TITLE: Use of ARCGIS to Monitor Cs137 at the Idaho National Laboratory

Abstract

The Idaho National Laboratory is a U.S. Department of Energy site located in southeastern Idaho. The INL is required to perform environmental monitoring of anthropogenically introduced contaminants. One primary contaminant of interest is radioactive Cs-137 which is resident in INL soils due to past operational activities and atmospheric weapons testing. Collection of field data is performed using vehicle mounted and portable radiation detector units. All data are combined in ArcGIS and displayed over georeferenced satellite images and digital elevation models. The use of the ArcGIS geostatistical analysis package enhances the ability to identify areas of elevated Cs-137 concentration. Combining current monitoring results with meteorological wind pattern maps allows for siting of new and improved monitoring locations. Use of the ArcGIS package provides an integrated analysis and mapping protocol for use in radioactive contaminant monitoring.

Introduction

Located 51 km (32 mi.) west of Idaho Falls, Idaho, the INL is a government-owned, contractor-operated facility managed by the DOE. Occupying 2,305 km^2 (890 square miles) of the northeastern portion of the eastern Snake River plain, the INL encompasses portions of five Idaho counties: Butte, Jefferson, Bonneville, Clark, and Bingham. The site consists of high desert terrain and resides over the Snake River Plain aquifer. Figure 1 shows the location of the INL.

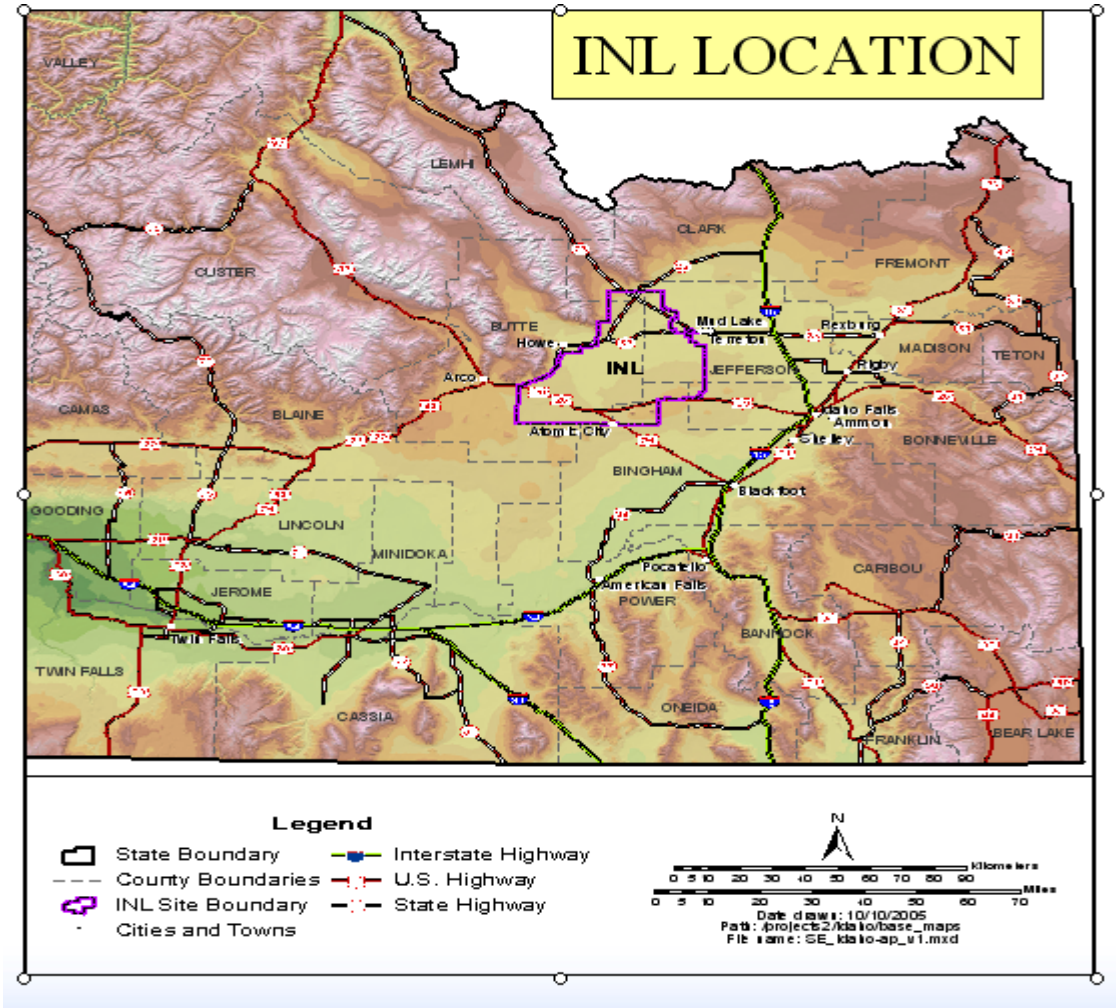

Figure 1. Location of the Idaho National Laboratory.

The INL is required by contract and regulations to perform yearly environmental monitoring of certain contaminants. These data are reported to federal and state agencies under various legal agreements. Radioactive Cs-137 is one of the monitored contaminants. This radioactive isotope is present in INL soils due to past operational activities and atmospheric weapons testing. Cesium-137 is monitored at a level determined from risk-based concentration tables developed by the state of Idaho, and adopted by the U.S. Environmental Protection Agency. For an excess cancer induced mortality risk value of 1.0 E-06, the risk based concentration for a 30 year residential scenario with an external exposure pathway is 0.23 pCi/g[1]. Since Cs-137 is a radioactive gamma-ray emitting isotope, it can be measured directly using standard gamma-ray spectroscopy measurement systems described in the next section. The INL and U.S. Department of Energy personnel established a monitoring network of 290 locations to monitor the Cs-137 soil concentrations on an annual basis. Yearly measurements of some of 290 points have taken place since 1984. Obtaining these measurements is expensive, time consuming, and laborious. The techniques described in this paper were used to predict the Cs-137 values at locations where no measurements occurred. These locations were then contoured and mapped in order to visualize the Cs-137 prediction surfaces.

