Prepared in cooperation with the U.S. Army Corps of Engineers Sacramento District

Characterization of Major Lithologic Units Underlying the Lower American River Using Water-Borne Continuous Resistivity Profiling, Sacramento, California, June 2008

By Lyndsay B. Ball and Andrew P. Teeple

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Conversion Factors

SI to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
meter (m)	1.094	yard (yd)
	Area	
square kilometer (km^2)	247.1	acre
square meter (m^2)	10.76	square foot (ft^2)
hectare (ha)	0.003861	square mile (mi^2)
square kilometer (km^2)	0.3861	square mile (mi^2)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
°F=(1.8×°C)+32
Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:
°C=(°F-32)/1.8
Vertical coordinate information is referenced to the depth below water surface.
Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83)

Characterization of Major Lithologic Units Underlying the Lower American River Using Water-Borne Continuous Resistivity Profiling, Sacramento, California, June 2008

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Abstract

The levee system of the lower American River in Sacramento, California, is situated above a mixed lithology of alluvial deposits that range from clay to gravel. In addition, sand deposits related to hydraulic mining activities underlie the floodplain and are preferentially prone to scour during high-flow events. In contrast, sections of the American River channel have been observed to be scour resistant. In this study, the U.S. Geological Survey, in cooperation with the U.S. Army Corps of Engineers, explores the resistivity structure of the American River channel to characterize the extent and thickness of lithologic units that may impact the scour potential of the area. Likely lithologic structures are interpreted, but these interpretations are non-unique and cannot be directly related to scour potential. Additional geotechnical data would provide insightful data on the scour potential of certain lithologic units. Additional interpretation of the resistivity data with respect to these results may improve interpretations of lithology and scour potential throughout the American River channel and floodplain.

Resistivity data were collected in three profiles along the American River using a water-borne continuous resistivity profiling technique. After processing and modeling these data, inverted resistivity profiles were used to make interpretations about the extent and thickness of possible lithologic units. In general, an intermittent high-resistivity layer likely indicative of sand or gravel deposits extends to a depth of around 30 feet (9 meters) and is underlain by a consistent low-resistivity layer that likely indicates a high-clay content unit that extends below the depth of investigation (60 feet or 18 meters). Immediately upstream of the Watt Avenue Bridge, the high-resistivity layer is absent, and the low-resistivity layer extends to the surface where a scour-resistant layer has been previously observed in the river bed.

Introduction

The lower American River levee system is situated on Quaternary deposits of clay, silt, sand, and gravel as well as sand deposits derived from hydraulic mining activities (Asch and others, 2008). If located near the ground surface, these sand deposits have the potential to preferentially scour during flood events and may threaten the integrity of the levee system. To identify areas of high scour potential, it is important to understand not only the extent of these sand deposits but also the extent and thickness of scour-resistant layers that may limit the river's access to these deposits. To assist the U.S. Army Corps of Engineers (USACE) with the management of the lower American River levee system, the U.S. Geological Survey (USGS) has used a series of geophysical techniques to improve our understanding of the geology of the American River floodplain and channel. In 2007, the USGS collected frequency-domain electromagnetic, capacitively coupled resistivity, and direct-current (DC) resistivity data on the right-bank floodplain (with respect to the downstream direction of flow) to identify sand deposits preferentially prone to scour (Asch and others, 2008). In this study, water-borne DC resistivity data were collected to characterize potentially scour-resistant units within and below the American River channel.

The surface geology of the lower American River channel and floodplain is dominated by Holocene stream channel and alluvial deposits that are absent in some locations and may reach up to 80 feet (ft) (24 meters (m)) in thickness (Helley and Harwood, 1985). The upper member of the Pleistocene Modesto Formation, mapped in the southern floodplain of the study area, consists of unconsolidated, unweathered gravel, silt, sand, and clay and is generally considered to be topographically higher than the Holocene deposits in the area (Helley and Harwood, 1985). The Modesto Formation has been identified by the U.S. Army Corps of Engineers as a potentially scour-resistant unit that they suspect underlies parts of the American River. Several electrically conductive layers (approximately 50 ohm-meters (ohm-m)) identified and interpreted by Asch and others (2008) likely indicate a high-clay content unit that may in some places represent this suspected scour-resistant layer. In this study, the collection of geophysical data was extended into the American River channel using a water-borne continuous DC resistivity profiling (CRP) technique. A 5-mile (mi) (8 kilometer (km)) long stretch of the American River, from the Campus Commons Golf Course (about 3,000 ft or 0.9 km north of the H Street Bridge) to the Rio Americano High School (about 1.5 mi or 2.4 km east of the Watt Avenue Bridge) was targeted for characterization (fig. 1). The study area extent is similar to that of work completed by USGS along the north bank of the river in the summer of 2007 (Asch and others, 2008).

