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April 1988

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FINAL REPORT

Ground Conductivity Measurements Adjacent to the Kesterson Ponds 1, 2, and 5

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April 1988
Introduction

A reconnaissance ground conductivity survey was performed by Lawrence Berkeley Laboratory (LBL) over the Freitas Ranch property adjacent to Ponds 1, 2, and 5 of the Kesterson Reservoir, Merced County, California (Fig. 1). The purposes of the survey were to determine the background electrical conductivity of near-surface soils and rocks and to search for anomalies that could be attributed to the infiltration of irrigation drainwater from the Kesterson ponds into the native groundwater beneath the ranch.

Analysis of water samples obtained from many shallow holes within the Reservoir show that conductivities of the drainwater are several times greater than those of the native groundwater. Specific conductances of the native groundwater are in the range of 300 to 400 millisiemens per meter (mS/m), whereas conductivities of contaminated groundwater range up to 1000 to 1700 mS/m because of the high Na, Cl, and SO₄ concentrations (LBL, 1987b). Saline agricultural drainwater used to flood the Kesterson ponds has entered the shallow sandy aquifer beneath the ponds by seeping through the near-surface layer of fine-grained sediments. The plume of infiltrating drainwater is expected to migrate eastward, partly as a result of groundwater mounding, caused by filling the Kesterson ponds, and partly as a result of the prevailing direction of regional groundwater flow.

In this study we have attempted to map the drainwater plume using commercially available electromagnetic instruments calibrated by the manufacturer to give ground conductivity readings directly. We employed the Geonics EM31 and EM34-3 instruments, which are described in a later section. We had also planned to use the Geonics EM16R, a VLF radio-frequency device, but hard ground conditions made it too difficult to emplace electrodes without damaging them.
Fig. 1. Location map (above) and aerial photograph (facing page) showing the area covered by the ground conductivity survey adjacent to the Kesterson ponds. The photograph is taken from a black-and-white aerial photomosaic of the Kesterson Wildlife Refuge made by CH2M-Hill.
Location of Survey Area

Ground conductivity measurements were made over a portion of the Freitas Ranch, just east of by the San Luis Drain and adjacent to Ponds 1, 2, and 5 of the Kesterson Reservoir. The survey area is located in Sections 15, 16, 21, and 22, T.8 S., R. 10 E., 13 miles north of Los Banos and 7 miles east of Gustine in the San Joaquin Valley (Fig. 1). The area is covered by the San Luis Ranch and Ingomar 7.5-minute quadrangle topographic sheets.

Site Characteristics

The average elevation of the area is 70 feet above mean sea level, and the surface varies from flat to slightly undulating. Several drainage features are found on the ranch. In addition to a system of man-made canals that once distributed waters to the area, an intermittent stream channel cuts across the southeast part of the area. The channel, dry during the survey, appears to carry seasonal runoff in a northerly direction into Salt Slough. An oxbow lake, presumed to be a relict feature of the ancestral San Joaquin River, exists at the south end of the survey area. Salt crystals and desiccation cracks suggest that this area, dry at the time of the survey, is subject to periodic inundation and evaporation. The ranch is now used for cattle and horse grazing.

The survey was conducted during the first two weeks of October 1987. Days were dry and hot (80 to 90 °F); nights were cool.

Color aerial photographs were taken of the Kesterson Reservoir area by CH2M-Hill at monthly intervals from late November 1987 through mid-March 1988. During this period the area received most of its annual rainfall, and the new vegetation created color contrasts that were helpful in identifying ground conductivity anomalies associated with high-salinity soil conditions.
Principles of Electromagnetic Measurements

The electromagnetic measurement of ground conductivity relies on the laws of electromagnetic induction. Although the mathematical formulation is rather complicated, the basic principles, as diagrammed in Fig. 2, are simple. A transmitter coil (T) energized with an alternating current produces a time-varying magnetic field \( H_p \) that induces weak eddy currents in the earth. These eddy currents decay with depth but produce secondary magnetic fields \( H_s \) that are detected along with the primary field \( H_p \) by a receiver coil located a known distance away from the transmitter. The strength of these secondary fields is a function of ground conductivity, frequency of the current, and transmitter-receiver separation (McNeill, 1980). If the operating frequency and separation are known, the terrain conductivity can be easily determined. In practice, it is possible to distinguish the weak secondary field from the much stronger primary field because \( H_s \) is 90° out of phase with \( H_p \).

