Imaging Beneath Hanford's Tank Farms with Electrical Resistivity Geophysics – An Innovative Approach

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ABSTRACT

An electrical resistivity geophysical survey was conducted in and around the T tank farm at the Hanford Site. The geophysical survey was deployed in two methods to identify soils that are electrically conductive from waste introduced through planned and unplanned releases. The first method relied on the traditional use of surface electrodes arranged along linear transects. This method was highly successful outside the tank footprint and over the cribs and trenches on the periphery of the farm. The surface resistivity data showed low resistivity anomalies directly beneath these waste disposal areas. The second deployment strategy relied on using site infrastructure for transmitting current and conducting the voltage measurements. Wells, which penetrate below the metal pipes and tanks that caused the unsuccessful surface deployment inside the farm, were very successful at imaging low resistivity anomalies that were likely caused from the leaking tanks. In particular, tank T106 showed a large area of affected soil, which matches hydrological expectations and borehole data obtained from the area. Overall, the method proves valuable in imaging parts of the subsurface previously not possible with other approaches.

INTRODUCTION

The Hanford Site in eastern Washington is home to 177 underground storage tanks, which contain approximately 1.9×10^8 Ci in 2×10^5 m^3 of waste in a viscous liquid, sludge, and salt cake waste form [1]. The tanks were in use from 1943 to 1986 to store a fraction of the waste generated during the processing of approximately 110,000 tons of uranium in one of nine reactors and the reprocessing of 74 tons of plutonium in one of five chemical plants [2]. The tanks are organized into tank farms; there are 18 tank farms on the Hanford Site.

There are two types of tanks on the Hanford Site: single-shelled tanks (SSTs) and double-shelled tanks (DSTs). The SSTs were in use from 1943 to 1964 and vary in size from 208 m^3 to 4400 m^3. Of the 149 SSTs, 67 have been confirmed or assumed to have leaked, with approximately 3800

m^3 of liquid released to the soil. To reduce the leak potential, DSTs were used from 1964 to 1986. There are no known or assumed leaks from the DSTs.

The Department of Energy is currently managing the waste in the SSTs by moving it to safer locations and eventually into a more secure waste form. Waste retrieval is a difficult process due to the engineering problems posed by the varied tank waste forms and the health and safety risks associated with workers. Waste retrieval methods vary by the amount of sludge and integrity of the tank. If, for example, the tank is structurally sound, the waste can be retrieved by a rapid and inexpensive method of high pressure jets and pumps. If, on the other hand, the tank is of questionable integrity, a more time consuming and expensive vacuum retrieval system in combination with a mobile retrieval system must be used [1]. On the Hanford Site, the more expensive retrieval system must be used on the 67 questionable tanks without regard to volume leaked or confirmation of leak.

A system that could potentially verify the leaking status of a tank could reduce retrieval costs by millions of dollars for each tank. Currently, a series of steel-cased wells, that surround each of the tanks, is used to monitor for potential tank leaks. Most wells terminate in the vadose zone, above the water table. Gross gamma and spectral gamma logging tools have been applied in the tank farms to measure the content of gamma-emitting radionuclides. Neutron logging has also been used to determine the water content of the surrounding soil. The limitations of well logging with these tools include the small volume of soil measured by the logging devices, and the frequency by which the measurements are acquired. The neutron moisture logging, under very dry conditions, can image outward from the well less than one meter. As the soil moisture increases, the volume decreases significantly. The spectral gamma logging tool has an even smaller detection radius. Additionally, these tools may take up to one day to fully image a single well. With typically over 60 wells per farm and the limited volume that is interrogated, a full characterization of a tank farm could preclude the method as a means of finding a new leak in a timely manner.

The limitations associated with dry well monitoring prompted the search for a more sensitive characterization technique that could be deployed within the tank farms without installation of additional subsurface infrastructure. Prior electrical resistivity surveys conducted on neighboring Hanford sites, had demonstrated the ability to render a three-dimensional image showing the distribution of electrical resistivity, an electrical property that describe the resistance of current flow through a medium. The electrical resistivity method is well suited for the Hanford Site, given the electrically resistive soil and the very conductive liquid waste. Additionally, after set up, the imaging of an entire farm using the wells could be less than one day.

A trial of an electrical resistivity geophysical method was conducted at the T tank farm. The method was applied in the traditional sense, where small "surface electrodes" were temporarily installed on the ground surface, and nontraditionally by using existing site infrastructure as electrodes. The objective of the geophysical surveying was to demonstrate that the electrical resistivity method could be applied to the tank farms as a method for mapping tank waste leaked to the subsurface despite the electrically complex environment.