In 2006, the INL Environmental Monitoring gamma-ray spectroscopy group performed measurements at 290 locations. This data was analyzed using standard gamma-ray spectroscopy analysis software and the data was then converted to shapefiles for use in ArcGIS, version 9.2. The main goals of this work were as follows:

- Identify areas of the INL where the Cs-137 concentrations exceed 0.23 pCi/g
- Perform statistical data analysis
- Perform prediction and probability kriging and develop Cs-137 prediction and probability surfaces
- Use kriging predictions and probabilities in conjunction with meteorological information to refine measurement locations
- Build multiyear database to closely monitor Cs-137 concentration trends and increase measurement efficiency

Results of the 2006 effort were presented at the 2007 ESRI International User's Conference and are detailed in Oertel and Giles[6]. Those data were analyzed using the ArcGIS Geostatistical Analyst extension in order to determine the best possible prediction and probability surfaces, and also to use meteorological data to locate additional data points in areas where there appeared to be large data gaps. Based on that work the number of measurement locations increased from 290 to 343 in 2007. This paper will detail the 2007 results and compare and describe new geostatistical techniques applied to the field measurement data.

For 2007, the Cs-137 measurement locations are shown in Figure 2, with details of the main individual facilities provided in Figures 3 through 6. These figures show that most of the measurement locations are clustered around the individual facilities; however, some of the measurement locations extend from the extreme southwest to the northeast, along the lines of prevailing wind directions.

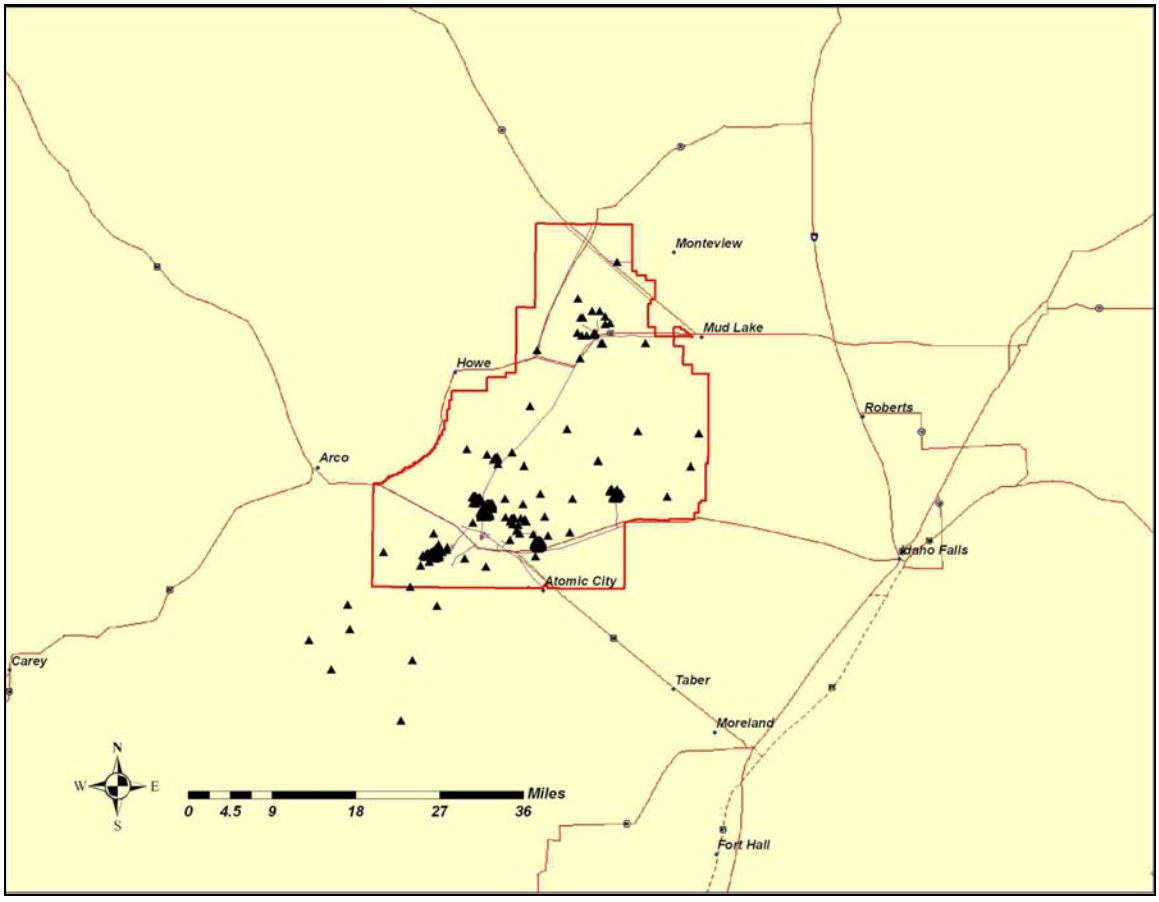

Figure 2. Location of 2007 Environmental Monitoring Points.

