The BC Cribs and Trenches Geophysical Characterization Project: One Step Forward in Hanford’s Cleanup Process

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ABSTRACT

A geophysical characterization project was conducted at the BC Cribs and Trenches Area, located south of 200 East at the Hanford Site. The area consists of 26 waste disposal trenches and cribs, which received approximately 30 million gallons of liquid waste from the uranium recovery process and the ferrocyanide processes associated with wastes generated by reprocessing nuclear fuel. Waste discharges to BC Cribs contributed perhaps the largest liquid fraction of contaminants to the ground in the 200 Areas. The site also includes possibly the largest inventory of Tc-99 ever disposed to the soil at Hanford with an estimated quantity of 400 Ci. Other waste constituents included high volumes of nitrate and U-238.

The geophysical characterization at the 50-acre site primarily included high-resolution resistivity (HRR). The resistivity technique is a non-invasive method by which electrical resistivity data are collected along linear transects, and data are presented as continuous profiles of subsurface electrical properties. The transects ranged in size from about 400-700 meters and provided information down to depths of 60 meters. The site was characterized by a network of 51 HRR lines with a total of approximately 19.7 line kilometers of data collected parallel and perpendicular to the trenches and cribs. The data were compiled to form a three-dimensional representation of low resistivity values. Low resistivity, or high conductivity, is indicative of high ionic strength soil and porewater resulting from the migration of nitrate and other inorganic constituents through the vadose zone. High spatial density soil data from a single borehole, that included coincident nitrate concentrations, electrical conductivity, and Tc-99, were used to transform the electrical resistivity data into a nitrate plume. The plume was shown to extend laterally beyond the original boundaries of the waste site and, in one area, to depths that exceeded the characterization strategy. It is unknown whether the plume reached the water table, located approximately 104 meters below ground surface.

INTRODUCTION

Planned and unplanned radiological releases have occurred to the subsurface within the vadose zone at the Hanford Site in Eastern Washington. Several of these releases have resulted in contamination of the local groundwater, which subsequently discharges to the Columbia River. One of the planned releases occurred at the BC Cribs and Trenches area, a 50-Acre disposal site located south of the 200 East Area (see Fig. 1). The site contains 20 unlined trenches ranging in length from about 30m to 170m and 6 cribs. Within the time period from 1956 to 1958, approximately 30 Mgal of mixed liquid waste (radiological and hazardous waste) was discharged to the trenches and cribs. The design concept behind the trenches and cribs was one that would retain the radiological constituents by the subsurface sediments through ion exchange. The concept is referred to as specific retention.