This report presents the methods and techniques used in this study. Results are presented, including a characterization of the extent and thickness of possible lithologic units underlying the investigated stretch of the lower American River that may potentially be scour resistant.

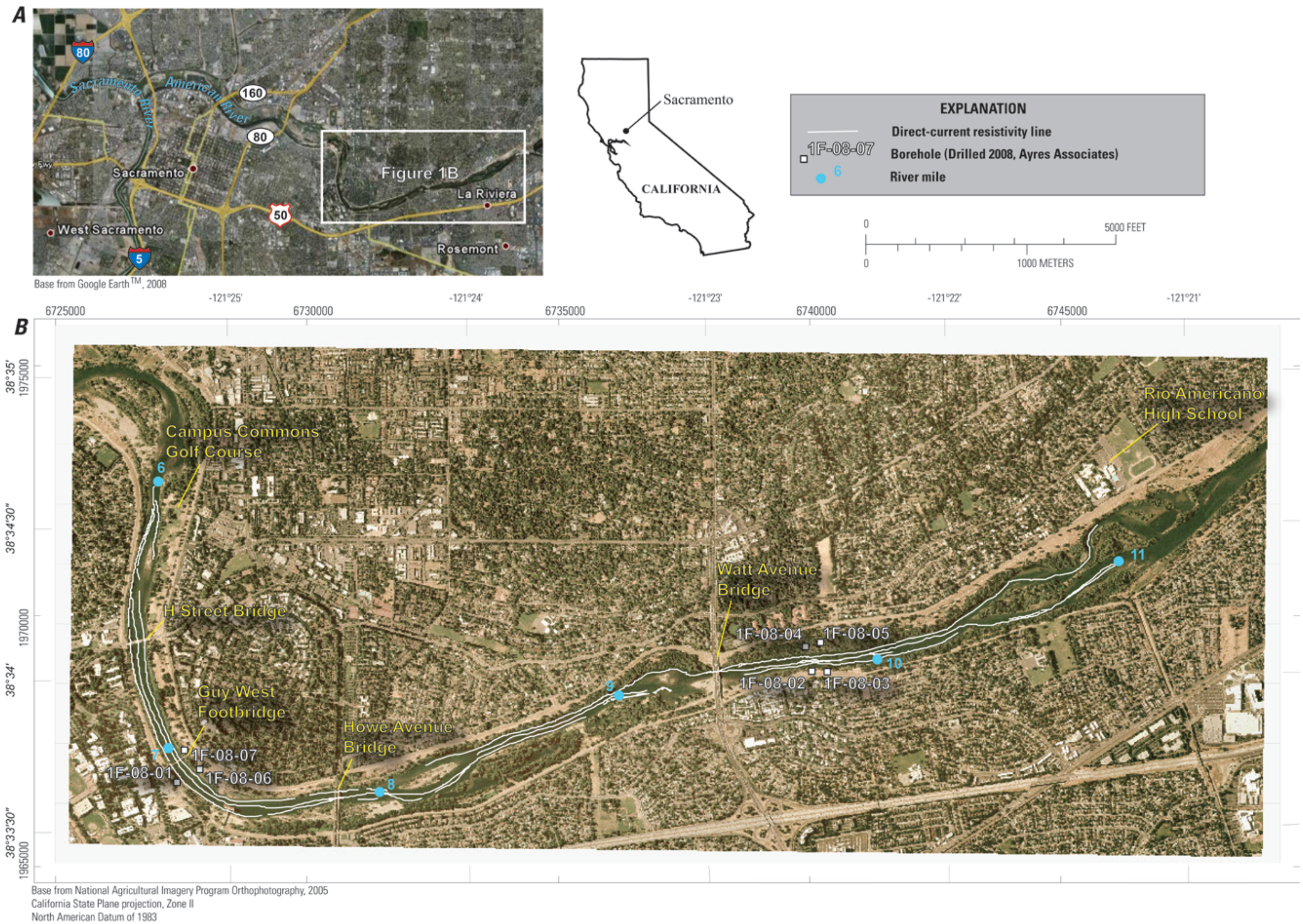

Figure 1. *A*, the study area with respect to the city of Sacramento and *B*, direct-current resistivity lines on the lower American River.