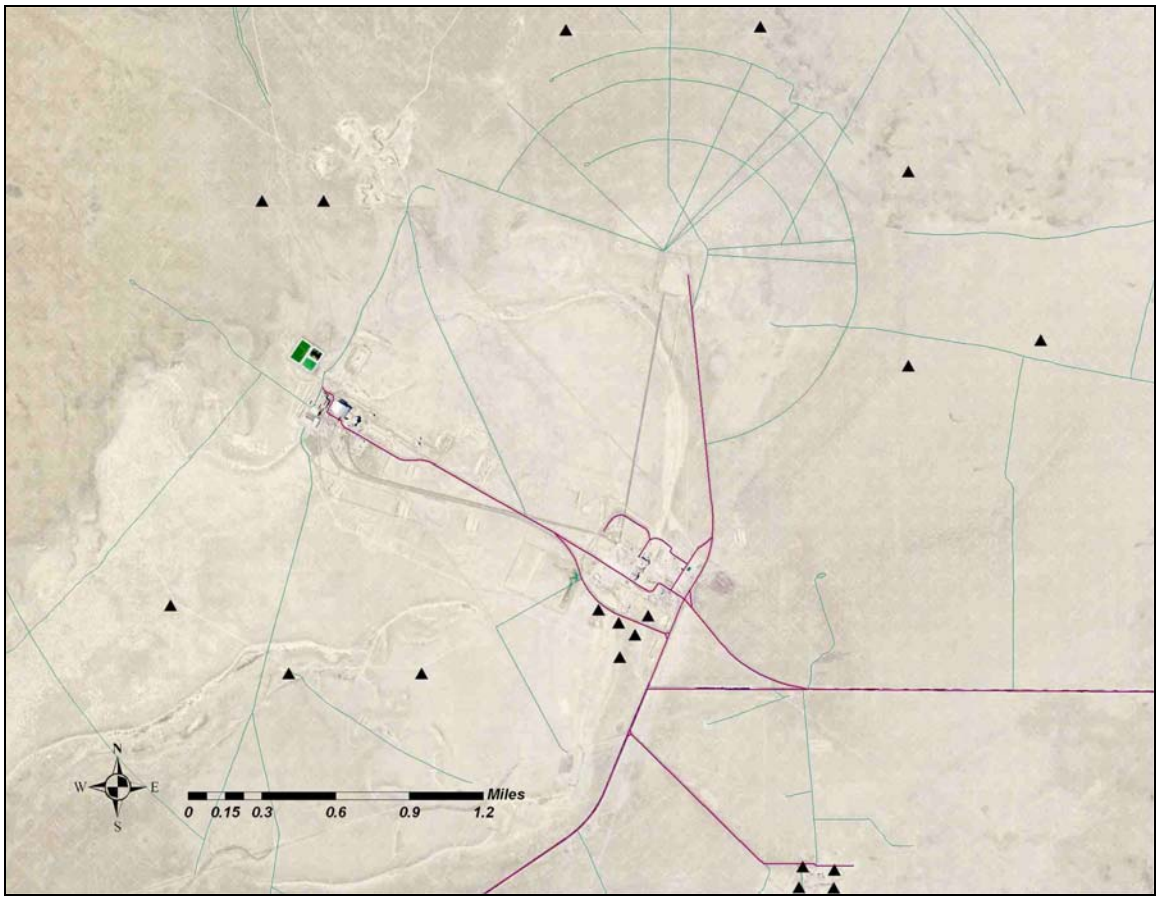

Figure 3. Points near the Test Area North facilities at INL.

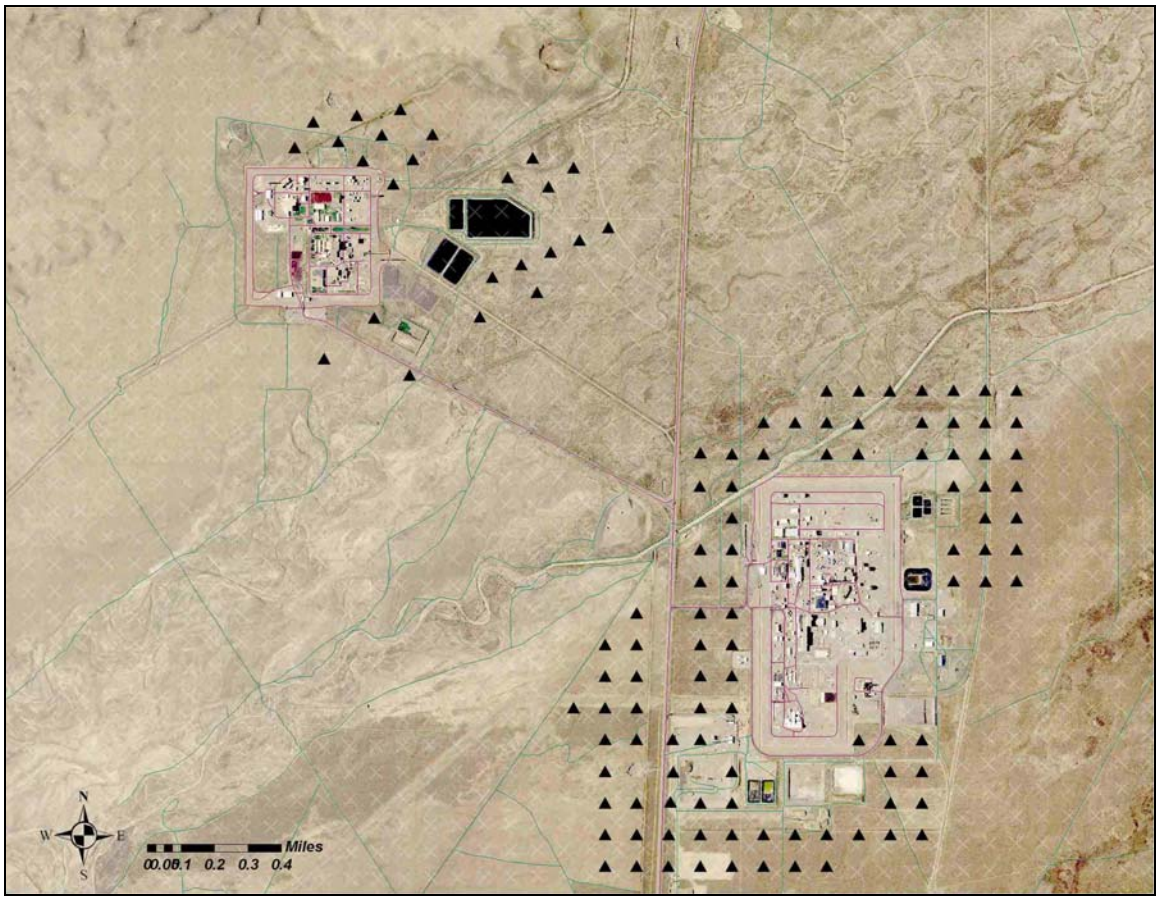

Figure 4. Points located near Reactor Test Complex and Idaho Nuclear Technology and Engineering Center.