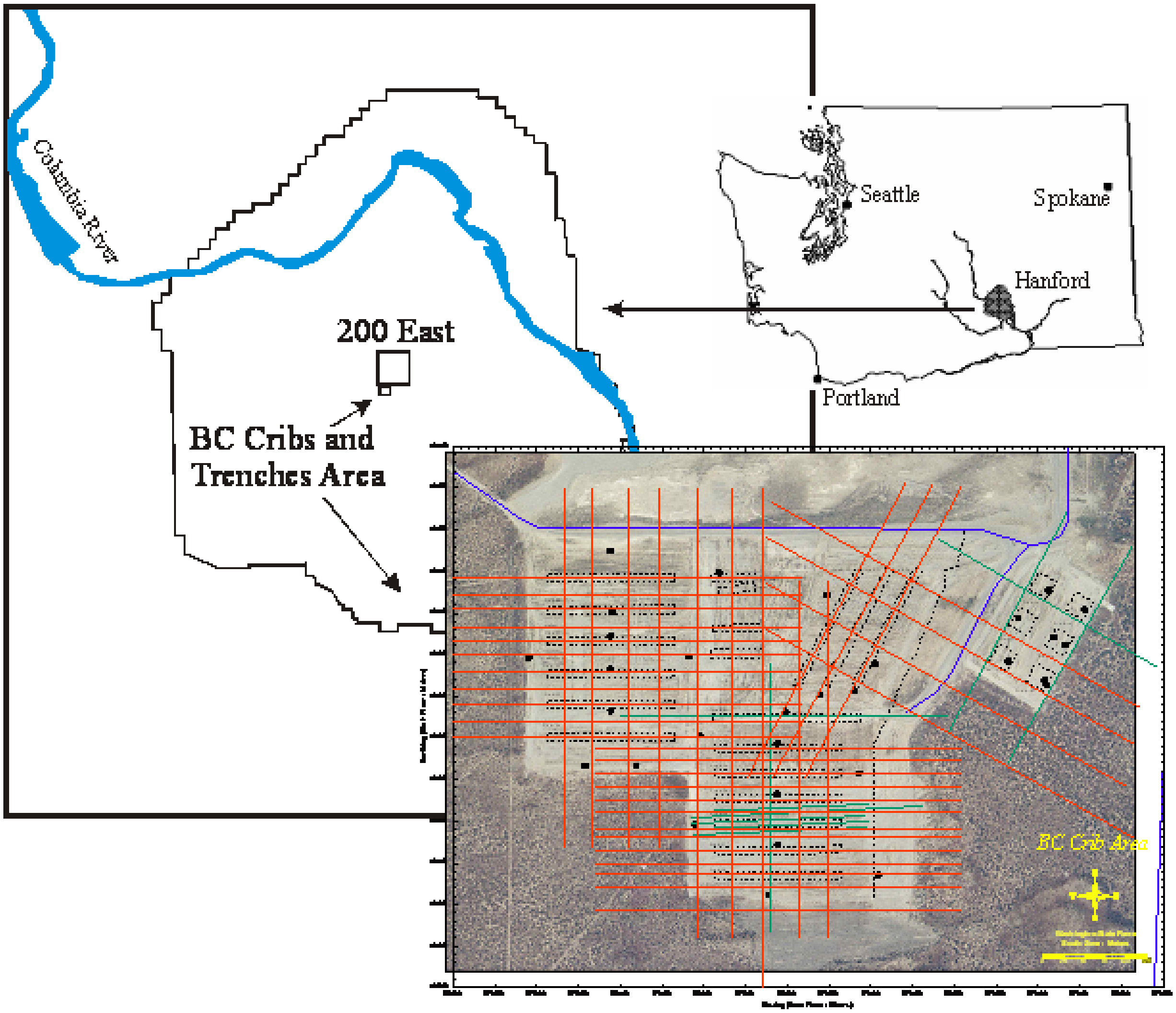

Fig. 1. BC Cribs and trenches site location, south of 200 east

Since disposal, several previous borehole geophysical studies (spectral gamma logs) were completed at the BC Cribs and Trenches area [1,2,3] to ascertain the effectiveness of the trenches to adhere to the provisions of specific retention. The studies were aimed at quantifying the vertical migration of several radiological constituents of the waste including Cs-137, Co-60, Sb-125, and Eu-154. The studies showed that no significant vertical migration had occurred for these specific constituents during the period of 1977 to 1999 [2]. One radiological constituent of particular concern, that was not analyzed in these borehole geophysical studies, was Tc-99. The heptavalent state of Tc-99, pertechnetate (TcO_4^-), presents a number of challenges due to its long half-life (213,000 yrs) and its high rate of mobility [4].

Recently, borehole core samples taken from the center of one of the disposal trenches [5] has confirmed the presence of Tc-99 at a depth ranging from 25 to 44m below ground surface with a maximum concentration of 1.6×10^6 pCi/L. Additionally, it was found that high concentrations of chlorides, nitrates, and sulfates were coincident with Tc-99. Addition of these other analytes provides a target suitable for HRR imaging.

Based on the borehole results, it did not appear that contamination had reached the water table. Lateral migration of the Tc-99 plume is postulated as a likely explanation for the limited vertical distribution. For lateral migration to occur, anisotropic hydraulic properties must exist, where alternating layers of coarse and fine-grained sediments preferentially direct the contaminated liquid away from the source zone. To test the lateral migration hypothesis, a rigorous field mapping procedure needed to be employed to ensure sufficient coverage of the area. The field procedure should be deployed from the surface due to the considerable expense of drilling in a highly contaminated area. Additionally, the technique must be accurate enough to identify specific depths of concern.