RESEARCH SITE

The T tank farm is in the northern portion of the 200 West Area near the T Plant (Figure 1) and is surrounded by a number of cribs and trenches. The T tank farm was constructed between 1943 and 1944 and first received waste from T Plant. The tanks were filled to capacity soon after they entered service. Due to limited tank storage capacity, liquid waste from the T tank farm was discharged to the surrounding cribs and trenches. Most of the cribs and all of the trenches received waste directly from the SSTs as overflow [3].

The T tank farm consists of twelve 100-series SSTs, four 200-series SSTs, waste transfer lines, and tank ancillary equipment. The 100-series SSTs are 23m in diameter and 9m tall. The four 200-series SSTs are 6.1m in diameter and approximately 8 meters tall. As noted in Figure 1, 7 of the 16 SSTs in T tank farm are designated as assumed or confirmed leakers [4,5], which are shaded in the diagram. The 200-series SSTs are thought to be of high integrity.

The results of field investigation and historical characterization activities have been used to develop a conceptual model for the nature and extent of contamination in the vadose zone beneath the T tank farm. Myers [4] identifies two major contamination zones in the T tank farm. These include waste losses near tanks T-106 and T-103 and waste losses near tank T-101. A detailed listing of the leak events and subsequent investigations is provided in Table I. Two sources of information are listed to demonstrate the uncertainty in the estimated leak volumes.

The following generalizations are intended to provide an overview of the contaminant plumes from the two major contamination sources within the T tank farm:

- The contamination zone near tanks T-106 and T-103 results from the combined effects of an estimated 435,000L leak from tank T-106 and an 11,400L transfer line leak from tank T-103. The contaminant plume from these sources is estimated to be approximately 76 meters (250 feet) in diameter centered near the southeast quadrant of tank T-106 and extending to a depth of approximately 27 to 30 meters (90 to 100 feet) below ground surface.
- Historical process records indicate that waste losses from tank T-101 were the result of overfilling the tank in 1969 by as much as 38,000 liters (10,000 gallons) [6]. Based on historical data and spectral gamma data, the contaminant plume from the tank T-101 leak extends to a depth of approximately 36.6 meters (120 feet) below ground surface and has migrated in a southerly direction. Groundwater monitoring data collected around the T tank farm indicate that some contamination has reached the unconfined aquifer.
- Several recent (fiscal years 2004 through 2006) drilling and sampling activities within WMA T have further characterized inorganic contamination in the vadose zone. These include wells C4104 and C4105 near tank T-106 and wells 299-W11-25B, 299-W11-41, 299-W11-45, and 299-W11-47 outside the fence surrounding the farm. Figure 2 shows the

concentration of inorganics that comprise the bulk of the waste as well as soil moisture as a function of depth. In general, the sulfate and nitrate concentrations are highest close to waste management facilities.