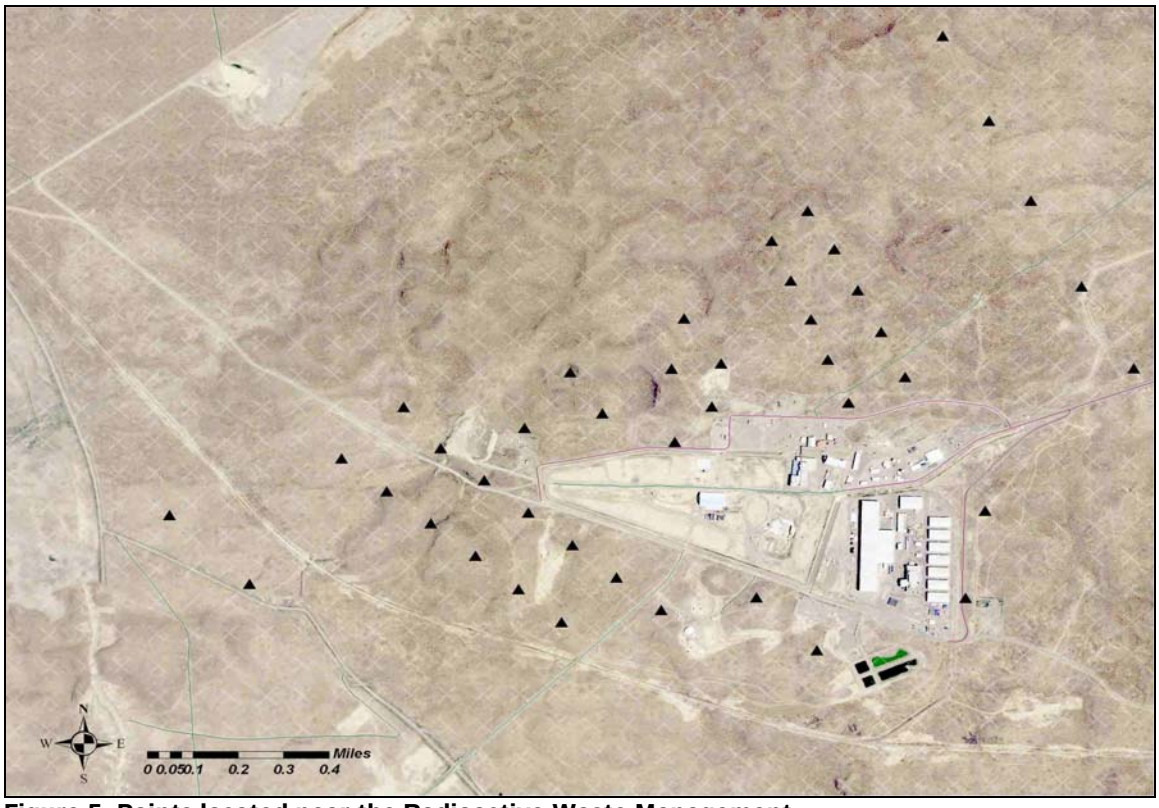

Figure 5. Points located near the Radioactive Waste Management Complex

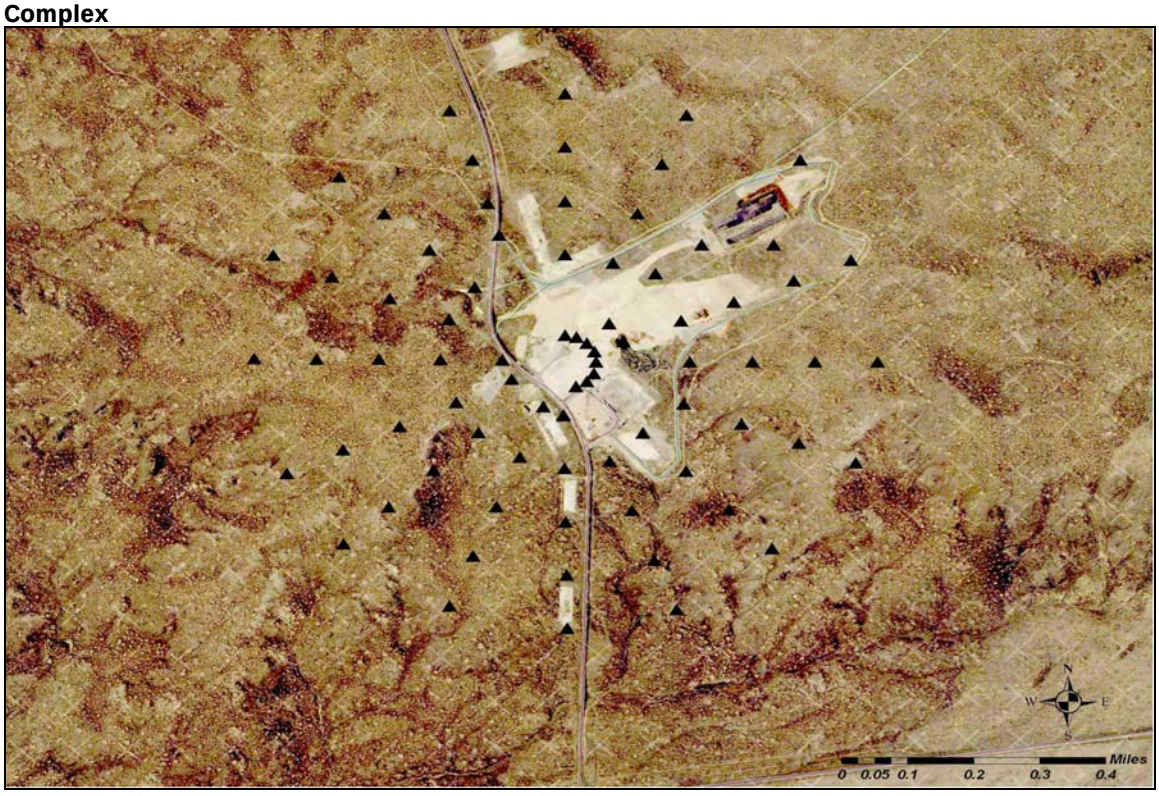

Figure 6. Points located near the Auxiliary Reactor Area.

Field Measurements

The systems used for this field measurement effort consisted of high purity germanium detectors mounted 1 meter above the ground on a tripod. A portable multichannel analyzer system (ORTEC® DigiDART [ORTEC, 801 South Illinois Ave., Oak Ridge, TN 37831]) was coupled to the detector, and the system was controlled by a field-rugged computer. The height of the detectors above the ground (1 meter) facilitated an uncollimated field of view approximately 20 m in diameter. Figure 7 shows a typical field setup for the *in situ* germanium detector systems.