High Resolution Resistivity (HRR) is a surface geo-electrical technique capable of measuring changes in electrical properties of the subsurface with high accuracy. The anions, along with radiological and heavy metals, form a solution that has a higher ionic strength than the associated host material. The contrast in electrical properties of the subsurface due to the ionic strength of disposed effluent provides an excellent target for HRR. This study, therefore, used HRR to map the extent to which a nitrate plume may have migrated laterally over the time period since disposal. The work presented here is a continuation of the paper by Rucker et al. [6], that includes a much larger sample area and a more complete survey.

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 ( ) is a volumetric property measured in ohm-meters that describes the resistance of current flow within a medium. It's 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 [7]. 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 electrodes (metal rods). Earth-to-electrode coupling is typically enhanced by pouring water around the electrodes. The electrodes are placed along linear transects 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 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 dipole-dipole, Wenner and Schlumberger arrays. Their use depends upon site conditions and the information desired.

Since the earth property of resistivity is the desired product, an inverse calculation (or inverse model) is needed to convert the measured voltage potential to resistivity. Inversion refers to the operation of estimating earth parameters, given the measured potential, input current, and boundary conditions. The inverse calculation assumes that each measurement of potential was a result of a homogeneous earth:

$$\rho_a = 2\pi \frac{V}{I} K \qquad \text{(Eq. 3)}$$

where K is the geometric factor accounting for the half-space of the earth. Other assumptions used in Equation 3 is isotropy (i.e., no directional dependence of resistivity) no displacement currents (using a DC or low frequency current application), and the resistivity is constant throughout, such that Laplace’s equation can be assumed. Since the degree of heterogeneity is not known *a priori*, a true resistivity is not calculated. To obtain a true resistivity, tomography is required, which generates a model of true resistivity given the measurements of apparent resistivity, electrode arrangement, and other boundary conditions.

For the work on the Hanford Site, we used a pole-pole array to collect high resolution resistivity (HRR) data. For the pole-pole array, one electrode from each of the current and potential pairs is fixed effectively at infinity, while the other current and potential electrodes act as “rover” electrodes. Practically, the infinite electrodes are spaced approximately 2 to 10 times the distance of the furthest separation of the rover electrodes, which can be up to 200 meters apart. The pole-pole array provides higher data density, increased signal to noise ratio, and requires less transmitted energy. Roy and Apparao [8] discuss the superiority of the pole-pole method when conducting shallow (near-surface) surveys.

The calculation of apparent resistivity is simplified in the pole-pole array:

$$\rho_a = 2\pi \frac{V}{I} (n * a) \qquad \text{(Eq. 4)}$$

where *a* is the basic electrode spacing and *n* is the integer multiplier as the current and potential electrodes incrementally separate. The geophysical survey at the BC Cribs site included a fixed a-spacing of 3 meters and n increased from 1 to 27. For a complete survey, each electrode has one turn at transmission, while potential measurements occurs at all other electrodes in the array.

The linear transect arrangement produces a two-dimensional data set of resistivity as a function of x and z, where z is the dimension into the earth and x is along the surface. Although resistivity is a function of the volume over which the measurement is made, its location is typically plotted as a point for ease of representation. The location of the point is a function of n and is referred to as the depth of investigation. Hallof [9] demonstrated that the intersection of two 45^0 lines (with respect to the surface) extending downward from each of the transmission and receiving electrodes would produce a suitable pseudosection for interpretation. In this fashion, the pole-pole array has depths plotted at:

$$z = 0.5na\ , \qquad \text{(Eq. 5)}$$

which is a linear plotting method. For HRR, the location of n is a function of the maximum sensitivity of signal, which decreases as a logarithmic function as n increases. Once z is determined, the two-dimensional data set can then be presented as a contour plot, where isopachs of equivalent values are connected by a common line or color.

