RECLAMATION

Managing Water in the West

Geophysical Survey for Canal Seepage
Yuma Area Demonstration Project

Arizona and California Irrigation Canal Systems
Lower Colorado Region

U.S. Department of the Interior
Bureau of Reclamation
Yuma Area Office
Yuma, AZ

May 2009

Mission Statements

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian Tribes and our commitments to island communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Geophysical Survey for Canal Seepage Yuma Area Demonstration Project

Arizona and California Irrigation Canal Systems
Lower Colorado Region

prepared by

TECHNOS

Author:
Ronald Kaufmann, Vice President
P.G. Tennessee #3675

Reviewer:
Daniel Casto, Senior Geophysicist
P.G. Florida #2511

U.S. Department of the Interior
Bureau of Reclamation
Yuma Area Office
Yuma, AZ

May **2009**

Contents

Background

The U.S. Department of the Interior, Bureau of Reclamation (Reclamation) is investigating canal seepage in five water districts within the Yuma Area Office jurisdiction. The canals are part of a large network of unlined irrigation canals fed by the Colorado River. Groundwater in this area typically has a higher salinity level than the relatively fresh water in the canals. In addition to the concern over the loss of fresh water, seepage losses from canals can cause damage to surrounding crops by raising the levels of high-salinity groundwater in localized areas.

The use of surface geophysics has proved effective in locating and characterizing canal seepage. Geophysical surveys can provide a rapid, spatially-dense sampling of subsurface conditions in a non-invasive manner. In Australia, geophysical surveys are recommended as the most accurate method for assessing relative seepage in large scale surveys (IAL, 2008). Electrical resistivity and electromagnetics are the most common geophysical methods used for seepage investigations. Electrical resistivity is a proven, state-of-practice tool for the mapping of canal seepage (IAL, 2008; Watt and Khan, 2007; Engelbert, et al., 1997), and, when calibrated, resistivity can provide an estimate of seepage velocity (White, 1994).

Scope

Reclamation’s Yuma Area Office retained Technos, Inc. (Technos) to carry out a geophysical investigation as a demonstration project to show how surface geophysics can be utilized for rapid assessment of seepage in irrigation canals. Six unlined canals in five water districts located in Arizona and California were chosen for the demonstration project (Figure 1; Table 1).

Table 1. Survey Areas

District	Canal	Survey Length (miles)
Yuma County Water Users	East Main	8.4
Yuma County Water Users	Central	4.8
Bard	Mohave Lateral	3.5
Imperial	East Highline	11.5
GGMC Admin Board	Gila Gravity	13.9
Colorado River Indian Tribes	73-19-36 (*referred to as CRIT in this report*)	3.2

Marine resistivity data were acquired along a total of 45.3 miles of canals (Table 1). The marine resistivity data were used to develop electrical conductivity cross-sections and plan-view maps along each of the survey lines. The marine resistivity data were acquired between October 29th and November 6th, 2008.

Two anomalous locations within each water district site were selected for follow-up investigations utilizing a land-based resistivity survey. The land-based resistivity data were acquired between December 5th and 12th, 2008. Wells were drilled at each location and alluvium samples were obtained for sieve analysis by Reclamation. Geophysical logs were also acquired within each of the wells by a Reclamation subcontractor.

This report summarizes the methodology, survey parameters, limitations, and results for all resistivity measurements. Correlations are made to quantify the relationship between ground conductivity values and alluvium composition, which can then be used to characterize seepage potential.

Technical Approach

Survey Lines

Survey lines within the canals were defined by Reclamation as shown in Table 1. Survey lines within each canal were broken into segments as labeled in Figures 4, 25, 32, 33, 50, 51, and 71. The segment endpoints correspond to physical obstructions within the canals such as road crossings, control structures, and gates. Data were not acquired in short segments between structures (<500 feet) due to the length of the marine resistivity array.

Positions within the canals were obtained with a Lowrance LMS-520c differential GPS with a lateral accuracy of+/-3 feet. The GPS positions were recorded with the marine resistivity data at one-second intervals. Marine resistivity cross-sections are referenced to distance in feet from starting points noted on the figures. Geographic positions along the cross-sections are annotated as latitude and longitude using the NAD-83 datum.

The locations of the land resistivity arrays were established with a Trimble Ag-132 differential GPS with a lateral accuracy of +/-3 feet. Positions along the land resistivity lines are referenced to distance in feet. Data were acquired along survey lines oriented roughly parallel and perpendicular to the canals.