Figure 7: High Purity Germanium Detector used to measure Cs137 in soils

Using the *in situ* gamma-ray measurement method, the gamma-emitting radionuclides are identified by their specific photon energies, which are registered as spectral peaks. The peak count rate is related to the full absorption of unscattered gamma rays. If the detector is properly calibrated, the activities per unit mass of any radionuclide can be derived from the peak count rate using parameters that describe the soil characteristics (i.e., density, percent soil moisture, etc) and the distribution of the Cs-137 as a function of depth. The *in situ* technique is particularly well suited for studies such as this, because it quickly determines levels and types of contamination over large areas. Each measurement provides a weighted average over the detector field of view that is on the order of 315 m^2. The use of this technique to measure Cs-137 contamination in soils is well documented and has been used extensively at the INL and other USDOE sites[2,3]).

Following data collection, the raw gamma-ray spectra were stored and analyzed using the software package ISOTOPIC, [ORTEC, 801 South Illinois Ave., Oak Ridge, TN 37831]. The calculated concentrations were then paired to GPS positions representing each of the 345 measured points.

Exploratory Data Analysis:

Figure 8 shows a post plot of the Cs137 values above and below 0.23 pCi/g. Note that most of the points that exceed the Cs-137 risk-based concentration of 0.23 pCi/g are concentrated near four facilities, specifically the ARA (Auxiliary Reactor Area), Radioactive Waste Management Complex (RWMC), Test Area North (TAN), and INTEC (Idaho Nuclear Technology and Engineering Center)

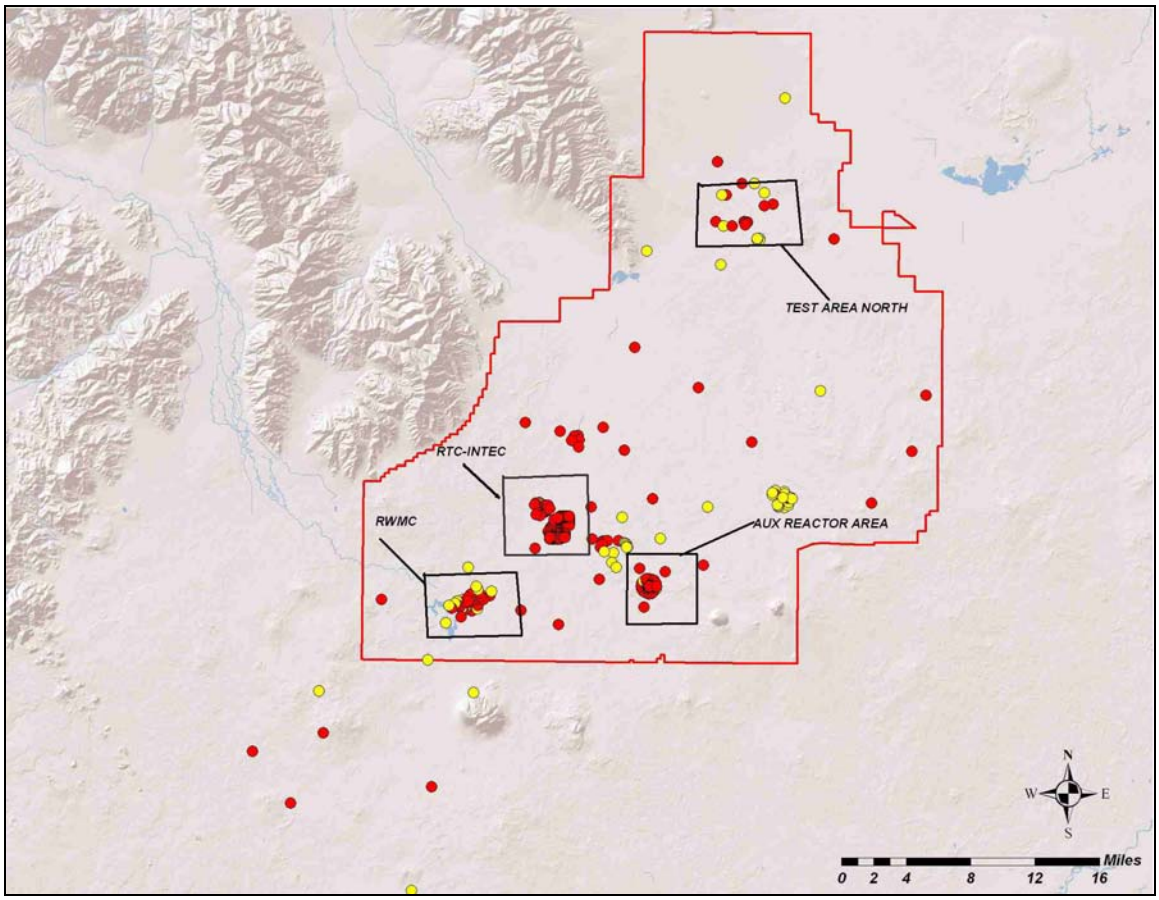

Figure 8. Post plot showing Cs-137 <0.23 pCi/g (yellow) and >0.23 pCi/g (red)

The mean measured Cs-137 concentration for the year 2007 data set was 1.02 +/- 2.83 pCi/g, compared to 0.95 +/- 2.19 pCi/g in 2006. In 2007 79% of the data exceeded 0.23 pCi/g compared to 52% in 2006. Part of this difference is due to the use of an exponential depth profile for Cs-137 in the analysis program in

2007. In 2006, the gamma-ray spectroscopy analysis software was used to estimate the depth distribution for the measurement locations. The 2006 data analysis showed that the Cs-137 distributions at the Materials and Fuels Complex, Critical Infrastructure Test Range Complex and Naval Reactor Facility were planar (i.e. all the Cs-137 is on the surface). As part of the 2007 monitoring activities, soil samples were collected at over 30 across the INL validate the depth distributions as estimated in 2006 using the gamma-ray spectroscopy analysis software. Results of this soil sampling showed that Cs-137 distributions across the INL can be approximated by an exponential distribution. For the points that were previously assumed to have a planar distribution, 40% of the Cs-137 values were greater than 0.23 pCi/g.Also in 2007, 15 data points were added based on the geostatistical analysis results from 2006. Of these 15 locations, 93% exceeded 0.23 pCi/g.

Examination of the 2007 data using a histogram showed that the data were highly skewed (skewness=14.4, kurtosis=240.4). Use of some geostatisitical models is improved if the data is normally distributed. Following logarithmic transformation, this data became more normal (skewness=0.72, kurtosis=3.8).