Depth of Investigation

The depth of investigation stems from a need to relate a measurement made at the surface to some particular depth in order that survey parameters can be optimized for target identification [10]. The traditional linear pseudosection has limitations with respect to a physical meaning of the earth. Many researchers, therefore, have taken a closer examination of the plotting method to allow for a more reasonable geological interpretation. The most widely accepted depth of investigation studies [8][11][12] defined a depth of investigation characteristics (DIC) model for determining the depth of a measurement. The DIC was determined by finding the depth at which a thin horizontal layer within a homogeneous background makes the maximum contribution to the total measured signal at the surface. The results were similar to those presented before: the depth of investigation is a linear function of electrode spacing and places no emphasis on actual resistivity values. At its extreme, the linear plotting methodology fails when an infinitely conductive layer is placed within the earth. A large electrode separation would still prevent signal from penetrating the layer.

Fink [13] extended the work of Roy and Apparao [8] to include the dipole-dipole array and showed that the maximum sensitivity of the DIC curve was a power function of dipole separation:

$$Q_{DIC} = 1.5455 n^{-0.7542} \qquad \text{(Eq. 6)}$$

where Q_{DIC} is the peak value of the DIC curve for each value of n. Furthermore, the depth at which the maximum sensitivity occurs, Z_{DIC}, was found to be:

$$Z_{DIC} = -0.2853 n^{0.8732} . \qquad \text{(Eq. 7)}$$

Two generalizations can be obtained from Equation 7. The first stems from the fact that the pole-pole array is a special arrangement of the dipole-dipole array, where the n spacing is a fraction of the a-spacing. Practically, a field survey with infinite poles is never achieved and the poles are actually a finite distance away from the two rover electrodes. Fink [13] discusses the implications of fractional n-spacings in a dipole-dipole survey. Second, Equation 7 can be generalized in the form of:

$$Z_{DIC} = c * n^{b} \qquad \text{(Eq. 8)}$$

where c and b are fitting parameters for measured data, if ground truth data exist for comparison. An example would be borehole data showing a target depth of a conductive anomaly. Over the years, much work has gone into reshaping Equation 8 to allow additional parameters to control the depth plotting methodology through empirical data analysis. Today, HGI calls its method of data presentation “Geometric Inversion”, which is a proprietary algorithm that also includes a topographic static correction to adjust for terrain effects.

METHODOLOGY

HRR relies on direct current injection into the ground and subsequent mapping of potential changes as a result of the current flow. To accomplish this, stainless steel electrodes are pounded into the ground at regular intervals, in which battery terminals are connected to one electrode (plus infinite remote) for current transmission and a volt meter reads the potential in all other electrodes. Mapping occurs by moving the transmitter to different electrodes and recording all possible transmitter and receiving pairs. To expedite data collection, we employed a Sting R-8 (Advanced Geosciences, Inc – Austin Tx) with smart electrodes to automatically switch the transmission and receiving electrodes and record the data.

HRR data were collected at the BC Cribs Site along 51 lines, ranging in length from 400m to 700m with total coverage exceeding 19 line-kilometers [6]. The first phase of measurements commenced in July 2004 and continued and lasted approximately 2 months; another two-month measurement period was conducted beginning in March 2005. The HRR line locations relative to the trenches and cribs can be seen in Fig. 1.

The HRR lines were structured such that a grid pattern of resistivity data could be collected. The grid pattern would allow a geostatistical analysis to reconcile natural spatial structure and to fill in the areas that were not covered by the measurement strategy using an unbiased linear estimator. Additionally, the lines extended past the known disposal facilities into the adjacent properties such that sufficient background can be collected. The background measurements are necessary to distinguish the plume’s edge.

RESULTS

Fig. 2 shows the HRR data as a solid mass derived from apparent resistivity values less than 175 ohm-m. The plot was interpolated in three dimensions using the compiled HRR. The Rockworks program was used for interpolation, which employs an anisotropic inverse-distance weighting algorithm to interpolate the data.