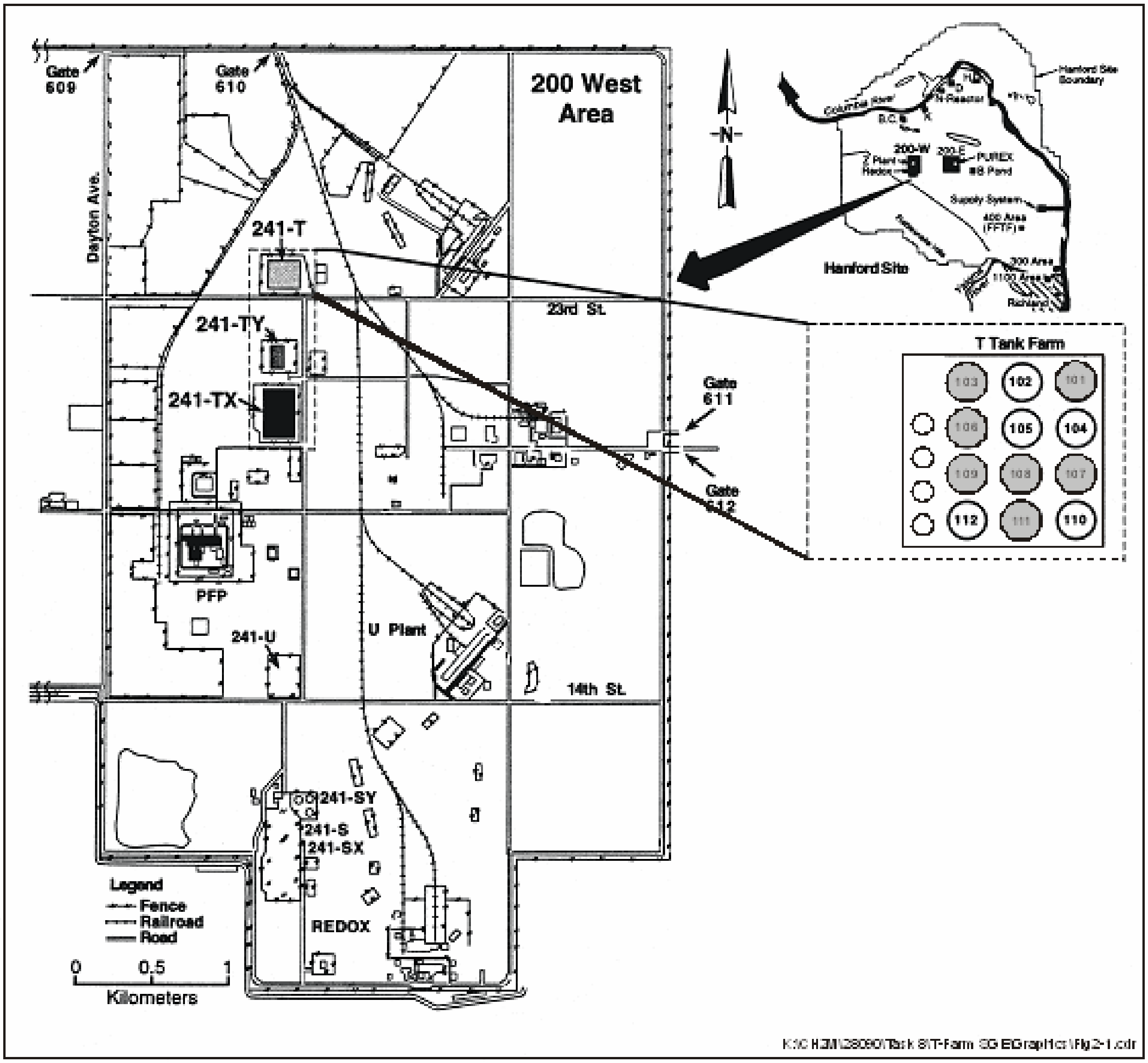

Figure 1. Location of the T Tank Farm in the 200 West Area of Hanford [6].

Table I. T Tank Farm Tanks Classified as Assumed/Confirmed Leakers and Estimated Leak Volumes.

Tank	RPP-23405 [9]		HNF-EP-0182 [4]	
	Estimated Leak Volume (gallons)	**Estimated Leak Date**	**Estimated Leak Volume (gallons)**	**Estimated Leak Date**
T-101	10,000	1969	7,500	1992
T-103	3,000	1973	<1,000	1974
T-106	115,000	1973	115,000	1973
T-107	–[a]	1984	–[b]	1984
T-108	1,000	1974	<1,000	1974
T-109	1,000	1974	<1,000	1974
T-111	1,000	1971	<1,000	1979, 1994

Notes:

[a] This tank is classified as an assumed leaker, although no liquid level decreases were observed for any of these tanks. RPP-23405 concludes that, in general, vadose zone activity near these tanks is negligible and does not support a volume inventory.

[b] Based on 19 tanks with the assumption that the cumulative leak volume was 150,000 gallons from these tanks for an average volume of 8,000 gallons for each of the 19 tanks.