Electrical Resistivity

Overview

Resistivity measurements are made by placing electrodes in contact with the soil or water. A DC electrical current is injected between one pair of electrodes while the voltage across the other pair of electrodes is measured. The resistivity measurement represents the apparent resistivity averaged over a volume of the earth determined by the resistivity of the subsurface materials, along with the electrode geometry and spacing (ASTM, 2005).

In this study, the resistivity data are presented as electrical conductivity (inverse of resistivity) in units of milliSiemens/meter (mS/m). The conductivity of coarse-grained materials such as sand and gravel is generally lower than that of fine-grained materials such as silts and clays. Since coarse-grained materials have a higher hydraulic permeability than fine-grained materials, seepage rates will generally be higher in coarser-grained materials (USBR, 1965; Houk, 1956; and Davis, 1952). Therefore, lower electrical conductivity values generally correspond to areas of high potential seepage (Engelbert, et al., 1997). Exceptions to this can occur in areas where the influence of shallow groundwater dominates the measurement.

Marine Data Acquisition

Marine data were acquired with an AGI SuperSting marine system using a cable towed on the water surface with an electrode spacing of six meters. The cable was towed upstream to keep the cable straight. An average current of 1 Amp was injected by the nearest two electrodes to the tow point. Eight dipole-dipole measurements were made at approximately four-second (10-foot) intervals as the cable was towed along the survey lines at an average speed of 1.8 MPH. In the East Main, East Highline, and Gila Gravity canals, the cable was towed by an inflatable boat (Figure 2). Water depths were recorded by the Lowrance LMS-520c and used in the data processing.

In the Central, Mohave, and CRIT canals, the cable was towed by a vehicle and personnel walking along the adjacent roads. Note that the GPS data were acquired from the vehicle on the adjacent road, and water depths were estimated.

Canal water specific conductance values were obtained with a YSI 3000 T-L-C meter. The specific conductance and depth of the water were used in the resistivity modeling.

Land Data Acquisition

Land resistivity data were acquired at two locations within each of the five water district study areas. The locations were selected based on the results of the marine data. At each location, measurements were obtained roughly parallel and perpendicular to the canal (except at Gila-Land-2, where an additional parallel line was substituted for the perpendicular line).

Land resistivity data were acquired with an AGI R1IP Sting/Swift system using 56 electrodes spaced five feet apart (covering a linear distance of 275 feet). The electrodes were attached to stainless steel stakes hammered into the ground. Water was poured around each stake to improve electrical coupling. Dipole-dipole measurements were made with maximum input currents of 200 or 500 milliamperes (mA), depending upon the local soil conditions.

Data Processing

The marine resistivity data were processed with EarthImager software by AGI. Data points having low signal levels (<0.2 millivolts (mV)) or discontinuous values were removed from the dataset prior to modeling. An iterative inversion modeling scheme was used to calculate two-dimensional (2D) models of subsurface conductivity to a depth of 45 feet.

The land resistivity data were processed with RES2DINV software by Loke. Noisy data points (>5% RMS error) were removed from the dataset prior to modeling. An iterative least-squares inversion was used to calculate 2D models of subsurface conductivity to a depth of 45 feet.

The resulting models were contoured and presented as 2D conductivity cross-sections in SURFER software (Golden Software). The models are shown using a constant conductivity scale to allow direct comparison among the different survey lines. Average conductivity values from the canal bottom to a depth of 45 feet were calculated and shown in plan-view to illustrate the general conductivity variations along each canal.

Data Quality and Repeatability

As a quality control measure, resistivity data were acquired twice along a segment of the Gila Gravity canal. The data were acquired on different days and processed separately. The resulting models confirm that the measurements are repeatable and that small variations in the path of the electrode array do not have a significant effect on the models (Figure 3).

The quality of the marine and land resistivity data is excellent, with generally continuous data having a high signal-to-noise ratio. Marine model RMS errors are less than 5%, indicating a good fit between the calculated model and measured data. Land model RMS errors range between 1.7 and 14.8%, with higher RMS errors generally due to heterogeneities in the near-surface materials.

Marine Model Resolution and Detectability

In wide canals (>45 feet), the conductivity is representative of the water in the canal and the sub-bottom materials. In narrow canals, materials along the sides of the canal can influence the measurements, and, therefore, the conductivity is representative of the water in the canal, sub-bottom materials, and materials along the sides of the canals.