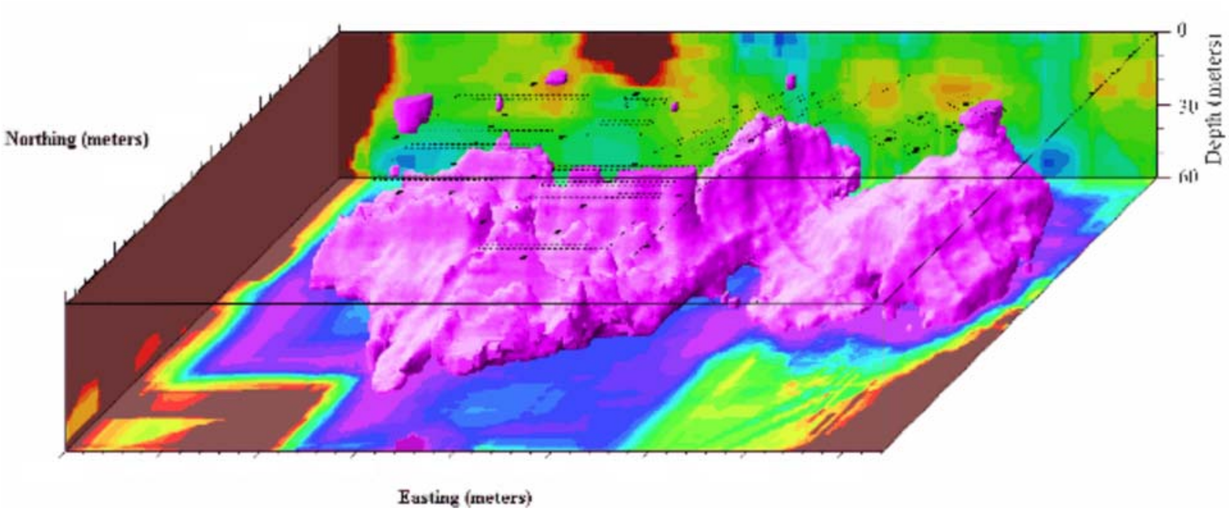

Fig. 2. 3D HRR data collected at the BC cribs site (Opaque from 80-175 ohm-m).

Volume estimates were produced for the plume at specific apparent resistivity values, similar to the area estimates obtained for the two-dimensional slices. Table I lists the absolute total volumes of the conductive plume at specified isopachs (3-D contours). The calculations of volume were simply the total number of pixels with the specified resistivity (or less) multiplied by the pixel volume of 5m x 5m x 2m = $50m^3$. Additionally, the change in pore volume due to the occupied conductive plume was determined by multiplying the total volume bounded by a specific resistivity value by the average difference in moisture content from before waste disposal (1956) to present day (2004). This calculation assumes that the contaminant causing the apparent resistivity anomaly is within the pore space only and not sorbed onto the solid soil grains. For nitrate and Tc-99, this is a fair assumption, since both constituents have a partition coefficient near 0 mL/g.

The moisture content data were obtained from [14] where it was determined that the difference in water content in the depths from 20 to 50 meters below ground surface was approximately 0.06 m^3 m^{-3}. The ‘before disposal’ moisture content was derived from statistical modeling assuming a correlation structure of subsurface heterogeneity. The present day moisture content was obtained from neutron probe data.

Table I. Volumes Bounded by Specific Apparent Rresistivity Values

Resistivity contour value (ohm-m)	**Total Volume bounded by contour (1000 m^3)**	**ΔPore Volume bounded by contour (1000 m^3)**
126 (purple)	538	32
137 (dark blue)	735	44
163 (cyan)	1,771	106
196 (yellow)	3,545	212
275 (orange)	8,825	530
407 (red)	15,487	929

The 175 ohm-meter isopach of Fig. 2 has a pore volume change of approximately 140,000 m^3. The total effluent volume disposed within the BC Cribs and Trenches was approximately 118,000 m^3. The two volumes are close, suggesting that the apparent resistivity plume could be used to estimate the size of a contaminant plume. Since nitrate was disposed in much greater amounts than the other constituent, it could be further reasoned that the plume is primarily nitrate.