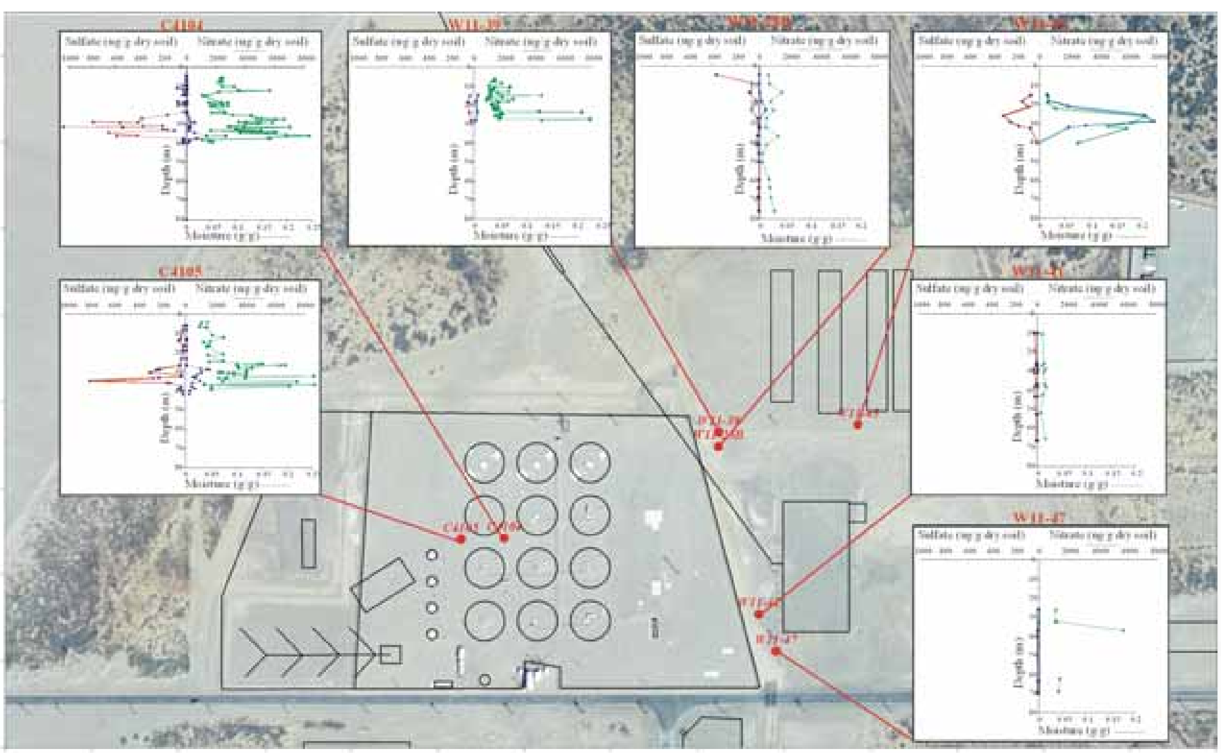

Figure 2. Nitrate and Sodium Concentrations around T Tank Farm [10].

THEORY

The resistivity method is based on the capacity of earth materials to resist electrical current. Earth resistivity is a function of soil type, porosity, moisture, and dissolved salts. The concept behind applying the resistivity method is to detect and map changes or distortions in an imposed electrical field due to heterogeneities in the subsurface.

Resistivity (ρ) is a volumetric property measured in ohm-meters that describes the resistance of current flow within a medium. The inverse, conductivity (σ) in Seimens/meter, describes the ease by which current will flow through a medium. Electric current can be propagated in rocks and minerals in one of three ways: electronic (ohmic), electrolytic, and dielectric conduction. The first way occurs in metals, where free electrons give rise to direct conduction of current. Rocks and non-metallic minerals have extremely high resistivities (low conductivities) and direct current transmission through this material is difficult. Porous media, on the other hand, carries current through ions, which is the second type of current propagation (electrolytic). Electrolytic conduction relies on the molecules within a pore space to have excess or deficiency of electrons. Here, the conduction varies with the mobility, concentration, and degree of dissociation of ions. Electrolytic conduction is relatively slow with respect to ohmic conduction due to the reliance on a physical transport of material resulting in chemical transformation [11]. The last type of propagation is dielectric conduction, which takes place in poor conductors or insulators. Dielectric conduction occurs under the influence of an externally applied alternating electric field, where atomic electrons are displaced slightly with respect to their nuclei.

In the field, the electric current may be generated by battery or motor-generator driven equipment, depending on the particular application and the amount of power required. Current is introduced into the ground through metal rods, called electrodes. Earth-to-electrode coupling is typically enhanced by pouring water around the electrodes. The electrodes are placed along linear transects, called survey lines, and provide points for both current transmission and voltage potential measurements.

Estimating resistivity is not a direct process. When current (I) is applied and voltage (V) measured, Ohms law is assumed. Resistance (R) in units of ohms can be calculated:

$$R = \frac{V}{I} \qquad \text{(Eq. 1)}$$

Resistivity and resistance are then related through a geometric factor over which the measurement is made. The simplest example is a solid cylinder (e.g. wire) with a cross sectional area of A and length, L:

$$\rho = R\frac{A}{L} \qquad \text{(Eq. 2)}$$

Hence, resistivity can be calculated by knowing the voltage, current, and geometry over which the measurement is made. In the earth, a hemispherical geometry exists. The hemispherical geometry is referred to as a half-space, due to the fact that all current applied at the surface travels into the ground; above the ground, air has an infinite resistivity.