The lateral resolution is mainly dependent upon the electrode spacing. The model blocks in the resistivity inversion have widths of approximately 2.5 feet. The model resistivity values were gridded at a 10-foot lateral spacing to show a smooth model. Depending on the resistivity contrast, features smaller than this spacing may be detectable, but their response will be averaged over this 10-foot interval.

The vertical resolution of resistivity measurements decreases with increasing depth. A conservative rule-of-thumb is that the thickness of the modeled layers can only be defined to within 30% of the depth of the strata. It is possible to detect layers that are thinner than 30% of the depth, but unlikely to resolve them into separate layers or calculate their true thickness. The models consist of 16 layers ranging in thickness from one foot at the surface to five feet at a depth of 45 feet.

Limitations

Resistivity models can contain artifacts due to interference of grounded metal objects such as utility lines, railroad tracks, and fences. These artifacts are annotated on the resistivity cross-sections presented in this report.

Results

General Observations

The unlined canals cut through alluvial sediments consisting of a broad mix of sands, silts, and clays. Table 2 summarizes the general conditions within each of the canals. Specific conductance measurements of the canal water have a median value of 1,010 microSiemens/centimeter (μS/cm) or 101 mS/m, with the lowest conductance in the CRIT canal, located well upstream of the others. The specific conductance readings and canal depths were used as fixed model constraints during the marine resistivity data inversion.

Detailed groundwater levels are not available for most of the study areas. However, regional maps and data from nearby piezometers provide a general range of groundwater depths (Table 2). The shallowest groundwater is located along portions of the East Main Canal and East Highline Canal. Specific conductance readings of the drainage water adjacent to the East Highline canal have an average specific conductance of 1,519 µS/cm (Keller-Bliesner Engineering, 2007). It is expected that the groundwater in all of the survey areas has a significantly higher specific conductance than the canal water.

Table 2. Canal Conditions

Canal	Surface Conditions	Survey Direction (up-stream)	Canal Water Conductivity (µS/cm)	Canal Width (ft)	Canal Depth (ft)	Groundwater Depth (ft)
East Main	Sandy/Silty	S → N	1,020	20-50	2-6	4-8[a]
Central	Silty/Clayey	W → E	1,040	20-40	2-4 (estimated)	6-8[a]
Mohave	Silty/Clayey	S → N	1,000	10-40	1-4 (estimated)	14-18[b]
East Highline	Sandy	N → S	995 (south) 1,030 (north)	100-130	5-9	<5[c]
Gila	Sandy Gravel	S→ N	1,060 (south) 990 (north)	60-100	9-12	N/A
CRIT	Silty	S → N	800	6-40	2-6 (estimated)	6-11[d]

Sources: [a] Reclamation, 2008; [b] Reclamation, 2007; [c] Keller-Bliesner Engineering, 2007; [d] CRIT, 2007

Resistivity Data

The marine resistivity data were acquired along a total of 45.3 miles of canals and are of excellent quality with a high-degree of repeatability (Figure 3) and lateral continuity. The modeled conductivity cross-sections show a broad range in conductivity values (1-500 mS/m), indicating that there are significant variations in geology (clay, silt, and sand) and possibly groundwater that are influencing the measurements. In most cases, the conductivity values are influenced by more than one factor within the volume of materials measured. For example, variations in clay and moisture content of the alluvium will both affect conductivity values. Table 3 lists typical conductivity values that are characteristic of various materials encountered in the survey areas.

Table 3. Characteristic Conductivity Values

Material	Conductivity (mS/m)
Canal Water	80-100
Groundwater	>150
Sand and Gravel	<10
Wet Clay/Silt	50-100

Land Resistivity Measurement Locations

Conductivity anomalies representing a broad range of values within the marine data were selected for follow-up measurements with land-based resistivity measurements (Table 4). The results for each of the canals are discussed in the following sections.