Generation of Prediction and Probability Surfaces

The geographic extent of the INL makes it impractical to measure enough locations to test whether the current monitoring program is adequate. To accommodate this, the Geostatistical Analyst in ArcGIS was used to predict Cs-137 concentrations at unmeasured locations from measured values. We also used the same tools to generate probability surfaces showing where the Cs-137 might exceed the 0.23 pCi/g level. This technique was applied in 2006 and those results are shown in reference (6). A similar approach to surface generation was taken for 2007 in order to analyze the effect of the added measurement points.

Kriging is an advanced geostatistical procedure that generates an estimated surface from a scattered set of points. Kriging in ArcGIS involves an interactive investigation of the spatial behavior of the Cs-137 concentration values followed by selection of the best estimation method for generating the prediction or probability surfaces. For kriging there is also association of some probability with surface predictions; that is, the values are not perfectly predictable from a statistical model. Therefore, we used kriging to not only try to predict Cs-137 concentrations at unmeasured locations, but also to assess the error of the prediction models.

Kriging is similar to other interpolators in that it weights the surrounding measured values to derive a prediction for an unmeasured location. The general formula for the predicted value is formed as a weighted sum of the data:

$$F(x,y) = \sum_{i=1}^{n} w_i f_i \qquad (1)$$

where F(x,y) is the predicted value at location x,y; n is the number of data points in the set, f_i are the values of the scattered measured points, and w_i are weights assigned to each point. This equation is essentially the same as the equation used for inverse distance weighted interpolation except that rather than using weights based on an arbitrary function of distance, the weights used in kriging are based on a model variogram.

With the kriging method, the weights are based not only on the distance between the measured points and the prediction location but also on the overall spatial arrangement of the measured points. To use this spatial arrangement in the weights, the spatial autocorrelation must be quantified and we used the standard variogram technique to accomplish this. The variogram defines the weights that determine the contribution of each data point to the prediction of new values at unmeasured locations. The following were the steps used in this geostatistical data analysis:[4,5]

1. Calculate the empirical semivariogram—Kriging, like most interpolation techniques, is built on the basic principle that things that are close to one another are more alike than those farther away (defined here as spatial autocorrelation). The empirical variogram is a means to explore this relationship. Pairs that are close in distance should have a smaller difference or variance than those farther away from one another. For this work the variance in Cs-137 data was plotted versus separation distance.

2. Fit a model—This is done by defining a model that provides the best fit through the points. This model quantified the spatial autocorrelation in the year 2007 Cs-137 data. For this work, a spherical model with a range of 35,181 meters and nugget of 3.33($pCi/g)^2$. The nugget represents a best estimate of Cs-137 measurement variability. The variogram reaches a plateau or sill at about 30,000 feet, beyond which there is no longer spatial dependence in the Cs-137 values. Figure 9 shows the variogram of the Cs-137 data from 2007. The best estimate fit for this data is a spherical function written as:

$$\gamma = 0.6*\text{Spherical}_{25595}+0.6*\text{Nugget} \qquad (2)$$

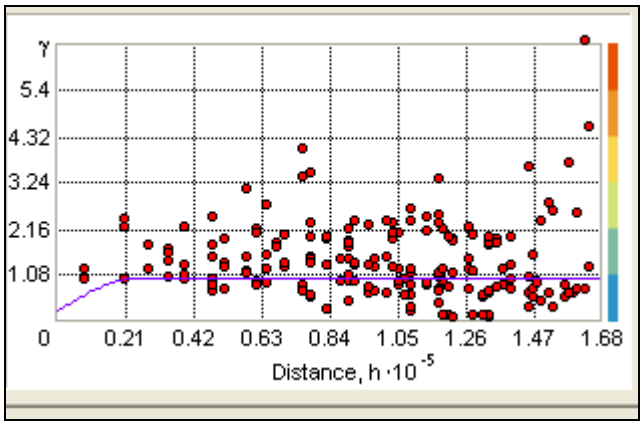

Figure 9. Variogram and best estimated function for Cs-137 data. The distance is in feet.

3. Create the matrices—the equations for kriging are contained in matrices and vectors that depend on the spatial autocorrelation among the measured sample locations and prediction locations. The autocorrelation values come from the spherical variogram model shown in equation 2. The matrices and vectors determine the kriging weights that were assigned to each measured Cs-137 value in the searching neighborhoods.

4. Develop a map-From the kriging weights for the measured values predictions were calculated over a finely spaced grid of locations. For this work, disjunctive kriging was used to generate prediction and probability surfaces.

Disjunctive kriging is applied to this data in order to decluster the data. The Cs-137 measurement locations and data are not randomly or regularly spaced. Figures 2 through 6 show that the measurement locations have high higher densities near some INL facilities, namely, INTEC and ARA. Declustering accounts for this skewed representation of the samples near these two sites by weighting them appropriately so that a more accurate surface can be created**.** The declustering occurs prior to construction of a variogram.

For the INL, there is a strong southwest-to-northeast wind gradient which adds a directional influence to the Cs-137 distribution. The geostatistical analyst allows use of this influence, called anisotropy, in the variogram model. Anisotropy was used when developing the prediction and probability surfaces for this data. Figure 10 shows the 2007 disjunctive kriging prediction surface results and Figures 11 and 12 show the disjunctive kriging probability surfaces for 2006 and 2007. These maps all indicate that the Cs-137 is higher in areas to the northeast of the INTEC, ARA, and TAN sites. There are also higher predicted concentrations to the southwest of the INTEC and ARA facilities. These areas partially lie between current bands of sample locations or in areas where no sample points are located. The disjunctive kriging probability map also indicates that there are areas near these facilities where the Cs-137 likely exceeds the 0.23 pCi/g