Causes of Ground Conductivity Anomalies

The electrical conductivity of a representative volume of a sedimentary rock is generally expressed through an empirical expression known as Archie's law (Archie, 1942):

\[
\sigma_B = a \sigma_w (\phi S)^m,
\]

where

- \( \sigma_B \) = the bulk conductivity of the rock,
- \( \sigma_w \) = pore fluid conductivity,
- \( \phi \) = average connected porosity (expressed as a fraction),
- \( S \) = liquid saturation,
- \( a,m \) = coefficients, determined experimentally,

that depend on rock type and fracture porosity
(or cementation of the rock).
Simplified diagram illustrating the principles of electromagnetic induction and ground conductivity measurements.
For most soils and rocks the bulk conductivity is strongly dependent on pore-water conductivity, $\sigma_w$, which is mainly a function of water salinity and temperature. Temperature increases water conductivity by making water a better solvent and reducing its viscosity.

The expected ground conductivity can be estimated using Eq. 1 (Keller and Frischknecht, 1966). For conditions typical of porous sandy rocks saturated with saline drainwater, such as found at Kesterson (LBL, 1987a), the parameters are approximately

$$
a = 1.0 \\
m = 1.65 \\
\phi = 0.35 \\
\sigma_w = 1,300 \text{ mS/m.}
$$

Using these values in Eq. 1 gives a bulk rock conductivity of 230 mS/m. It should be noticed that the calculated bulk rock conductivity will be dependent to some extent on the value chosen for $a$ and $m$, but the bulk rock conductivity will invariably be much less than the conductivity of the pore fluid. As shown in a later section, 230 mS/m is slightly greater than background values but slightly lower than the maximum values determined from the field measurements over the Freitas Ranch. However, it must be pointed out that the conductivity of rocks may be substantially enhanced by clays, such as smectites, with a high cation-exchange capacity. Clay-rich soils and rocks may be 2 to 5 times more conductive than predicted by Archie's law because of surface conduction effects at water-clay interfaces (Waxman and Smits, 1968).

Under natural conditions, $\sigma_B$ can vary substantially both laterally and vertically, depending on depositional and post-depositional processes that affect porosity, saturation, clay types and concentrations, and water salinity. Variations in $\sigma_B$ may show up sharply in electric well logs but are greatly smoothed out by the volume averaging that occurs in measurements with the EM31 and EM34-3. These instruments give an average conductivity over a lateral distance approximately equal to the depth of exploration (Table 1).
Table 1
Depth of Exploration of Geonics
Ground Conductivity Meters
(McNeill, 1986)

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Intercoil Spacing (m)</th>
<th>Approximate Depth of Horizontal Dipole Mode (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EM 31</td>
<td>3.7</td>
<td>7.0</td>
</tr>
<tr>
<td>EM 34-3</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>EM 34-3</td>
<td>40</td>
<td>30</td>
</tr>
</tbody>
</table>

Instrumentation

The EM31 consists of two coplanar loops mounted on a rigid boom, and it can be carried and operated by one person. With an intercoil spacing of 3.7 m, the EM31 has an effective exploration depth of 7 m.

The EM34-3 uses two circular coils, each about a meter in diameter, connected by cable to the electronics. Intercoil separations of 10, 20, or 40 m are allowed and are switch selectable. We used coil separations of 20 and 40 m to achieve a greater depth of exploration than possible with the EM31. The EM34-3 requires a two-person crew, but we ran all surveys with at least one additional person to flag stations and record the meter readings.

The EM34-3 coils can be oriented either horizontally to produce a vertical magnetic dipole (the VD configuration) or vertically to produce a horizontal magnetic dipole (the HD configuration). The VD configuration provides twice the exploration depth of the HD configuration and is more sensitive to lateral conductivity variations, such as narrow conductive channels. However, the VD mode is highly susceptible to coil misalignment, as we confirmed from tests.