Table 4. Land Resistivity Locations

Name	Canal	Section	Station (ft)	Lon (deg)	Lat (deg)	Conductivity from Marine Measurements
EMC-Land-1	East Main	A	7800	-114.6785222	32.5939084	High (~100 mS/m)
EMC-Land-2	East Main	D	3800	-114.6565474	32.6170710	Low (6-15 mS/m)
Mohave-Land-1	Mohave Lateral	A	750	-114.5344706	32.7728252	Very Low (2-10 mS/m) at depths of 10-30 feet
Mohave-Land-2	Mohave Lateral	H	300	-114.5173672	32.8148284	Mid-range values (40-60 mS/m)
EHC-Land-1	East Highline	A	3300	-115.2922536	32.9239232	Very High (100-500 mS/m)
EHC-Land-2	East Highline	E	6700	-115.2767350	32.7800946	Mid-range values (40-50 mS/m) to 45-foot depth
Gila-Land-1-West	Gila	D	2050	-114.4960596	32.7630234	Pockets of very low (<10 mS/m) in generally low area
Gila-Land-1-East	Gila	D	2050	-114.4956620	32.7629736	Pockets of very low (<10 mS/m) in generally low area
Gila-Land-2-West	Gila	F	9400	-114.4487262	32.8624478	Pockets of very high (100-500 mS/m) in generally high area
Gila-Land-2-East	Gila	F	9400	-114.4482456	32.8625864	Pockets of very high (100-500 mS/m) in generally high area
CRIT-Land-1	CRIT	B	1200	-114.3900946	33.9224254	Thin low (6-10 mS/m) above High (90-100) at depths > 20 feet
CRIT-Land-2	CRIT	F	500	-114.3947380	33.9386904	Low (4-10 mS/m) at depths < 20 feet

East Main and Central Canals

Marine Data

Figure 4 shows the locations of survey segments within the East Main and Central Canals (Yuma County Water Users). Figure 5 shows the average conductivity from the bottom of the canals to 10 feet below the bottom in plan-view. Conductivity cross-sections are presented in Figures 6 through 22.

The conductivity values range between approximately 4 and 200 mS/m with an average value of 52 mS/m below the canal bottoms. The thin upper layer of the models represents the canal water with an approximate conductivity of 100 mS/m. Sub-bottom zones of low-conductivity (<15 mS/m) are evident in Section D of the East Main Canal (Figure 10) and Sections A and B of the Central Canal. Thin, shallow areas of low-conductivity are also evident along portions of Sections C, E, and F of the Central Canal.

Shallow groundwater (< 6 feet) is indicated in the area of low conductivity measured within Section D of the East Main Canal (Reclamation, 2008). However, shallow groundwater is also indicated along Section A of the East Main Canal where there is relatively high conductivity (Figure 6). Also, relatively constant groundwater depths (eight feet) are mapped along the Central Canal where both low and high conductivity were measured. Therefore, groundwater depth variations along the East Main and Central Canals do not correlate with conductivity variations. This lack of correlation indicates that geologic variations (e.g. clay, silt, and sand) are likely the dominant factor in the conductivity measurements.

Land Data

Land resistivity measurements were obtained in both high and low conductivity areas (Figure 5). EMC-Land-1 is located within a broad conductivity high (>100 mS/m), while EMC-Land-2 is located within a broad conductivity low (<15 mS/m). The conductivity cross-sections for these land measurements are shown in Figures 23 and 24.

The conductivity values obtained at EMC-Land-1 (Figure 23) correlate well with the marine measurements at this location (Figure 7). A zone of high conductivity (>100 mS/m) lies at a depth of 10 to 30 feet below the canal road and extends up to the ground surface at field level. This high-conductivity zone correlates with fat clay identified in the well at this location with 99.4% fines reported in the sieve analysis (Reclamation, 2009).

Mohave Lateral

Marine Data

Figure 25 shows the locations of survey segments within the Mohave Lateral (Bard District). Figure 26 shows the average conductivity from the bottom of the canal to a 10 feet below the bottom in plan-view. Conductivity cross-sections are presented in Figures 27 through 29.

The conductivity values range between approximately 1 and 100 mS/m with an average value of 23 mS/m below the canal bottom. The upper layer consists of conductivity values in the 40 to 70 mS/m range extending to a depth of approximately 10 feet. Since the canal is shallow (1-4 feet), this layer likely represents an average of the canal water and sub-bottom materials with high clay content. A layer of low to very low (<10 mS/m) conductivity values are centered at depths of 10 to 30 feet within the cross-sections (Figures 27 to 29).

The Mohave Lateral has the lowest average conductivity of all the canals surveyed as part of this demonstration project. Groundwater maps indicate a greater depth to groundwater of 14 to 18 feet along this canal (Reclamation, 2007). The less-saturated conditions may be contributing to the lower overall conductivity values.

Land Data

Land resistivity measurements were obtained at two locations (Figure 26): Mohave-Land-1 in an area of very low conductivity (1-10 mS/m) and Mohave-Land-2 in an area of mid-range conductivity values (40-60 mS/m). The conductivity cross-sections for these land measurements are shown in Figures 30 and 31.