Acknowledgments

This work was funded through cooperation with the USACE Sacramento District. We gratefully acknowledge Ayres Associates for their support throughout this study, and we specially thank Bill Spitz, Tom Smith, and Adrian Aguilar for providing and operating the boat. Many thanks to Ginny McGuire and Jeff Lucius (USGS) and Nate Bradley (University of Colorado at Boulder) for lending their computer-programming talents to the data-processing effort; their work has made substantial contributions to the consistency and timeliness of these results.

Methods

Continuous Resistivity Profiling

Direct-current resistivity measurements are made by transmitting a known current through two current electrodes and measuring the electrical potential across two other electrodes; the resistance is calculated by dividing the measured voltage by the applied current using Ohm's Law. By multiplying the resistance by a geometric factor derived from the relative position of the current and potential electrodes, the apparent resistivity of the subsurface is calculated. Apparent resistivity is the electrical resistivity over an equivalent electrically homogeneous and isotropic subsurface and is used to represent the average resistivity of a more realistic, heterogeneous subsurface (Loke, 2000). Deeper apparent resistivity values may be calculated by increasing the distance between electrodes. Through inverse modeling of multiple apparent resistivity measurements, likely heterogeneous electrical structures can be identified and used for lithologic interpretation. The inverse-modeling procedure is explained in more detail in the following subsection.

The water-borne CRP technique, a specialized application of the DC resistivity method, was used to identify major lithologic units underlying the lower American River. Advanced resistivity meters with multiple data channels allow multiple potential measurements to be taken simultaneously with a single current transmission. By using an array of electrodes with various spacings, a vertical resistivity profile can be simultaneously developed. When the electrodes are placed in water, electrical contact is maintained without driving electrodes into the ground. Data are collected while the array is slowly pulled behind a boat through the water. CRP allows rapid collection of resistivity data with high horizontal resolution and in areas that could otherwise be logistically difficult to survey, such as below rivers. A more detailed explanation of the resistivity method can be found in Zohdy and others (1974). Further discussion of the water-borne CRP technique can be found in Ball and others (2006).