Both the EM31 and the EM34-3 are designed for use where the dimensionless induction number B is much less than 1:
\[ B = \frac{\omega \mu_0 \sigma_a s}{2} \ll 1, \]

where

\[ \begin{align*}
\sigma_a &= \text{apparent ground conductivity (S/m)}, \\
\omega &= 2 \pi f, \\
f &= \text{frequency (cycles/sec)}, \\
\mu_0 &= \text{permeability of free space (}4\pi \times 10^{-7}\text{ H/m)}, \text{ and} \\
s &= \text{intercoil spacing (m)}.
\end{align*} \]

For this condition the conductivity is directly proportional to the secondary to primary magnetic field ratio. The resulting equation is

\[ \sigma_a = \frac{4 \left( H_s \right)}{\omega \mu_0 s^2 \left( H_p \right)}, \quad (2) \]

where

\[ \begin{align*}
H_s &= \text{secondary magnetic field, and} \\
H_p &= \text{primary magnetic field.}
\end{align*} \]

If the conductivity exceeds the limit of the low-induction approximation, the linear relationship in Eq. 2 breaks down and the results are invalid. The breakdown point for the EM31 is approximately 800 mS/m; for the EM34 it is 1500 mS/m when the coils are oriented in the HD configuration and 200 mS/m when the coils are oriented in the VD configuration. Because of the high ground conductivities and the alignment problems encountered with the VD mode, we are relying strictly on the HD field data.
Test Line Results

Prior to the survey we tested the ground conductivity instruments on a 250-m-long line adjacent to Pond 7 (Fig. 1). That line was selected because it passes over several shallow wells from which waters were sampled and analyzed by LBL 2 years ago and again recently. The electrical conductivities of these waters were determined by means of a YSI electrical conductivity meter and are listed in Table 2. The ground conductivities, measured with the EM34-3 in the HD mode using a 20-m coil separation, are plotted in Fig. 3 along with the well locations.

<table>
<thead>
<tr>
<th>Well*</th>
<th>Well Depth (m)</th>
<th>Water Conductivity (mS/m)</th>
<th>Boron (ppm)</th>
<th>EM34-3 (mS/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LBL 22</td>
<td>6.1</td>
<td>610</td>
<td>500</td>
<td>2.1</td>
</tr>
<tr>
<td>KR 314B</td>
<td>11.9</td>
<td>850</td>
<td>4.8</td>
<td></td>
</tr>
<tr>
<td>KR 314C</td>
<td>24.1</td>
<td>360</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>LBL 23</td>
<td>6.1</td>
<td>428</td>
<td>470</td>
<td>1.4</td>
</tr>
<tr>
<td>LBL 24</td>
<td>6.1</td>
<td>477</td>
<td>650</td>
<td>1.3</td>
</tr>
</tbody>
</table>

* The wells are listed in order of increasing distance from the San Luis Drain.

The ground conductivity measurements show values (100 to 150 mS/m) typical of regional background out to nearly 200 m from the San Luis Drain. At that distance, there is an abrupt increase in ground conductivity to the 200 to 275 mS/m range. This anomaly is reflected to some extent in the water conductivities measured in December 1987, which also seem to indicate higher values in the well farthest from the drain (LBL 24).
Fig. 3. Ground conductivity profile along test and control line near Pond 7. Data were taken with the Geonics EM34-3 using a 20-m coil separation.
The lower ground conductivities (and low electrical conductivities of the groundwater samples) close to the Drain indicate that drainwater has not migrated more than 50 m away from the Drain at this location. The relatively low concentration of boron in the groundwater (1 to 4 ppm) compared to the drainwater (average of 15 ppm) indicates that migration of drainwater is not the cause of the elevated conductivities observed in the vicinity of LBL 24. The reason for the increases in ground conductivity and electrical conductivity of the groundwater farther away from the Drain is unknown. Hydrologic factors, such as past water operations on this property, and geologic factors, such as changes in lithology, may both account for the observed increases.

Description of the Survey Grid and Procedures

The ground conductivity measurements were made on a regular grid, along eleven lines trending approximately N60°W true north. These lines, whose endpoints are shown in Figs. 4, 5, and 6, are roughly parallel to the San Luis Drain where it borders Kesterson Pond 1. The grid origin was placed near a fence intersection close to well KR-47 and close to the southeast corner of Pond 1 (Fig. 1).

Lines were surveyed at 100-m separations using transit and chain. Measurement points were placed at 20-m intervals along those lines. The survey area covers approximately 2 km² and excludes the area occupied by the ranch buildings and corrals located at the end of Gun Club Road.

