride concentrations ranged from more than 500 to about 23,000 mg/L. For comparison, the average chloride concentration of seawater is 19,000 mg/L. Interpreted resistivities were 4.5 to 15 ohm-meters in other interior regions and as high as 20 ohm-meters near Arnold Road. Water-quality data collected as part of this study indicated an average chloride concentration of 60 mg/L for water in well 1N/22W-26J5, east of Arnold Road.

Soil conditions were considered to be a factor influencing resistivities and ground-water quality at depths of less than 15 feet. A generalized soils map compiled by the U.S. Department of Agriculture, Soil Conservation Service (1970), indicated that the soils on the Oxnard plain can be categorized, on the basis of salinity, as saline soils and moderately saline soils. Saline soils include tidal flats and soils of the Camarillo series. Saline soils developed in topographically lower areas where ground water discharged to the surface and evaporated. Generally, interpreted resistivities at a depth of about 15 feet were less than 4.5 ohm-meters in areas where saline soils were present (Fig. 3). Moderately saline soils include the Hueneme series and artificial-fill land; these soils coincided with areas of higher interpreted resistivities. Moderately saline soils developed in topographically higher areas such as along Arnold Road and north of Hueneme Road.

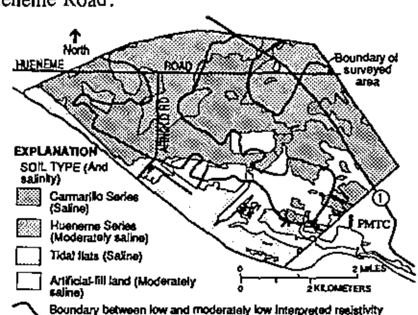

Figure 3. Soil types and salinity within the study area.

Interpreted resistivities near the base of the 'perched zone' at a depth of approximately 100 feet were less than 4.5 ohm-meters in all areas adjacent to the coastline and increased inland. Interpreted-resistivity values were as high as 45 ohm-meters north of Hueneme Road and near Arnold Road. Within these inland areas, interpreted-resistivities at a depth of 100 feet generally were higher than those at a depth of 15 feet. Along the coastline, however, the interpreted resistivities remained the same and in some areas actually decreased from those present at a depth of 15 feet (Fig. 2*B*). Available data indicate that the water table of this shallow 'perched zone' historically has been above sea level, indicating that lateral seawater intrusion probably is not the source of the low interpreted resistivities in the 'perched zone' along the coastline. The source more likely is the downward migration of seawater from wave action and high tides that inundate this area. Average chloride concentrations from ground water in the lower parts of the 'perched zone' ranged from about 60 mg/L in well 1N/22W-26J5 along Arnold Road, about 1.5 miles inland, to greater than 23,000 mg/L in well 1N/22W-27R5, 1/2 mile from the coast.

In the underlying Oxnard aquifer, interpreted-resistivity values at a depth of about 230 feet were low (< 1 to 4.5 ohm-meters) in a small area at PMTC. A statistically significant inverse relation was shown, using linear-regression techniques of least squares, between dissolved-solids concentration in water from the Oxnard aquifer in the survey area and interpreted resistivities at a depth of 230 feet. Therefore, interpreted-resistivities of materials in the Oxnard aquifer were considered to be most influenced by ground-water quality. Average chloride concentration in water from well 1S/21W-8L4 in this area was 14,750 mg/L. High chloride concentrations in this area probably are a result of lateral seawater intrusion. Moderately low interpreted resistivities (4.5 to 15 ohm-meters) were found in all other regions along the coast and inland about halfway to Hueneme Road. The data also indicate a narrow region of moderately low resistivities along the eastern boundary of the Oxnard aquifer that extends from PMTC northward (Fig. 2C). Available data show the presence of fine-grained deposits at this eastern limit of the Oxnard aquifer.

Moderately high interpreted resistivities (15 to 45 ohm-meters) extend from Arnold Road to north of Highway 1, the boundary of the study area. Even higher interpreted resistivities (45 to 70 ohm-meters) were found in some areas east of Arnold Road. The findings of the resistivity survey suggest that the extent of seawater intrusion into the Oxnard aquifer is significantly less than previously reported (Fig. 2C).

Saline Ground Water in the Oxnard Aquifer

The estimate of the areal extent of seawater intrusion into the Oxnard aquifer based on interpreted-resistivity data (for 230 feet below sea level) is smaller than the estimate based on chloride-concentration data collected from wells in the County of Ventura's seawater-intrusion monitoring-well network (Fig. 2C). Also, the distribution of chloride in the Oxnard aquifer determined from wells drilled as part of this study was significantly different from the distribution obtained by the County's monitoring-well network. This suggests that there may be other sources of chloride to the Oxnard aquifer in addition to seawater intrusion. Water-quality data collected as part of this study show that ground water from the soil zone and deeper parts of the 'perched zone' has an average chloride concentration greater than 5,700 mg/L. Interpreted-resistivity data show that the areal distribution of this poor-quality water is extensive. An additional source of increasing chloride concentrations in water from wells completed in the Oxnard aquifer is leakage of water from the overlying 'perched zone' through failed and corroded well casings (Izbicki, 1991). All wells completed in the Oxnard aquifer (and underlying aquifers) pass through the 'perched zone' and thus are potential conduits to deeper aquifers.