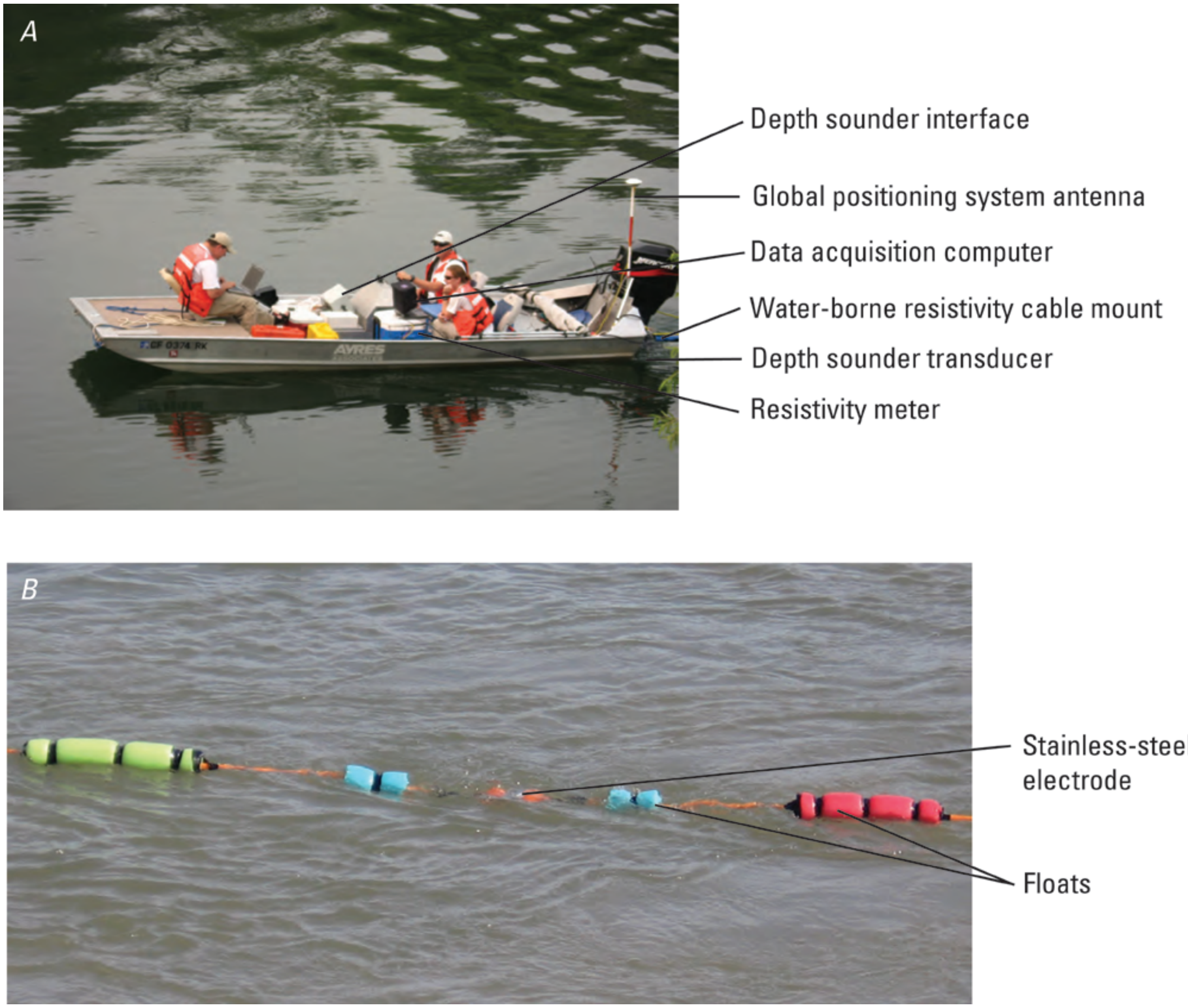

Figure 2. *A*, water-borne resistivity and auxiliary equipment set up on the boat (T. Smith, Ayres Associates) and *B*, the water-borne resistivity cable (L. Ball, U.S. Geological Survey).

Resistivity data were collected between June 24 and June 26, 2008, in three transects (right bank, center channel, and left bank) along the lower American River (fig. 1) with the Syscal Pro DC resistivity meter (IRIS Instruments, Orleans, France). A floating, 13-electrode cable was towed behind a boat (fig. 2). Geographic positioning data were collected using a DSM-232 decimeter horizontal accuracy global positioning system (GPS) (Trimble, Sunnyvale, California) with dual-frequency antenna and OmniStar HP real-time correction service (OmniStar, Inc, Houston, Texas). Bathymetric data were collected using a 455XPe single-frequency depth sounder (Innerspace Technologies, Carlstadt, New Jersey) with decimeter resolution. Changes in water-surface elevation were monitored through regular checks of GPS elevation. However, inconsistencies in elevation (greater than 3 ft or 1 m) were found to be unacceptable and therefore were not used to correct the elevation of the final data.

Bathymetric control provided by the depth sounder vertically references every data point to the river bed. The water-surface elevation is referenced to NGVD29 through bathymetric correlation between this survey and the 2006 Ayres Associates thlaweg profiles at River Mile 6 and 11, both locations showing less than 3 ft (1 m) of vertical movement between 1987 and 2006 (Ayres Associates, 2008). A linear trend along the line distance is used between those two mile markers to provide an approximated water-surface elevation. Relative water-level changes were monitored at the Howe Avenue boat ramp and found to be negligible throughout the day, with the largest change, a water-level drop of 0.2 ft (6 cm), occurring between June 25th and June 26th. Water-temperature and conductivity data were collected three times throughout the survey using an Orion Model 122 field conductivity meter (Orion Research Inc., Boston, Massachusetts) and were consistently found to be about 54 microsiemens per centimeter (μS/cm) at 17°C, or 164 ohm-m.

The resistivity cable used in this study was designed to define the thickness and depth of electrically contrasting layers up to a total depth threshold of 60 ft (18 m). To maximize the depth of investigation while maintaining the resolution of shallow layers that may represent thin (6 ft or about 2 m thick), scour-resistant lithologic units, an inverse Schlumberger array was used with shorter distances between electrodes towards the center of the cable (table 1, fig. 3). Forward models were developed using RES1DINV (Geotomo Software, Panang, Malaysia) with a series of electrical structures representing various water depths and conductive-layer thicknesses to optimize the cable design. The final electrode array positions are listed in table 1 and the cable schematic is illustrated in figure 3.