Field data are acquired using an electrode array. A four-electrode array employs electric current injected into the earth through one pair of electrodes (transmitting dipole) and the resultant voltage potential is measured by the other pair (receiving dipole). The most common configurations are pole-pole, dipole-dipole, Wenner and Schlumberger arrays. Their use depends upon site conditions and the information desired. Readers are referred to geophysical texts [11] for a description of the array types.

METHODS

Two deployment methods of electrical resistivity geophysics were tested in the T tank farm. The first method involved the use of surface electrodes placed along linear transects to obtain profiles of the subsurface. The electrodes were used to transmit current and read the resultant voltage potential. The data are presented as two-dimensional profiles. A total of 27 transects were used to cover the T tank farm and the surrounding cribs and trenches. Figure 3 shows the layout of the surface resistivity survey which included 12 survey line-kilometers, with electrodes spaced every 3m over a 57-acre area.

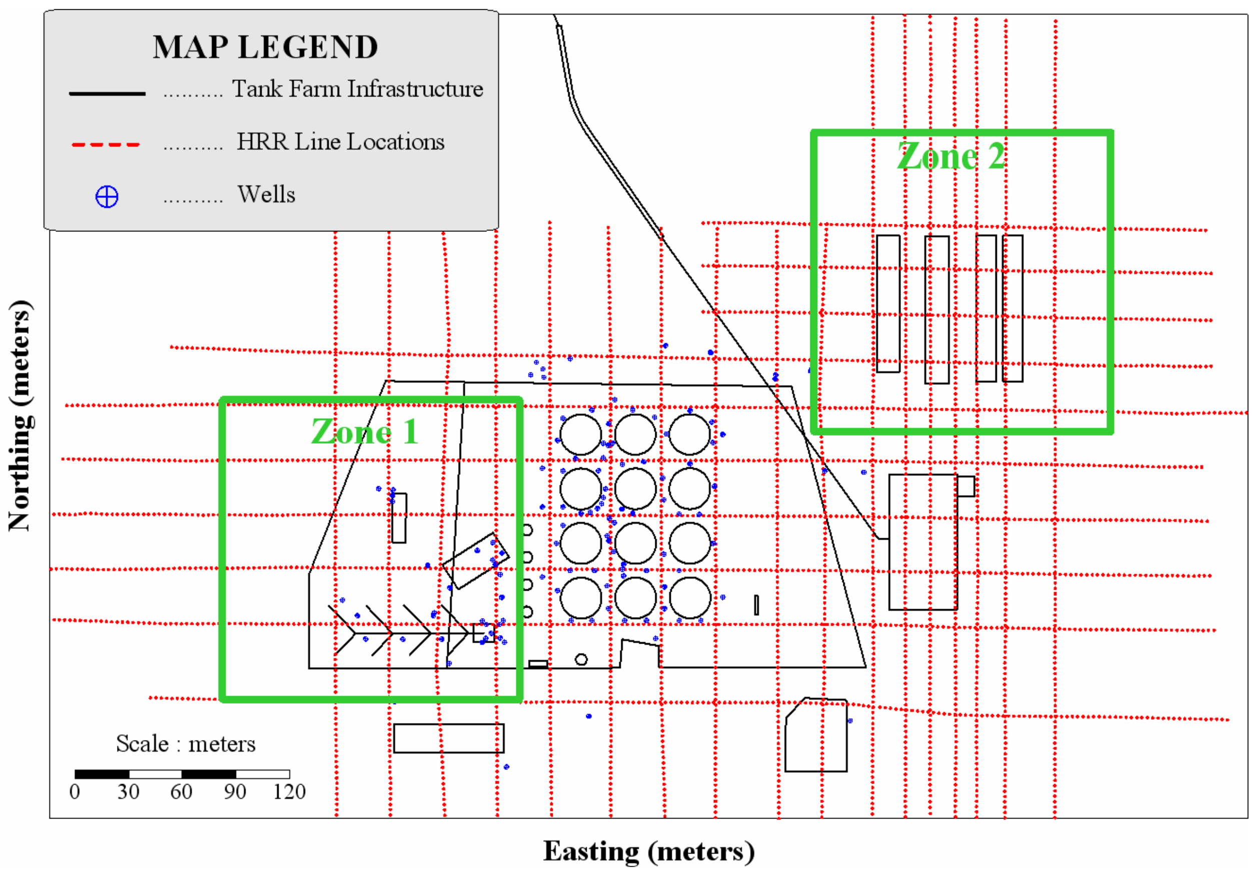

Figure 3. Layout of the geophysical survey for the T tank farm. Red lines indicate locations of the pole-pole resistivity (HRR) survey lines and the blue dots represent wells used for resistivity surveying.