Estimating Contaminant Plume Distribution from HRR data

A high-resolution soil sampling program was conducted at the BC Cribs and Trenches Site through borehole C4191, located near the center of the 216-B-26 Trench. Grab samples of soil (~1 kg of soil) from this borehole were extracted every 0.76 meters (2.5 feet) from 5.3 to 104 meters below ground surface. A total of 124 samples were taken, and 39 were characterized for moisture content, gamma energy, and water dilution tests to extract pore water for pH, electrical conductivity, and major anions and cations. Moisture content included thermogravimetric analysis; volumetric water content can be estimated from the gravimetric water content by multiplying by the bulk density (assumed to be 1.6 g/cm^3).

The soluble inorganic constituents were extracted with a 1:1 dionized water to soil sediment extraction method [15]. The water extraction method was necessary due to the low volume of antecedent moisture content, which was typically less than 50 mL. The left plot in Fig. 3 shows the results for electrical conductivity, nitrate concentration, and sulfate concentration versus depth.

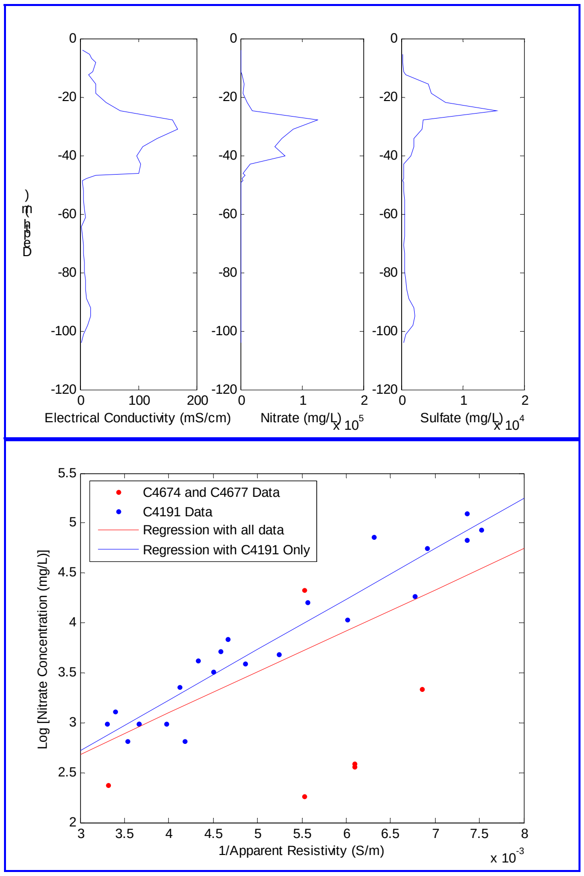

Fig. 3. Top) Borehole data of Electrical Conductivity, Nitrate Concentration and Sulfate Concentration within borehole C4191. Bottom) Scatter plot of Nitrate Concentration vs. HRR Data coincident with C4191.

Since the electrical conductivity of the porewater shows a strong correlation with the nitrate concentration, a scatterplot of the log-transformed nitrate concentration and HRR data was constructed. The right hand plot in Fig. 3 shows the scatter plot for co-located HRR and nitrate data and linear least square regression fits to the data. The blue scatter points represent data from C4191 and the red represent data from C4674 and C4677. These last two boreholes were used for confirmational sampling after the survey conducted in 2004 [6], and were collected approximately midway between Trench 216-B-25 and 216-B-26. The two regression lines are fit to all data for the red line and to C4191 only for the blue line. Clearly, the C4191 has a much lower scatter than the C4674 and C4677 data. The correlation coefficient for the C4191 data is 0.951 and for all data is 0.669. The low correlation with all data results indicates a general underestimation of apparent resistivity (overestimation of conductivity) corresponding to C4674 and C4677 nitrate concentrations. The underestimation of apparent resistivity could be the result of out-of-plane current flow towards a more conductive zone, such as under Trench 216-B-25 or 216-B-26.