Several steps that are not common to more traditional land-based DC resistivity surveys are necessary to prepare CRP data for inversion and interpretation. Because the geometric factor used to calculate apparent resistivity from the measured resistance is dependent on a consistent distance between electrodes, it is necessary for the resistivity cable to remain relatively straight throughout data collection. However, changes in water-flow direction and surface velocity can drag and bend the cable in ways that violate the assumption of consistent electrode spacing. Careful attention was paid to the position of the cable throughout the survey, and locations where electrode spacing could not be maintained were removed during data processing.

Table 1. Water-borne resistivity cable schematic

[C, current electrode; P, potential electrode]

Distance (feet)[1]	Electrode
49	P11
102	P9
154	P7
180	P5
207	P3
220	P1
231	C1
241	C2
253	P2
266	P4
292	P6
318	P8
371	P10

[1] Represents the distance from the beginning of the cable, not the distance from the boat.

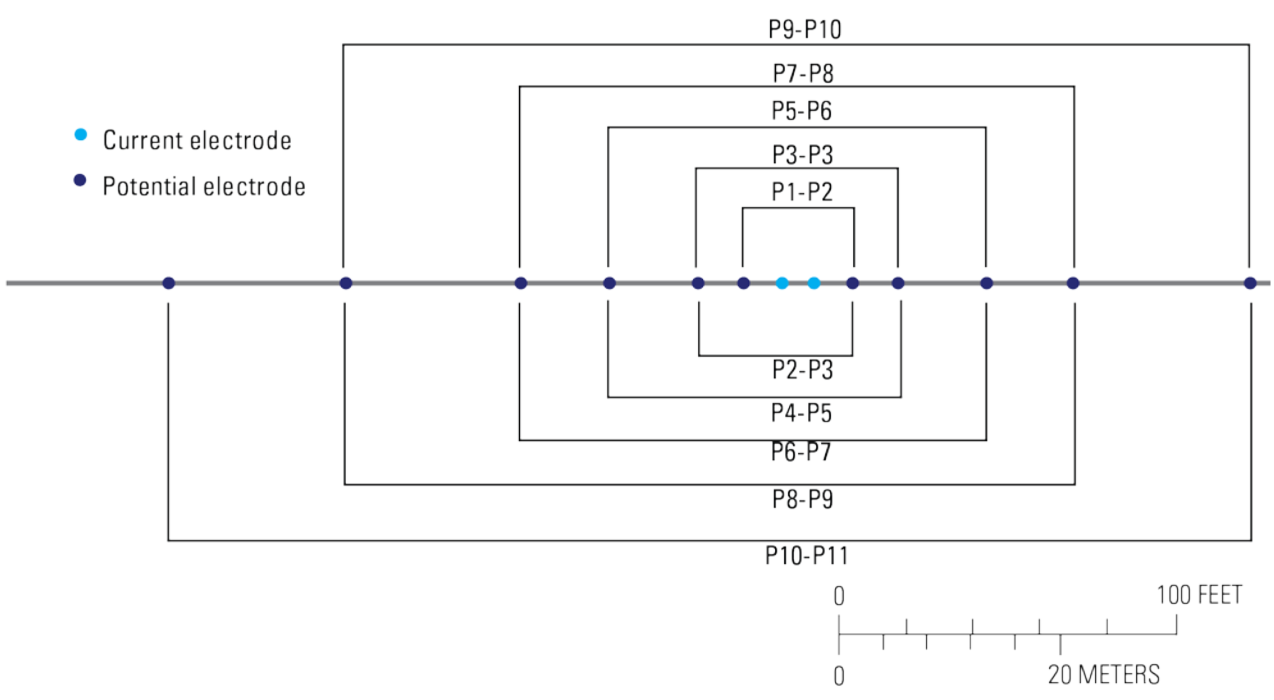

Figure 3. Schematic diagram showing electrode geometry of the water-borne resistivity cable. Brackets indicate the potential-electrode pair used in each measurement for the adapted inverse Schlumberger array, numbered in order of increasing depth penetration.