The measured voltage dataset obtained from the surface electrodes was modeled with an inversion algorithm to reproduce the spatial distribution of electrical resistivity. The resulting electrical resistivity distribution is used to interpret zones of high moisture or inorganic contamination. Equation 3 shows the mathematical model used for the modeling, which is based on the continuity equation:

$$\frac{\partial}{\partial x}\left(\frac{1}{\rho}\frac{\partial V}{\partial x}\right)+\frac{\partial}{\partial z}\left(\frac{1}{\rho}\frac{\partial V}{\partial z}\right)+I=0\,. \qquad \text{(Eq. 3)}$$

Inversion minimizes the difference between the modeled and measured voltage by iteratively solving the forward solution presented in Eq. 3. In each iteration, the subsurface distribution of electrical resistivity is logically changed such that the error between modeled and measured voltage is minimized. Several methods of inversion are presented in [12 ,13, 14]. For the modeling in this study, the code EarthImager3D [15] was used, and is based on the methodology of Labrecque [14]. The code can accommodate relatively large datasets and works well with the instrumentation used to collect the resistivity data, namely the SuperSing R8.

The surface electrical resistivity through the farm was of limited value, due to the large amounts of subsurface metallic infrastructure. The conductors included metallic infrastructure, transfer pipes, diversion boxes, fences, and the tanks. Therefore, the surface resistivity was relegated to the periphery of the farm, where the infrastructure was at a minimum. Figure 3 shows two zones, where the application of surface resistivity was successful. These zones coincide with discharge trenches and cribs, where approximately 1.5×10^5 m^3 of liquid waste was released to the ground. In particular, zone 1 received 97.5% of the total volume.

The large amount of infrastructure also prompted the second deployment methodology, which included using the existing infrastructure as transmitting and receiving electrodes. For this study, the infrastructure was limited to the drywells and groundwater wells, but previous investigations have also included the tanks [16]. The major difference between using the surface electrodes and the wells is the geometry of the electrodes. The typical electrode used in the surface electrical resistivity method is a cylindrical stake that penetrates no more than 29 centimeters (11.5 inches) into the ground. The stake is modeled as a point in space. A well is a very long stake (over 7m and up to 80m at T tank farm) that must be modeled as a line source or an equivalent mathematical representation in the model.

The wells were represented as a linear set of electrically conductive cells. Typically, dry sand in the Hanford Formation can be between 2500 to 10,000 ohm-m. Moist sand and sand with inorganic constituents can be as low as 1 ohm-m. The conductive cells of the wells were represented by values of 0.001 ohm-m. The very low resistivity allowed the current flux be constant along the length of the well. It has been demonstrated [10] that the modeling of the wells as linear conductors adequately represents the voltage field when compared to the analytical solution of a linear source.

Figure 3 shows the locations of wells around the T tank farm used in the modeling. A total of 110 wells were used for the measurements, divided into 17 groundwater wells and 93 wells completed in the vadose zone (and including drywells). The groundwater wells were primarily located on the periphery of the farm. The advantage of incorporating the wells in the measurement is that much of the electrode-to-ground contact exists bellow the metallic infrastructure level. This means that a large portion of the current avoids the metallic infrastructure thereby facilitating imaging of the soils directly. The major disadvantages are that the well locations may not be ideal or of sufficient density and the information obtained from the inversion has no vertical resolution. The target anomaly could be located anywhere along the length of the well and oriented in almost any direction and give a very similar voltage response. To represent the inversion results appropriately, a plan map of the distribution of electrical properties are typically shown. The plan map shows the footprint of low resistivity areas that could be linked to the high moisture or inorganic constituents.

RESULTS

The resistivity inversion results can be seen in Figure 4. Figure 4A shows the distribution of the low resistivity values in zones 1 and 2. The figure is a three-dimensional view from above, looking towards the northeast. Two resistivity values are shown, representing 0-60 ohm-m and 60-120 ohm-m. The smaller value of resistivity is a solid model rendering, while the larger value of resistivity is transparent to allow a direct viewing of the smaller values. The trenches, cribs, tanks, and the fence are also displayed on the plot for reference and sizing.