The nitrate concentration can be estimated from HRR data using the following transformation:

$$[NO_3^-] = 10^{a/\rho + b} \qquad \text{(Eq. 9)}$$

where a and b are the slope and intercept for the regression data. For all data, a = 412.19 and b = 1.447. For the regression of C4191 data only, a = 505.2 and b = 1.207. For the following analysis, the regression statistics with C4191 only will be considered. The C4191 statistics tend to predict a higher nitrate concentration, which is a more conservative estimate from a risk perspective.

Practically, the conversion from apparent resistivity to nitrate occurred on the three-dimensionally rendered HRR data produced from Rockworks. Rockworks created an interpolated dataset using an inverse distance algorithm. The data were saved in ASCII format and converted to nitrate concentration using a simple script in MATLAB. A total of 562,770 data points were converted to nitrate concentration, with each data point representing a pixel size of 50 m^3 (5 x 5 x 2 meters). An exclusion filter was applied that truncated the nitrate data to be between $1x10^3$ and $5x10^5$ mg/L.

Fig. 4 shows the three-dimensional nitrate plume using Equation 9 to convert apparent resistivity to nitrate concentration. Two concentration isopachs are shown: 30,000 mg/L and 5,000 mg/L with the latter isopach being the largest. A mass calculation was then applied to the plume, which assumed that all of the nitrate was in the pore fluid and an average volumetric water content of 0.085 cm^3 cm^{-3}. The water content was derived from the top 60 meters of the gravimetric water content from C4191 cores multiplied by a bulk density of 1.6 g cm^{-3} (Andy Ward, personal communication). A constant value of water content was used throughout the site for the mass calculation to avoid having to extrapolate data from a single borehole to the large rendered volume.

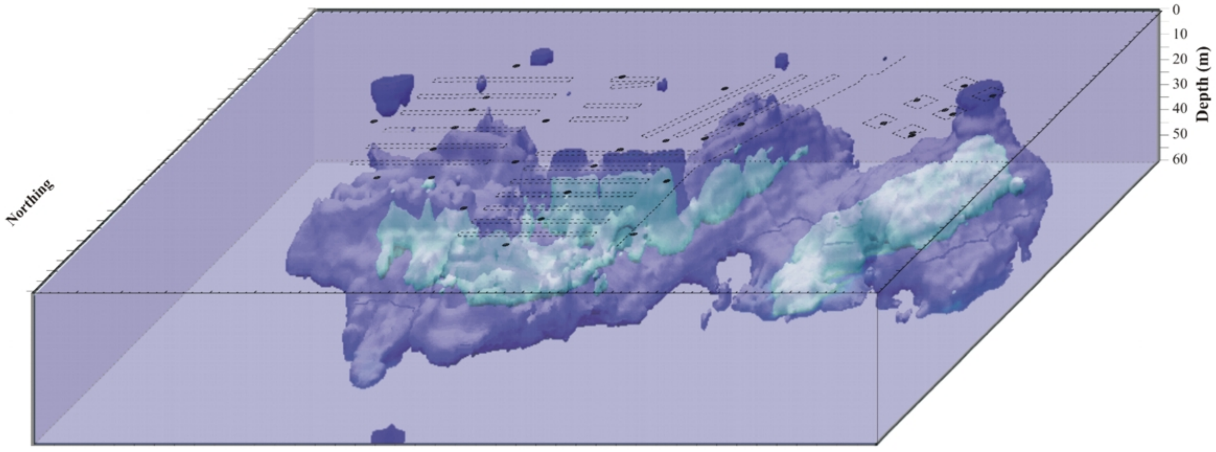

Fig. 4. Interpretation of Nitrate concentration from HRR Data. Outer plume = 5,000 mg/L. Inner Plume = 30,000 mg/L

The total mass of nitrate calculated at the BC Cribs was $24.3x10^6$ kg. This mass is in slight excess of the disposed mass of $22.6x10^6$ kg, suggesting an overestimation of nitrate mass especially considering that the entire plume was not adequately imaged with HRR. The area around the cribs showed that a conductive plume continues to depths beyond the sampling strategy of the current resistivity measurement campaign. The mass calculation, however, is a rough estimate but is sensitive to the exclusion filter for nitrate data truncation, volumetric water content, and the transformation equation to convert from apparent resistivity to nitrate concentration. It should be noted that the calculated nitrate plume was generated with data from a single borehole. An increased confidence in a contaminant plume can be gained by obtaining and analyzing more soil samples distributed throughout the site.