Mohave-Land-1 data indicate a zone of low conductivity (<10 mS/m) at a depth of 5 to 30 feet below the canal road and 5 to 15 feet below the field level (Figure 30). The land values are in general agreement with the marine data at this location (Figure 27), however, the low conductivity zone is thinner in the land cross-sections. In all cases, a layer of mid-range conductivity values extend from the surface to a depth of 5 to 10 feet. The upper layer of mid-range conductivity values correlate with clay observed on the surface. The clay overlies a zone of sand and gravel identified in the well at this location, which correlates with the low-conductivity zone.

Mohave-Land-2 data (Figure 31) indicate heterogeneous conditions in the upper 20 feet, with mid-range conductivity values that are in general agreement with the marine data at this location (Figure 29). The conductivity values at this location are higher than most of the survey line, indicating a transition into materials with higher clay content at the northern end of the survey line. This interpretation is supported by high fines reported in the sieve analysis at this location (Reclamation, 2009).

East Highline Canal

Marine Data

Figures 32 and 33 show the locations of survey segments within the East Highline Canal (Imperial District). Figures 34 and 35 show the average conductivity from the bottom of the canal to 10 feet below the bottom in plan-view. Conductivity cross-sections are presented in Figures 36 through 47.

The conductivity values range between approximately 30 and 500 mS/m with an average value of 83 mS/m below the canal bottom. The upper five to nine feet of the models represents the canal water with an approximate conductivity of 100 mS/m. Sub-bottom conductivity values are significantly higher in northern sections of the canal survey area (A, B, and C) compared with southern sections (D and E). In general, a layer with mid-range conductivity values of 30-60 mS/m lies below the bottom of the canal. This layer is variably thick and is generally thicker in the southern sections of the canal survey area. High to very high conductivity values (>>100 mS/m) underlie this layer in much of the northern sections of the canal survey area.

The East Highline Canal has the highest average conductivity of all the canals surveyed as part of this demonstration project. Recent studies have shown a very shallow depth to groundwater (<5 feet) in the immediate vicinity of the canal (Keller-Bliesner Engineering, 2007). Fluid conductivity measurements indicate significantly higher groundwater conductivity compared with the canal water in the northern survey area (Southwestern Exploration Services, LLC, 2009). It is likely that the high to very-high conductivity layer in the northern sections of the canal survey area is a result of the shallow groundwater.

Land Data

A high conductivity area (EHC-Land-1) and mid-range conductivity area (EHC-Land-2) were selected for land resistivity measurements (Figures 34 and 35). The conductivity cross-sections for these land measurements are shown in Figures 48 and 49.

EHC-Land-1 is located in an area of high to very high conductivity values in the marine data (Figure 36). However, the land cross-sections indicate more complex conditions, with both high and low conductivity areas at this location (Figure 48). A thin layer of high conductivity (>100 mS/m) is evident parallel to the canal from the surface to a depth of approximately 10 feet. This layer pinches out to the west and transitions to low conductivity. Below 10 feet, the conductivity cross-sections indicate a gradual transition from mid-range to high conductivity values with depth. The sieve analysis from a well at this location report sandy silt and clay with a high percentage of fines. It is likely that the high conductivity layer is responding to fines in the alluvium and groundwater conductivity.

EHC-Land-2 is located in an area of mid-range conductivity values in the marine data (Figure 47). Except for some near-surface heterogeneity, the land measurements correlate well with the marine data at this location (Figure 49). Fluid conductivity logs show similar values as the canal water and much lower values than at EHC-Land-1, which indicates that shallow groundwater is not a factor at this location (Southwestern Exploration Services, LLC, 2009). The mid-range conductivity values correlate with silty sand and clay with a high percentage of fines reported in the sieve analysis (Reclamation, 2009).

Gila Gravity Canal

Marine Data

Figures 50 and 51 show the locations of survey segments within the Gila Gravity Canal (GGMC Admin Board). Figures 52 and 53 show the average conductivity from the bottom of the canal to 10 feet below the bottom in plan-view. Conductivity cross-sections are presented in Figures 54 through 68.

The conductivity values range between approximately 2 and 500 mS/m with an average value of 39 mS/m below the canal bottom. The upper 9 to 12 feet of the models represents the canal water with an approximate conductivity of 100 mS/m. Sub-bottom pockets of low conductivity (<15 mS/m) are evident throughout the survey area, with the lowest values in portions of Section B (Figure 56), the northern portion of Section C (Figure 61) and southern portion of Section D (Figure 62). These zones of low conductivity extend from the canal bottom to the maximum depth of the models (45 feet) in many locations. Broad areas of high conductivity values with pockets of very high conductivity (>>100 mS/m) are located in the northern portion of Section F (Figures 67 and 68).