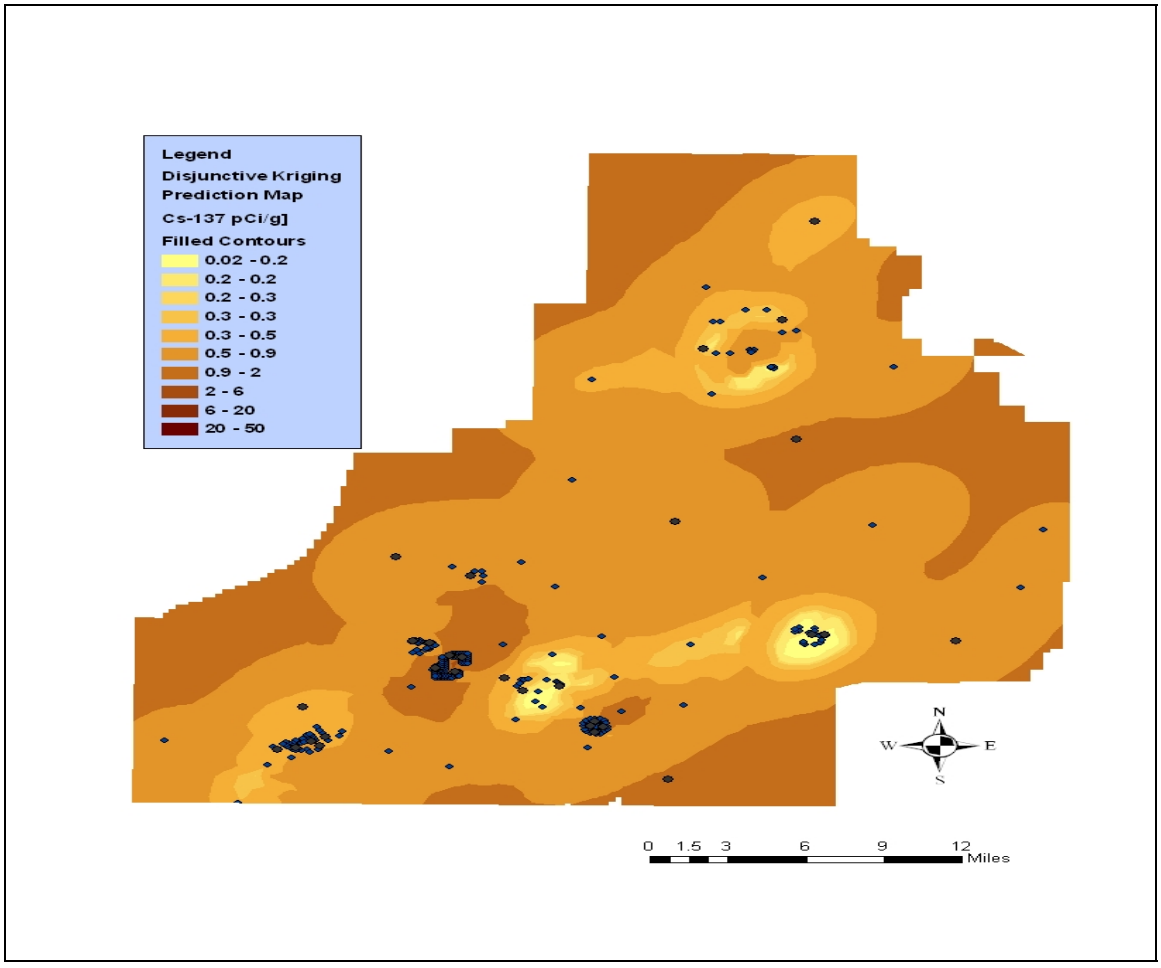

Figure 10. Disjunctive kriging prediction surface for 2007. Values are in pCi/g of Cs137

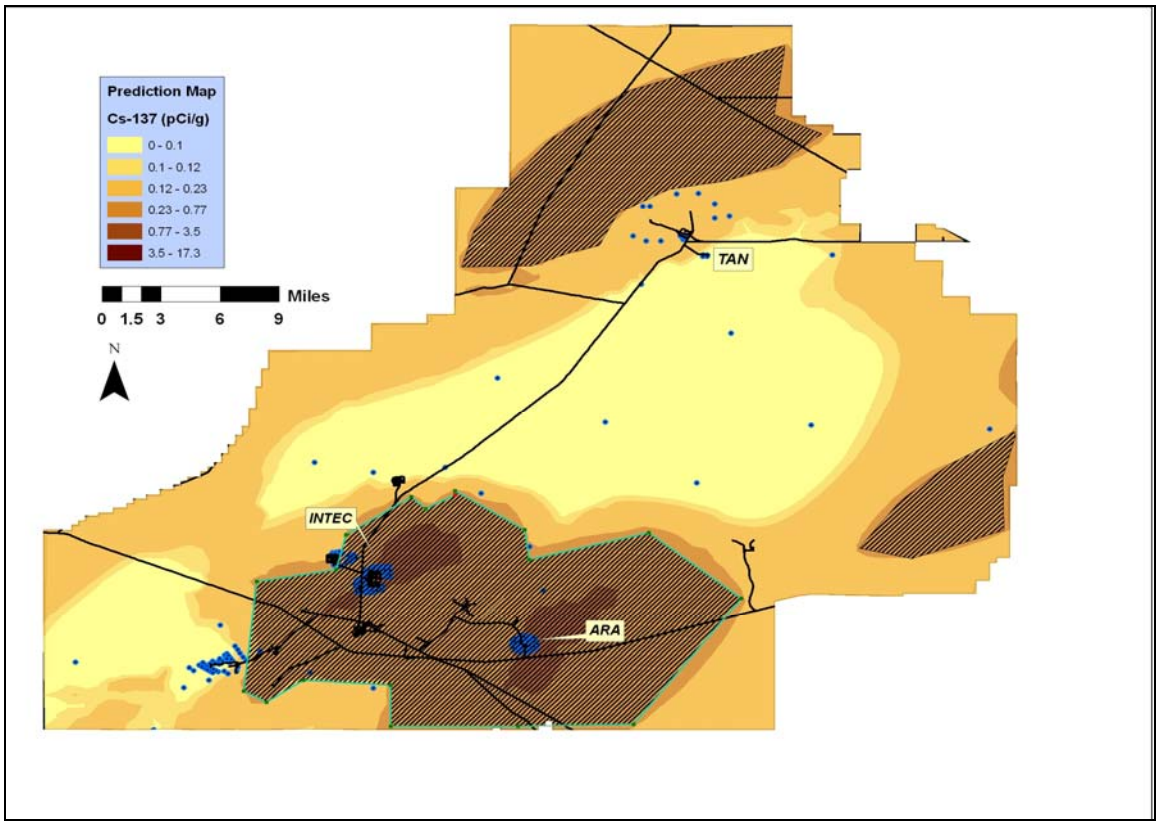

Figure 11. Disjunctive kriging probability surface for 2006 using anisotropic adjustment. Surface is probability that Cs-137 exceeds 0.23 pCi/g. Hatched areas are those in which additional measurement points were placed in 2007 based on judgmental sampling considerations.