To be useful for mapping lithologic layers, resistivity data must be matched with accurate spatial-positioning data. Because the GPS and depth sounder are located in the boat while the resistivity data are approximately located at the center of the electrode array, a spatial offset was applied to each measurement that is equivalent to the distance to the center of the array from the GPS antenna mount; on average this offset is 67.5 m. Because the GPS is located in the boat, the first several tens of meters of every collection event, or line, lack spatial and bathymetric data. For some lines, the end of a previous line may provide an overlapping boat track that can be used to manually replace these data; however, river conditions (shallow water, navigation hazards, recreational use, and so forth) did not always allow lines to overlap and resulted in small gaps in survey coverage between individual collection lines. In addition, bathymetric data were smoothed using a combination of non-linear and low-pass filters to minimize the influence of small changes (less than 1-m wide) on the resistivity inversion results.

Two-Dimensional Inverse Modeling

To help determine the probable heterogeneous distribution of electrical resistivity from apparent resistivity measurements, a numerical inverse-modeling process is used. Data were inverted using a two-dimensional (2-D) finite-element least-squares approximation through EarthImager 2-D version 2.2.9 (Advanced Geosciences, Inc., Austin, Tex.). A starting model consisting of rectangular blocks of individual resistivity values was developed using a combination of the average measured apparent resistivity values and a priori knowledge of the electrical structure, including water depth and conductivity data. The inversion program determined the calculated system response over that model, referred to as the “calculated apparent resistivity,” on the basis of the field data-collection parameters. The root-mean-square (RMS) error between the measured and calculated apparent resistivity sections was used to determine the appropriateness of the model. The inversion program then iteratively reduced the RMS error by altering the model resistivity values and recalculating the apparent resistivity. When the RMS error between the calculated and measured apparent resistivity no longer improved between iterations by more than 1 percent of the total RMS error or a total of 8 iterations were completed, a solution was reached. The final inverse model represents a non-unique estimate of the probable distribution of electrical resistivity within the subsurface. This inversion process is described in detail by Loke (2004); inversion parameters used in this study are provided in table 2.

Because CRP data are collected while moving, individual lines of data can be several kilometers in length. A full 2-D inversion of such long lines is computationally expensive, time consuming, and unnecessary given the relatively small electrode array over which measurements are made. Long lines of field data were divided into 300-m (984-ft) segments with 60 percent overlap between segments to minimize inversion time. These segments were rejoined into a single line at the end of the inversion process. This approach occasionally results in a segmented appearance in the final displayed profiles. While in some lines this is visually noticeable, it is typically cosmetic and does not affect the overall geologic interpretation. Following inversion, data were reunited with their original geographic coordinates and water-depth data for visualization.

Table 2. Summary of inversion parameters used in processing water-borne resistivity data.

[Min., minimum; Max., maximum; mV, millivolt; ohm-m, ohm-meter; %, percent]

Parameter	Setting used
Inversion method	Robust
Robust data conditioner	1
Robust model conditioner	1
Mesh thickness incremental factor	1.1
Depth factor	1.1
Min. voltage accepted (mV)	0.2
Min. resistance accepted (ohm)	0.0001
Min. apparent resistivity accepted (ohm-m)	1
Max. apparent resistivity accepted (ohm-m)	1000
Rough conditioner	0.2
Max. number of iterations	8
Max. RMS model error (%)	3
Starting model (below riverbed) (ohm-m)	Average section apparent resistivity
Water-column resistivity (ohm-m)	164
Damping factor	100
Horizontal/vertical roughness ratio	0.1
Lagrange multiplier	100

Geophysical Characterization of Major Lithologic Units

The inverted resistivity profiles reveal a variety of resistivity features ranging from 25 to 1,000 ohm-m, shown on a linear color scale ranging between 50 to 500 ohm-m in figure 4. There is consistently a low-resistivity layer (less than 100 ohm-m) in the bottom of half of the profile, from about 30 to 60 ft (9 to 18 m) below the water surface. This low-resistivity layer is likely indicative of a high-clay-content layer. Also consistent throughout the study area is a moderate-resistivity layer (about 150 ohm-m) that represents the water column and correlates well to the bathymetric data. There are more variations in the resistivity structure of the upper 30 ft (9 m) below the river bed, which we discuss in sections from downstream to upstream, as labeled in figure 4. A consistent color scale is used throughout this study and has been chosen to represent interpreted low-resistivity features as blue, moderate-resistivity features as cyan, green, and yellow, and high-resistivity features as red.