Land Data

Land resistivity measurements were obtained at two locations (Figure 53): Gila-Land-1 in an area of very low conductivity (2-15 mS/m) and Gila-Land-2 in an area of very high conductivity (100-500 mS/m). At Gila-Land-1, data were obtained along parallel and perpendicular lines on each side of the canal. At Gila-Land-2, data were obtained along parallel lines along each side of the canal (a perpendicular line could not be obtained at this location due to heavy vegetation). The conductivity cross-sections for these land measurements are shown in Figures 68 through 70.

Gila-Land-1 conductivity cross-sections on both sides of the canal indicate low conductivity values that extend to the ground surface at field level (Figures 68 and 69). The low conductivity values are in general agreement with the marine data

(Figure 61), however, the land data indicate mid-range conductivity values below 20 feet compared with low conductivity values in the marine data. Slightly lower conductivity values are evident on the eastern side of the canal compared with the western side. The low conductivity values correlate with sand and gravel observed at the surface and within the well at this location (Reclamation, 2009).

Gila-Land-2 conductivity cross-sections on both sides of the canal indicate a zone of low to mid-range conductivity values from the surface to a depth of 20 feet below the canal road (Figure 70). The low conductivity values in the upper 20 feet are likely due to the coarse-grained materials within the canal road. High to very high conductivity values are evident below a depth of 20 feet. The high conductivity areas correlate with the marine data at this location (Figure 67). The fluid conductivity log indicates very high fluid conductivity (Southwestern Exploration Services, 2009), which may be related to a groundwater contaminant plume in this area based on conversations with Reclamation personnel. Sieve analysis show silt and clay with a high percentage of fines (Reclamation, 2009). Therefore, the high-conductivity zone is likely due to a combination of fines in the alluvium and groundwater conductivity factors.

CRIT Canal

Marine Data

Figure 71 shows the locations of survey segments within the CRIT canal (Colorado River Indian Tribes). Figure 72 shows the average conductivity from the bottom of the canal to 10 feet below the bottom in plan-view. Conductivity cross-sections are presented in Figures 73 through 75.

The conductivity values range between approximately 4 and 200 mS/m with an average value of 38 mS/m below the canal bottom. The upper two to six feet of the models represents the canal water with an approximate conductivity of 80 mS/m. A thin layer of low conductivity (<15 mS/m) is evident in Sections A, B and F from the canal bottom to depths of approximately 20 feet. In a portion of Section B, the low conductivity layer overlies an area of high conductivity (90-100 mS/m). Sections C, D, and E show much less lateral variability than the other sections, and have mid-range conductivity values of 30-80 mS/m.

Land Data

Land resistivity measurements were obtained at two locations (Figure 72): CRIT-Land-1 in an area of low conductivity (6-15 mS/m) above high conductivity (90-100 mS/m) and CRIT-Land-2 in an area of low conductivity (4-15 mS/m) at depths less than 20 feet. The conductivity cross-sections for these land measurements are shown in Figures 76 and 77.

CRIT-Land-1 data indicate low to mid-range conductivity values, with the lowest values located in the field along the perpendicular survey line (Figure 76). The low conductivity zone extends to depths of 20 feet below field level and correlates well with the marine data at this location (Figure 73). The low-conductivity zone correlates with sand and a low percentage of fines (Reclamation, 2009). Below this zone, a layer of high conductivity is likely due to a combination of higher fluid conductivity (Southwestern Exploration Services, LLC, 2009) and clay (Reclamation, 2009).

CRIT-Land-2 data indicate a low conductivity layer from the field level ground surface to a depth of approximately 10 feet (Figure 77). These values correlate well with the marine data at this location (Figure 75) and with a low percentage of fines (Reclamation, 2009). Mid-range conductivity values underlie this layer to a depth of 45 feet, and correlate with silty-sand and a higher percentage of fines (Reclamation, 2009).

Correlation with Well Measurements

The geophysical logs and sieve analysis obtained at each well provide supporting evidence for the relationship between the conductivity values and alluvium composition. In order to quantify the correlation between surface geophysical data and well measurements, the conductivity models developed from land measurements were sampled at five-foot depth intervals at the locations of the wells. The correlations between the surface and downhole measurements are presented below.