We obtained at least three conductivity values at each station, one with the EM31 and two with the EM34-3 employing the HD configuration and intercoil spacings of 20 and 40 m. In addition, we took EM34-3 readings with the VD configuration on a number of lines. However, for reasons explained above, the VD readings are not being considered.
Fig. 4. Isoconductivity contours based on measurements with the Geonics EM31 adjacent to Ponds 1, 2, and 5.
Fig. 5. Isoconductivity contours based on measurements with the Geonics EM34-3 adjacent to Ponds 1, 2, and 5. A 20-m intercoil separation was used.
Fig. 6. Isoconductivity contours based on measurements with the Geonics EM34-3 adjacent to Ponds 1, 2, and 5. A 40-m intercoil separation was used.
Data Reduction

Because conductivities in the survey area approach the limit of the low-induction-number approximation, the data had to be corrected for slightly nonlinear behavior (McNeill, 1980). The corrected conductivities for the EM31 and the EM34-3 surveys are shown in Figs. 4, 5, and 6.

Both the EM31 and the EM34-3 HD-mode readings are highly sensitive to near-surface conductivities, and these may mask the effects of deeper variations. To overcome this problem, we followed a simple and effective procedure that transforms the EM34-3 depth-response function to one less sensitive to the near-surface conductivity (McNeill, 1985). The procedure is to calculate a new apparent ground conductivity ($\sigma_{an}$) at each station:

$$\sigma_{an} = 2 \sigma_{40} - \sigma_{20},$$

where $\sigma_{40}$ and $\sigma_{20}$ are the apparent conductivities at the 40- and 20-m intercoil spacings, respectively.

This operation alters the effective depth-response function to one that has zero sensitivity at the surface and maximum sensitivity to conditions at depths of about 0.25 times the larger intercoil separation. Thus the numerical procedure yields a ground conductivity map (Fig. 7) that emphasizes conditions in the 8- to 16-m depth range. Figures 6 and 7 have many common features, as might be expected, but Fig. 7 shows small regions with negative values of apparent conductivity. Negative values of conductivity have no physical meaning other than to indicate where ground conductivity varies abruptly over distances of less than 40 m. Because of its close resemblance to the VD-mode response, we refer to Fig. 7 as a pseudo-VD isoconductivity map.

One profile (A-A') has been constructed (Fig. 8) to show lateral conductivity variations across the area.
Fig. 7. Pseudo-VD mode isoconductivity map calculated from the data in Fig. 5 and 6.
Interpretation

The complexity of the conductivity variations diminish with increased coil separation. During the survey, we noticed that the EM31 responded to topographic irregularities and apparent variations in soil moisture and salinity. Small anomalies present in Fig. 4 correlate with such surface features as dry lake and creek beds, which show on the aerial photo in (Fig. 1). The effect of these surface features diminished with an increase in intercoil separation of the EM 34-3 (i.e., larger coil separations tend to filter out the surface effects). Having three data sets and the color aerial photographs was extremely useful because they allowed us to distinguish between subsurface and near-surface conductors. We have divided the survey area into seven regions (Fig. 9) so that we can refer to specific anomalies.

Conductivities are lowest in the eastern portion of the survey area (Area A), farthest from the Kesterson Ponds. We consider the values encountered (150 to 200 mS/m) to be normal background levels, but it should be noted that they represent high salinity conditions, which are typical of the regional soils (Soil Conservation Service, 1952). Values in the same range were also measured along our short test line near Pond 7 and by Hanson and Grismer (1987), who made extensive ground conductivity measurements near Mendota.

As can be seen from the four isoconductivity maps (Figs. 4 to 7), the highest conductivity values (400 mS/m) are adjacent to Ponds 1 and 2 on lines 0, 1, 2, and 3 (Area B). The absence of surface features to explain this high-conductivity anomaly suggests that it is caused by seepage and migration of drainwater from the Kesterson ponds. If we define the position of the leading edge of the plume as being where the ground conductivity measured with the EM34 (40-m coil separation) declines to background values (Fig. 8), it would appear that the leading edge of the plume has migrated about 350 m from the San Luis Drain. Conductivity values indicate that the average migration distance (defined as the point where the conductivity is midway between the conductivity values associated with undiluted drainwater and background levels) is about 200 m. The large difference between the distance that the leading edge
Conductivity Profile A-A'

- EM31
- EM34, 20-m Dipole Spacing
- EM34, 40-m Dipole Spacing

Fig. 8. Ground conductivity profile data along line A-A' (Figs. 3, 4, and 5).
Figs. 9. Subregions of the survey area discussed in the text, and an interpretation of the geophysical results.
of the plume has migrated and the average migration distance suggests that the plume disperses as it moves downgradient. Area D appears to be influenced by drainwater migration in a manner similar to that in Area B, except that the leading edge of the plume is much closer to the San Luis Drain.