Casing failure has been confirmed in well 1N/22W-27R1 (Fig. 4), which is part of Ventura County's seawater-intrusion monitoring-well network. This well is in what was reported to be one of the most highly intruded parts of the Oxnard aquifer. Chloride concentrations in water from this well, which is reported to be perforated from 125 to 213 feet below land surface, have increased from less than 70 mg/L in 1950 to 1,900 mg/L in 1990 (County of Ventura Public Works Agency, 1991). The increasing chloride concentration in water from this well has been attributed to seawater intrusion. However, less than 150 feet away, at a multiple-well cluster installed as part of this study, water from well 1N/22W-27R4 (perforated in the Oxnard aquifer), had a chloride concentration of 180 mg/L in November 1990 (Fig. 4). Water from well 1N/22W-27R5, (perforated in the 'perched zone') had a chloride concentration of 23,000 mg/L and a higher water level than that found in the well perforated in the underlying Oxnard aquifer. The downward hydraulic gradient at this site allows water of poor quality to move from the overlying 'perched zone' through failed well casings into the Oxnard aquifer. After the completion of this nearby multiple-well cluster site (wells 1N/22W-27R3, -27R4, -27R5), the County of Ventura's monitoring well (1N/22W-27R1) was developed and pumped by the U.S. Geological Survey. After 4 hours of pumping, the specific conductance of water from the well stabilized at 2,400

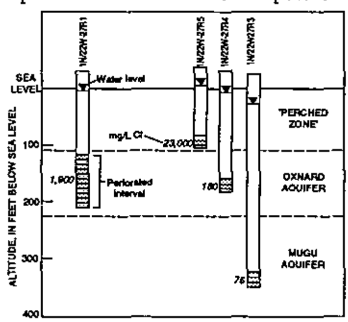

Figure 4. Water levels and chloride concentrations for selected wells.

μS/cm. In 1989 this well yielded water that had 11,000 μS/cm. This suggests that those wells in the monitoring-well network that do not have pumps may not have been adequately purged to yield a representative sample. Similar results were obtained at a multiple-well cluster installed near another Ventura County observation well, 1N/21W-32Q1.

To determine if other monitoring wells in the study area may have failed, 25 upper-aquifer-system wells in Ventura County's monitoring network were inventoried. Most of these wells are abandoned irrigation wells and are not pumped between sampling intervals. An attempt was made to determine the integrity of well casings by measuring well depths, thereby helping to assess the quality of the data collected from each well. Well depths were shallower than reported for 10 of 12 wells measured, including well 1N/22W-27R1. The measured depths for three wells were more than 50 feet less than reported, and no depth measurements were made on 13 wells because casing access does not exist. In addition to failed monitoring wells there are more than 340 abandoned wells in the surveyed area alone. Only 31 of these wells are known to be properly destroyed. Furthermore, areas with a high density of wells coincide with areas of increasing chloride concentrations and low interpreted resistivities in the Oxnard aquifer. These data suggest that improperly destroyed wells, failed well casings, or leaking sanitary seals may contribute significantly to the increase in chloride in water within the Oxnard aquifer. Further investigation is necessary to verify the extent and contribution of these potential sources.

In addition to seawater intrusion and leakage of water through well casings, there may be another source of saline water. The map in figure 2*C* shows moderately low interpreted resistivities along the northeastern edge of the survey. This eastern edge of the Oxnard aquifer once was fed by ground water discharging to the surface and contains fine-grained deposits. As in the 'perched zone,' evaporation of water at the surface may have resulted in the accumulation of salts within the aquifer materials. Pumping from the Oxnard aquifer near this area may induce the migration of this potentially saline ground water. However, additional data would be required to confirm this possible source of saline water.

Conclusions

Interpreted resistivities in the upper aquifer system beneath the Oxnard plain were lowest along the coast, and became higher in a landward direction and with increasing depth. Most of the overlying 'perched zone' had extremely low interpreted resistivities and contained saline ground water. The underlying Oxnard aquifer had low interpreted resistivities in the area of Point Mugu Missile Test Center. All other coastal sections and interior regions of the Oxnard aquifer had higher interpreted resistivities. The estimate of the areal extent of seawater intrusion in the Oxnard aquifer based on interpreted-resistivity and water-quality data obtained as part of this study is smaller than the estimate based on chloride-concentration data collected from wells in the County of Ventura's seawater-intrusion monitoring-well network. A field inventory found that the integrity of the casings of the abandoned irrigation wells used in the monitoring-well network was questionable, and suggested that the failure of these and several hundred other improperly destroyed or abandoned wells in the Oxnard plain has occurred. Because of the downward hydraulic gradient present in the upper aquifer system, leakage of saline water from the overlying 'perched zone' through failed well casings or sanitary seals is a likely source of increasing chloride concentration to the Oxnard aquifer. Saline water may also be present within the fine-grained deposits along the eastern limit of the Oxnard aquifer. Pumping near these fine-grained materials may induce the migration of potentially saline water to wells.

Appendix--References

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