Geophysical Logs

Geophysical logs were obtained in each of the wells and include natural gamma, dual-induction, fluid temperature and conductivity, resistivity, and neutron measurements (Southwest Exploration Services, LLC, 2009). The fluid conductivity and induction logs have the most significance for this study.

Fluid conductivity measurements in screened portions of the wells show conductivity values ranging between 820 and 10,870 µS/cm. Conductivity values in three of the wells are significantly above the conductivity of the canal water. These high fluid conductivity wells include EHC-1, Gila-2, and CRIT-1. Shallow groundwater is responsible for the elevated readings at EHC-1 and CRIT-1, while a possible groundwater contaminant plume is responsible for the elevated readings at Gila-2. Omitting the data from these three wells, the fluid conductivity values range between 860 and 1,610 µS/cm, which are values similar to the canal water conductivity (Table 2). The R^2 correlation coefficient between the fluid conductivity data and the conductivity models developed from land surface measurements is 0.03 after the data from the three high-conductivity well locations are removed from the analysis. Therefore, variations in fluid conductivity have little to no impact on the conductivity models, except at locations where high-conductivity groundwater or contaminants are within the measurement range of the resistivity survey (~45 feet).

At the three locations where high fluid conductivity is a factor, a sieve analysis shows that the alluvium contains silt and clay with a high percentage of fines. Therefore, we can infer that the canal water is contained within an impervious bottom or sub-bottom at these locations, allowing the high-conductivity groundwater to be in closer proximity to the canal.

The induction logs show variations in bulk conductivity that correlate well with the conductivity models developed from land surface measurements. The R^2 correlation coefficient between these two conductivity datasets is 0.74, which improves to 0.82 when the three high fluid conductivity wells are removed from the correlation analysis (Figure 78). Therefore, the conductivity models developed from the land surface measurements are consistent with measurements obtained in the wells. Variations from the linear correlation are due to differences in resolution and volume of measurement between the two methods.

The conductivity models have no apparent correlation with the natural gamma logs. The natural gamma logs should be representative of clay content, and, therefore correlate well with conductivity variations. However, the natural gamma logs show a high-degree of variability and different background values at the various well locations. Therefore, the natural gamma log may be impacted by other gamma emitters besides clay in the alluvial sediments.

Sieve Analysis

Reclamation obtained alluvium samples at selected intervals within each of the wells and provided a sieve analysis for each sample (Reclamation, 2009). The percentages of fines, defined as silt and clay passing through the 0.075 mm screen, were compared to the conductivity model values at the well locations (Figure 79). Data from the three wells where high fluid conductivity was measured (EHC-1, Gila-2, and CRIT-1) were omitted from the analysis.

The correlation between the percentage of fines in the alluvium and modeled conductivity values has a moderately high R^2 coefficient of 0.59 (Figure 79). Deviations from the linear correlation are due to a couple of factors:

- A group of five samples show relatively high conductivity values with a low percentage of fines (Figure 79). In each of these five samples, there is a high percentage of fine sand, one screen size larger than the fines cutoff of 0.075 mm. Therefore, it is likely that the relatively high conductivity is responding to higher fines content in the fine sand than represented by the discrete sample within this zone.

- Three samples with a high percentage of fines and high conductivity deviate from the linear correlation (Figure 79). In each of these cases, there is a large percentage of clay in the samples that likely has a non-linear relationship with conductivity.

The good correlation between the percentage of fines in the alluvium and the modeled conductivity indicate that the conductivity models can be used to identify areas of low fines content, which have a higher potential for seepage. The linear relationship developed from the geophysical data and sieve analysis is:

% Fines = (0.66) **s** ***+ 2.66;***

where **s** ***is the modeled conductivity in mS/m.***

For water-retaining embankments, soil is generally required to have 25% fines to be considered impervious (Reclamation, 2004). For canals, a conservative threshold of 12% is generally thought to be acceptable to prevent significant amounts of seepage (based on conversations with Reclamation personnel). This 12% threshold equates to approximately 15 mS/m in the correlation analysis. Conductivity values less than 15 mS/m are interpreted in the conductivity cross-sections as areas with less than 12% fines content.