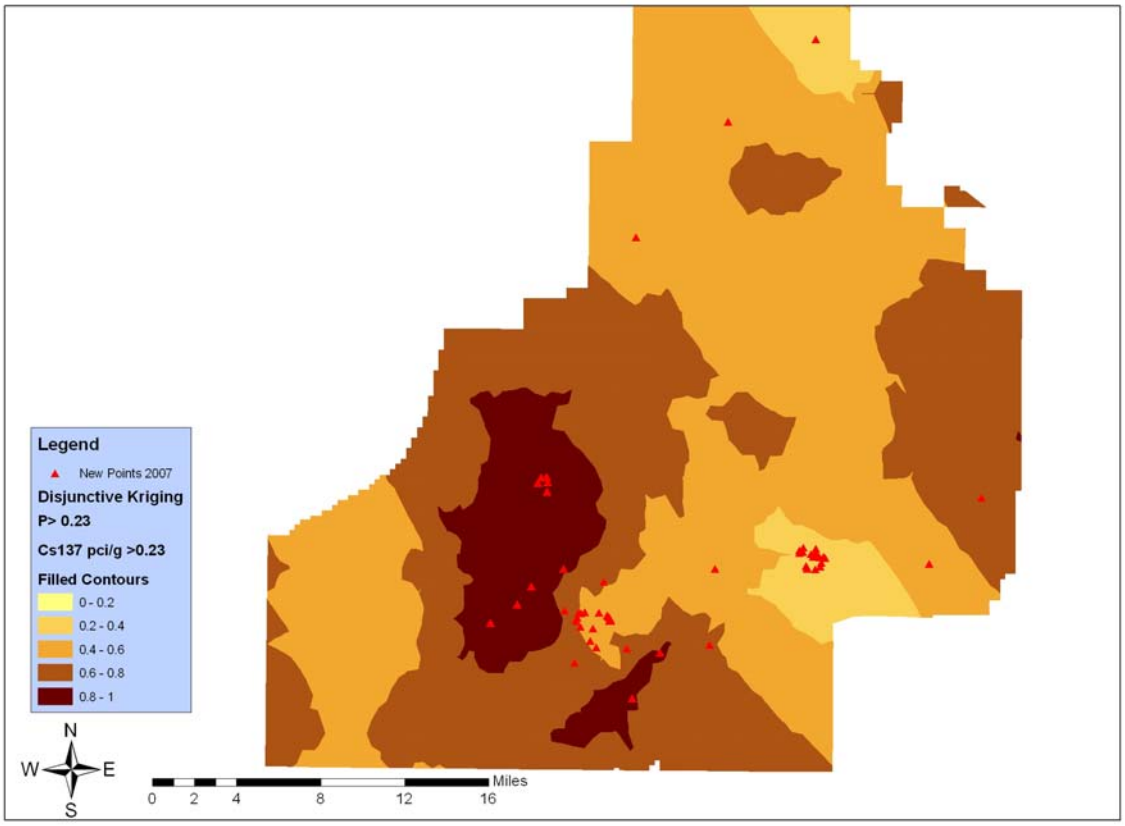

Figure 12. Disjunctive kriging probability surface for 2007 using anisotropic adjustment. Surface is probability that Cs-137 exceeds 0.23 pCi/g.

Figure 11 shows the 2006 probability surface with darker hatched areas indicating areas where additional points were located for the 2007 monitoring season. Comparing Figures 11 and 12 shows that the areas of higher exceedance probabilities for 2007 are much larger relative to those in 2006. In addition the actual probability surface values have increased relative to 2006. Thus the addition of new measurement locations in 2007 has provided for both qualitative and quantitative bases for performing additional measurements. This is essentially the same conclusion drawn from 2006 data.

As mentioned previously, the increase in exceedance probabilities and probability surface values is due in part to the analysis parameters used for the field gamma-ray spectra. Additionally, placement of the supplemental points was largely judgemental based on the 2006 exceedance probability surface, and accessibility of measurement locations. Based on the 2007 results shown in Figure 12, a more sophisticated method is needed for placement of supplemental points, and replacement of existing monitoring locations.

One approach to this is outlined in reference 7. Use of a type of automated network densifier model in the ArcGIS framework is being studied. This method has the potential to optimize field measurement locations. The automated network densifier model creates an enhanced monitoring network by adding supplemental points at the locations where they are most needed to reduce the overall prediction uncertainty. The prediction standard error geostatistical surface, the input data for the model, is updated at each iteration as the model appends one additional sampling point to the current monitoring network each time the model is run. A second approach to be tested in 2008 and 2009 will continue with data analysis and additional GIS-based geostatistical studies, leading to final model development. Advanced geostatistical modeling will focus on using the primary sampled data (i.e., Cs-137 concentrations in soil) along with environmental information which is extensively available across the entire INL site. Environmental information to be used

within a GIS database includes elevation, slope steepness, slope aspect, downwind distance and direction from known source areas of Cs-137, soil type, and landform type. These data will be used in a Bayesian probability analysis to assign scores (i.e., probabilities) at each GIS pixel location for the likelihood of having high concentrations of Cs-137. These Bayesian scores then serve as secondary information (known at every location across the site) in a geostatistical interpolation method known as KED (Kriging with External Drift) to provide enhanced spatial mapping of the primary attribute of interest, Cs-137. Results of these two efforts will be presented in 2009 and 2010.

Summary

The Idaho National Laboratory conducted radioactive Cs-137 measurements at 290 locations during 2006 and 344 locations in 2007. These measurements were performed using insitu gamma spectroscopy. The measurements were necessary in order to satisfy USDOE environmental monitoring requirements. Since the INL is such a large site, geostatistical analysis was used to predict the Cs-137 values at unmeasured locations. Disjunctive kriging models produced prediction and probability surfaces. The disjunctive kriging results in 2006 were then combined with meteorological data to determine whether additional measurements were needed to assess Cs-137 at unmeasured locations. The results showed that an additional 55 measurements are needed to augment the additional database and improve spatial coverage of these measurements. The additional 2007 data indicates a need for much more sophisticated geostatistical analyses such as network densification and application of Bayesian statistical techniques in order to more efficiently locate field measurement points.

References

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