While distinct contrasts in resistivity were resolved by these data, the lithologic source of these contrasts cannot be known with certainty without more geotechnical data, such as coring in the river. In the following discussion, we interpret likely lithologic structures, but these interpretations are non-unique and cannot be directly related to scour potential. Results from erodibility studies being performed by Ayres Associates (T. Smith, Ayres Associates, oral commun., June 2008) on recently cored boreholes may provide insightful data on the scour potential of certain lithologic units. Additional interpretation of the resistivity data presented here and in Asch and others (2008) with respect to these results may improve interpretations of lithology and scour potential throughout the American River channel and floodplain.

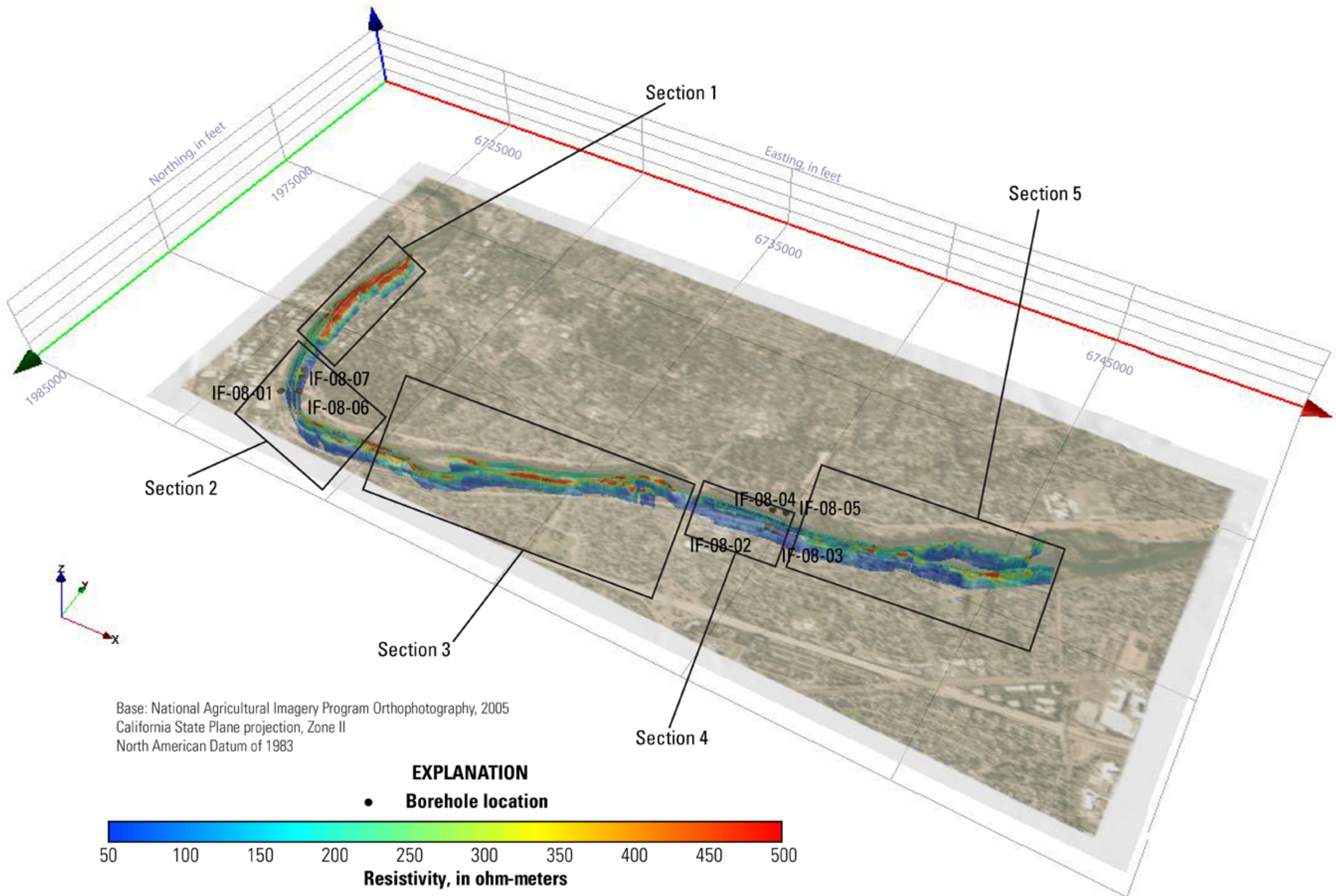

Figure 4. Three-dimensional map, looking down on the study area to the Northwest, showing inverted resistivity profiles below the partially transparent aerial photography. Delineated sections indicate areas of similar resistivity structure.