CONCLUSION

A total of 51 HRR lines using a pole-pole array were acquired in and around the BC Cribs and Trenches Site, totaling to approximately 19 line-kilometers of coverage. The majority of the data were collected parallel and perpendicular to waste disposal sites that included 16 trenches and 6 cribs. A few HRR lines were extended south of the site to test a hypothesis that wildcat dumping of liquid waste occurred outside of the disposal site boundaries. The data acquisition strategy included the supposition that many closely-spaced HRR lines could be combined to form a single pseudo-3D plume of apparent resistivity. Parallel lines were spaced approximately 15 meters apart allowing for a high spatial resolution of data coverage so that interpolation could be completed with higher confidence. Additionally, sufficient data was collected immediately adjacent to the site (background) so that the plume's geometry could be identified with accuracy.

The Rockworks software package was used for the three dimensional rendering of the HRR data. The 3-D interpolation was completed with an inverse distance algorithm on a pixel size of 5 by 5 by 2 meters. A total of 562,770 pixels were needed to cover the site to a depth of 60 meters. Volume estimates of the resistivity plume showed that an isopach between 163 ohm-meters and 175 ohm-meters would effectively represent the total effluent disposal volume of 118,000 m^3 assuming a site-wide change in volumetric water content of 0.06 cm^3 cm^{-3}.

Ground truth measurements of soil samples collected through the center and near the 216-B-26 trench were analyzed in light of the apparent resistivity data. The highest spatial resolution came from borehole C4191, where grab soil samples were analyzed for moisture content, electrical conductivity, inorganics, and a few radionuclides at every 2.5 feet from the surface to the water table. The data were compared to co-located HRR apparent resistivity data and relationships were developed to transform apparent resistivity to nitrate. A nitrate plume of 5,000 mg/L and 30,000 mg/L was generated based on data from this one borehole and a mass balance showed that the estimated mass and known disposed mass agreed quite well. More ground truth samples are needed, however, to give greater confidence about any representation of a particular waste constituent.

Suggestions for future work to help refine the geophysical presentation of a contaminant plume are as follows:

1. The geometric inversion model used in our HRR data presentation has a few drawbacks, including the smearing of plume edges, depth estimations, and 2D geometry. Three dimensional electrical resistivity tomographic inversion could solve these issues. To enhance the inversion process, a new method should be developed that simultaneously solves the hydrologic problem as well as the electrical geophysics problem. This approach will ensure that the ERT results are agreeable from a hydrologic stand point. Other work [14] has already shown that the fate and transport of both nitrate and Tc-99 at BC Cribs can be modeled using STOMP (Surface Transport Over Multiple Phases, a fate

and transport numerical simulator developed by Pacific Northwest National Laboratory). If constitutive relations are developed that can relate the distributed water content and nitrate concentration from the hydrologic model to electrical resistivity, then modeling the electrical geophysics should be rather easy, given sufficient computing resources.

2. In this report, we presented resistivity data as a three dimensionally-rendered plume from a series of two dimensional data sets. There was a high degree of correlation among the two-dimensional data, and the approach of combining the individual data sets into one large 3D resistivity plume seemed appropriate. Furthermore, circumstantial evidence existed that allowed estimation of the distribution of nitrate around the site. However, more evidence should be gathered to help increase the confidence in estimating the distribution of nitrate using the HRR method. Collection of additional soil samples at specific depths is recommended for comparison to the HRR data. The soil samples should be sufficiently spread out over the site to cover the ranges in measured resistivity from background to the most conductive regions.

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