A small, well-defined anomaly exists immediately east of the Freitas Ranch buildings and corrals (Area C). No surface feature was apparent at the time of the survey. The anomaly is most likely due to highly saline soil conditions. The anomaly disappears with deeper-probing methods, and it correlates with an area that remains bleached in the photographs throughout the rainy season.

Adjacent to Pond 1 on lines 0 and 1 is a low-conductivity zone (Area E). The low conductivity is attributed to the fact that saline drainwater has not been added to Pond 1 since the summer of 1985. Most likely, less saline native groundwater has since displaced and diluted the plume of high-salinity drainwater that seeped through Pond 1 prior to 1985. Dilution may also occur with time in other areas of the Freitas Ranch adjacent to the ponds.

The oxbow dry lake in the southern part of the survey area (Area F) correlates with a conductivity anomaly of about 300 mS/m that appears on all four isoconductivity maps. Because the deeper part of the anomaly occurs only over the western part of the dry lake, we believe that we are seeing the effects of soil salinization and intrusion of subsurface saline water, possibly seepage from Pond 1 that occurred before 1985. The low-conductivity region upgradient may represent the trailing edge of the plume.

A well-defined anomaly occurs in the center of the survey area (Area G) on the EM31 isoconductivity map. The anomaly diminishes with increasing EM34-3 coil separation and disappears in the pseudo-VD map. It also correlates in part with an area on the aerial photographs that does not have normal green vegetation by January. For these reasons we are almost certain that it is caused by near-surface salinity and not by drainwater migration.
Summary and Conclusions

A reconnaissance ground conductivity survey over a 2 km² area adjacent to Kesterson Ponds 1, 2, and 5 reveals a highly saline near-surface environment. Soil conductivities indicated by direct-reading electromagnetic instruments exceed 150 mS/m everywhere in the survey area and for the three depths of investigation (approximately 7, 15 and 30 m) provided by the instruments. Similar background readings have been reported for the Mendota area.

Several individual conductivity anomalies of 300 to 400 mS/m were mapped within the area. The only one that correlates with a surface feature occurs over an oxbow depression at the south end of the survey area. The depression appears to have been periodically flooded; mud cracks and salt crystals are visible at the surface. The size of the anomaly decreases with depth of investigations, indicating a surficial cause. However, a deeper component remains in the pseudo-VD conductivity map, indicating that the anomaly may be due in part to saline water migration from Pond 1.

An extensive conductivity anomaly adjacent to Pond 2 (lines 1, 2, 3, 4, and 5) is well-defined for all three depths of investigation. On the basis of anomaly shape, location, and magnitude, we conclude that the high conductivity is due, at least in part, to seepage of drainwater from Pond 2. The leading edge of the plume extends approximately 350 m from the San Luis Drain.

East and north of the Freitas Ranch buildings and corrals, two discrete conductivity anomalies were detected on at least two lines. The narrow, slightly arcuate shapes of these anomalies suggest that they may be due to old stream channels. Whatever their cause, they are shallow features.

A narrow conductivity anomaly was delineated near the center of the survey area on lines 5, 6, and 7. Because this anomaly is strongest in the EM31 results and is totally absent in the 40-m-separation EM34-3 results and in the pseudo-VD map, we conclude that it is probably a very shallow salinization feature.
Recommendations for Future Work

Although we offer possible causes for the ground conductivity anomalies detected at the study area, a complete understanding of these high-conductivity zones requires drilling, logging, and water analyses. To verify the findings presented in this report, we recommend that each significant anomaly be further studied by means of several shallow drill holes. The holes should be completed in the fashion of those previously drilled, and each should be logged using an EM induction logging tool. The lithologies and mineralogies of each hole should be studied, and water samples should be collected for geochemical analyses.

We also suggest that repeated ground conductivity measurements be made at future times as a way of monitoring remediation processes.

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References