Section 1

Section 1 is the farthest downstream section, beginning at the Campus Commons Golf Course and extending to about 1,000 ft (300 m) south of the H Street Bridge. This section is characterized by a high-resistivity layer (greater than 500 ohm-m) to an average depth of about 30 ft (9 m), underlain by a low-resistivity layer (plate 1). This structure may represent a low clay-content unit, such as a sand and gravel layer, overlying a unit of higher clay content that extends below the depth of investigation. This structure is generally consistent and seen in the left-bank, center, and right-bank profiles.

Section 2

Section 2 extends from about 1,000 ft (300 m) south of the H Street Bridge to immediately west of the Howe Avenue Bridge. This section is characterized by an extensive low-resistivity layer that extends from about 10 to 20 ft (3 to 6 m) depth to below the depth of investigation (plate 2). Immediately above this layer, we see inconsistent moderate- to high-resistivity layers that generally extend to the riverbed. These layers are generally thinner and lower in resistivity value than the upper layer in Section 1. This structure may represent a sand and gravel unit immediately above a higher clay content unit. Borehole logs that exist for this floodplain near this area (Tom Smith, Ayres Associates, written commun., August 2008) indicate substantial clay units at depth, intermixed with some sand and silt units—these log data generally support this interpretation.

Section 3

Section 3 extends from just west of the Howe Avenue Bridge to the Watt Avenue Bridge. This section is characterized by an intermittent high-resistivity layer that, when present, is between 15 and 35 ft (4.5 to 10.5 m) in depth (plate 3). The remainder of the section is dominated by low-resistivity features similar to those seen in other sections. This structure may represent intermittent sand and gravel deposits overlying a higher clay content unit.

Section 4

Section 4 begins at the Watt Avenue Bridge and extends east for about 3,500 ft (1.6 km). In this section, the low-resistivity layer occurs immediately below the river bed (plate 4). The river here is quite shallow and the river bed comprises a unit that has shown increased stability in repeated bathymetric surveys between 1987 and 2006 (Ayres Associates, 2008). This layer may be continuous within the depth of investigation. However, there are some small increases in resistivity in the subsurface that may indicate a slight reduction in clay content or coarsening of material at 10 to 25 ft (3 to 7.5 m) depth, noted by the transition from deep blue to cyan on the resistivity color scale. Borehole logs indicate that there are substantial sandy silt layers that exist below clay units in the floodplain. This small increase in resistivity may indicate that these sandy silt layers also exist below the river.

Section 5

Section 5 extends from 3,500 ft (1.6 km) east of the Watt Avenue Bridge to the upstream portion of the study area near the Rio Americano High School (plate 5). This section is similar in resistivity structure to section 2, with intermittent moderate to high resistivity features at the surface extending to inconsistent depths between 10 and 30 ft (3 to 6 m), and infrequently these moderate resistivity features extend to nearly 60 ft (18 m). Below this, a low-resistivity layer similar to that seen throughout the study area extends below the depth of investigation. This resistivity structure may represent intermittent sand and gravel deposits above a higher clay content unit.

Conclusions

The American River in Sacramento, California, is situated above a mixed geology of alluvial deposits that range from clay to gravel. Sand deposits related to historic hydraulic mining activities underlie the floodplain and are preferentially prone to scour during high-water events. In contrast, sections of the American River channel have been observed to be scour resistant. In order to understand how floods may impact the integrity of the levee system, an improved understanding of the geology is required. In this investigation, the USGS explored the resistivity structure of the American River channel to characterize the extent and thickness of lithologic units that may impact the scour potential of the area.

Resistivity data were collected in three profiles along the American River using a water-borne continuous resistivity profiling technique. After processing and modeling these data, inverted resistivity profiles were used to make interpretations about the extent and thickness of possible lithologic layers. In general, an intermittent high-resistivity layer extends to a depth of up to 30 ft (9 m). This layer is underlain by a consistent low-resistivity layer that likely indicates a high-clay content unit that extends below the depth of investigation of 60 ft (18 m). The high-resistivity layer is completely absent immediately upstream of the Watt Avenue Bridge, and the low-resistivity layer extends to the surface where a scour-resistant unit has been observed in the river bed. Additional boring data may improve the lithologic interpretations presented in this report, and results of ongoing erodibility analyses would allow for more robust interpretation of scour potential to be made.

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