The distribution of electrical resistivity in zone 1 implies that the plume has migrated downward and westerly, with some north-south migration as well. A large volume of liquid waste was discharged in these cribs over a short time period. The high mass flux rate would likely have caused vertical migration of the plume. Interpretation of the inversion modeling show the plume represented by the 60 ohm-m value is located approximately 60m below ground surface. The depth of the 120 ohm-m plume is approximately 90m. The inversion results suggest that the plume has reached the water table located 72m below ground surface. Nitrate, sulfate, and other analytes have been measured in the groundwater near this region, which confirms the presence of the plume.

In zone 2, the resistivity anomalies marked by both 60 and 120 ohm-m are smaller than that seen in zone 1. The large plume extends down to a depth of approximately 60m and the inner plume extends to a depth of 40m below ground surface. As in zone 1, the plume shows a general migration towards the west, with much of the concentration directly below the T-16 trench and less below trenches T-14, T-15, and T-17. Inventory records [17] indicate that all of the trenches received approximately the same volume. However, the resistivity data suggest that the T-16 trench may have received slightly more waste than the others.

The results of resistivity measurements inside the tank farm can be seen in Figure 4B. These results were obtained by inverting the resistivity data collected using the wells and is referred to as well-to-well (WTW) inversion. In the figure, three resistivity values are represented. The smaller value of 0-7 ohm-m is indicative of soils with higher moisture or higher ionic strength from the inorganic constituents. As the resistivity value increases, the degree of moisture or inorganic concentration decreases.

Around the 100-series tanks, the lowest resistivity value appears to be near or migrated from tanks T-101, T-103, and T-106 which matches the records of known leaky tanks. The resistivity distribution around T-106, in particular, shows a large footprint of low values migrating towards the southwest. Several borehole logs concentrated in this area of the tank confirm the presence of nitrate, sodium, and sulfate which are the likely contributors to the resistivity anomaly. In addition to the main sources of leaks identified from Figure 1, there also appears to be low resistivity anomaly near tanks T-110 and T-112. These tanks were not identified as having leaked.

The second area of interest in Figure 4B is the low resistivity values near the 200-series tanks and the cribs on the western side of the tank farm. The resistivity anomaly around the cribs obtained from the WTW inversion matches the distribution from the surface resistivity data in Figure 4A. The plot also reveals some low values near the 200-series tanks. These tanks have been traditionally considered as non-leakers, and the resistivity anomaly beneath this area is surprising. The anomaly could have originated from the nearby cribs. Further ground truthing is need to confirm their integrity status.

CONCLUSION

An electrical resistivity survey was conducted in the T tank farm on the Hanford Site. The method aims to produce a three-dimensional distribution of electrical properties that can be linked to zones of high moisture or high inorganic concentration. Given the electrically resistive nature of the sands and silts comprising the Hanford Formation, electrically conductive salts originating from tanks and waste disposal cribs and trenches are excellent targets for the method. Additionally, the method is capable of imaging down to the water table, located approximately 72m below ground surface at the T tank farm.

Due to the complex nature of the tank farm, two deployment strategies of the resistivity method were tested. The first relied on the traditional use of surface electrodes placed along linear transects and oriented orthogonally to ensure complete coverage. The transects covered both tank areas and nearby disposal cribs and totaled approximately 12 line-kilometers. Surface resistivity was successful outside the tank farm fence over the cribs and trenches. The method was highly successful outside the farm, but was not successful through the farm. The failure was likely the result of near-surface metallic infrastructure used to transport waste from the T Plant. The metal is more electrically conductive than the waste, thereby channeling current preferentially away from the contaminated soil.