Conclusions

The results of the marine and land resistivity surveys show a broad range of conductivity values (1-500 mS/m) from the surface to a depth of 45 feet. Based on a correlation with well data, the measurements are primarily influenced by grain size, with higher conductivity corresponding to a higher percentage of fines in the alluvium. Shallow, high-conductivity groundwater produces higher measured conductivity values at some locations, and reduces the measured effect of grain size variations. However, sieve analyses at these locations show alluvium with a high concentration of fines that appear to be sealing the canal water from the groundwater.

In order to assess the potential for seepage using the conductivity data, it is necessary to examine the data in relation to the canal bottom. A conductivity threshold of 15 mS/m or lower corresponds with a 12% or lower concentration of fines in the alluvium. Alluvium with a low concentration of fines (<12%) within 10 feet of the bottom is interpreted as having the highest potential for seepage. These areas comprise approximately 25% of the total survey area, based upon the conductivity data, and are listed in Table 5. However, not all of these areas may be currently problematic if alluvium with a sufficient concentration of fines seals the canal sides and bottom (e.g. Central Canal and Mohave Lateral).

Marine resistivity measurements show great promise for rapid assessment of seepage in unlined irrigation canals. The low-conductivity areas identified in the data can now be targeted for quantifying seepage rates and possibly installing canal lining to remediate seepage.

Table 5. Areas with High Seepage Potential Interpreted from Conductivity Data

Canal	Sections with <12% Fines within 10 feet of Canal Bottom	Conditions
East Main	D	Sandy conditions observed on surface and in well.
Central	A,B,C,E,F	Silty and clayey conditions observed at surface may be presently sealing these sections of the canal. However, low-conductivity zones (low concentration of fines) occur within 10 feet of canal bottom.
Mohave Lateral	A,B,C,D,E,F,G	Thin layer of clay (upper 10 feet) presently sealing the canal. However, low-conductivity zones correlating with sand and gravel occur within 10 feet of canal bottom.
East Highline	None	Mid-range to high conductivity values indicate high concentrations of fines in alluvium. Sections A and B show very high conductivity due to shallow groundwater. Silt and clay likely sealing the canal water from the groundwater at these locations.
Gila Gravity	B,C,D,E,F	Thick zones of low-conductivity correlate with sand and gravel.
CRIT	A,B,F	Thin zones of low-conductivity correlate with sand.

References

ASTM, 2005, Standard guide for using DC resistivity measurements for subsurface investigations, D6431-99 (2005), ASTM International, West Conshohocken, Pennsylvania.

Colorado River Indian Tribes (CRIT), 2007, Water data from Lateral 73 piezometers, CRIT Water Resources.

Davis, C.V., 1952, *Handbook of applied hydraulics*, 2nd edn, McGraw-Hill, New York.

Engelbert, P.J., Hotchkiss, R.H., and Kelly, W.E., 1997, Integrated remote sensing and geophysical techniques for locating canal seepage in Nebraska, Journal of Applied Geophysics, vol. 38, p. 143-154.

Houk, I.E.,1956, *Irrigation engineering Vol. 2 - Projects, conduits and structures*, Wiley, New York.

Irrigation Australia Limited (IAL), 2008, Techniques for identification and measurement, IAL website, http://www.irrigation.org.au/seepage/3_3_techniques.html

Keller-Bliesner Engineering, LLC, 2007, Canal seepage interception, Appendix G within the Imperial Irrigation District Efficiency Conservation Definite Plan, May 2007.

Southwestern Exploration Services, LLC, 2009, Geophysical logging field report, May 7, 2009.

U.S. Department of the Interior, Bureau of Reclamation (Reclamation), 2009, Sample gradation analysis, May 8, 2009.

U.S. Department of the Interior, Bureau of Reclamation (Reclamation), 2008, Depth to groundwater map, Yuma Project Valley Division

U.S. Department of the Interior, Bureau of Reclamation (Reclamation), 2007, Depth to groundwater map, Yuma Project Reservation Division, Bard and Indian Units

U.S. Department of the Interior, Bureau of Reclamation (Reclamation), 2004, Guidelines for performing foundation investigations for miscellaneous structures, October, 2004.

U.S. Bureau of Reclamation (USBR), 1965, *Irrigation operator's handbook* Vol. 1, Lecture notes, Bureau of Reclamation, Denver.

Watt, J. and Khan, S., 2007, The use of geophysics to model channel seepage, MODSIM 2007 International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, December 2007, pp. 1471-1477. ISBN : 978-0-9758400-4-7.

White, P.A., 1994, Electrode arrays for measuring groundwater flow direction and velocity, Geophysics, vol. 59, no. 2, p. 192-201.

List of Figures