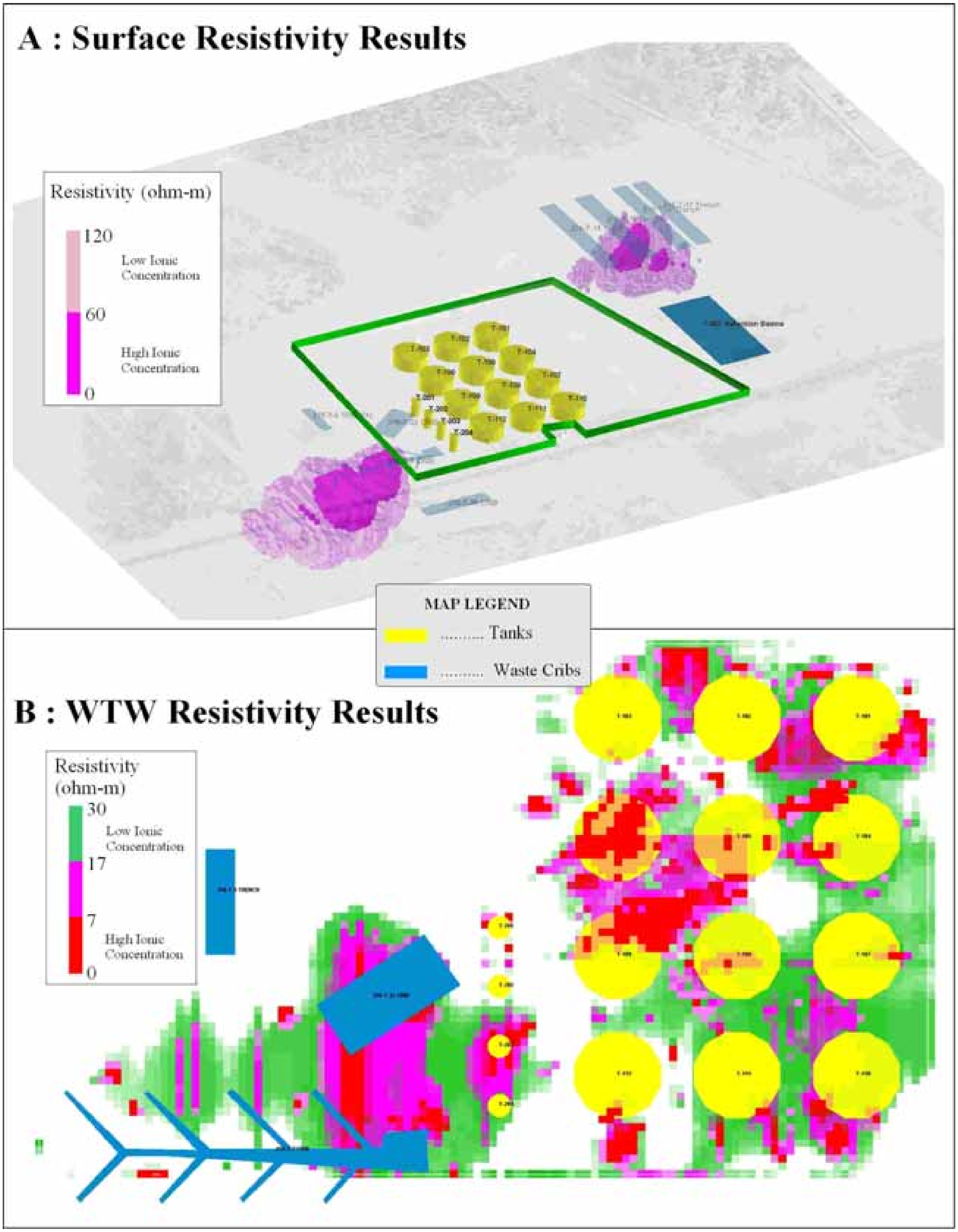

Figure 4. A) The distribution of electrical resistivity from the surface data in zones 1 and 2. B) Resistivity results for the well-to-well (WTW) geometry.

The results of the surface resistivity data over the cribs showed areas of low resistivity that can be linked to past waste disposal activities. In the area over the western cribs, where approximately 1.35×10^5 m^3 of liquid waste was disposed, a large volume of soil has been affected by the waste. From the modeling, it appears that the waste has reached the water table, which can be corroborated by groundwater monitoring data.

The second deployment method used the wells within and around the tanks to map the distribution of resistivity. The wells allowed the electrical current to penetrate below the infrastructure. The direct use of site infrastructure in the resistivity measurements proved to be successful. Locations of low resistivity matched hydrologic expectations of known tank leak locations. Additionally, the method confirmed the low resistivity interpretations from the surface resistivity method over the western cribs. Lastly, the distribution of low resistivity values may have identified other areas of concern around tanks that have been previously thought of as non-leakers. These include tanks T-110 and T-112. A corroboration of other techniques capable of measuring electrical properties should be used to confirm the model results, including electromagnetic induction. These other techniques could, in theory, be used together with the DC resistivity data to help constrain the inverse model and add vertical resolution to the resistivity anomaly. At the very least, the method can help site borehole locations for a follow up comprehensive characterization through drilling.

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