Use of ArcGIS in Environmental Monitoring at Idaho National Laboratory

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ABSTRACT

Idaho National Laboratory (INL) is a U.S. Department of Energy site located in southeastern Idaho. 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 is 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 look for areas of higher 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

Idaho National Laboratory (INL) is a U.S. Department of Energy (US-DOE) facility located 51 km (32 mi) west of Idaho Falls, Idaho. Occupying 2,305 km^2 (890 mi^2) of the northeastern portion of the eastern Snake River plain, 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 aquifer. Figure 1 shows the location of INL.

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. Cs-137 is monitored at a level determined from risk-based concentration tables developed 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]. Because 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. INL and US-DOE 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.

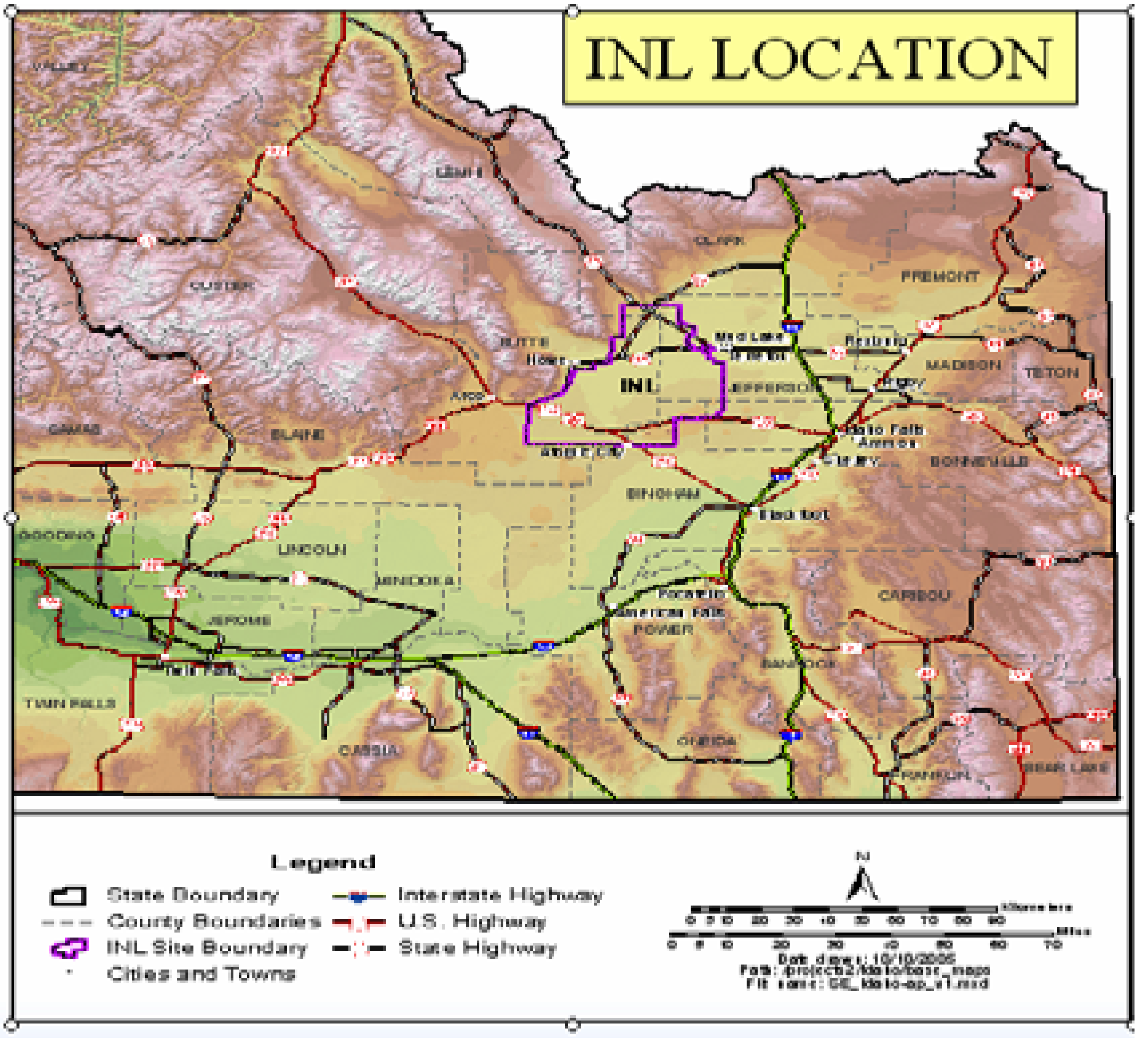

Figure 1. Location of Idaho National Laboratory.

In 2006, the INL environmental monitoring gamma-ray spectroscopy group performed measurements at 290 locations (see Figure 2). 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 are as follows:

- Identify areas of Cs-137 that exceed 0.23 pCi/g
- Perform exploratory data analysis
- Perform prediction and probability kriging, and develop Cs-137 prediction and probability surfaces
- Use kriging predictions and probabilities along with meteorological information to refine measurement locations.
- Build a multiyear database to closely monitor Cs-137 concentration trends and increase efficiency of the measurement process.

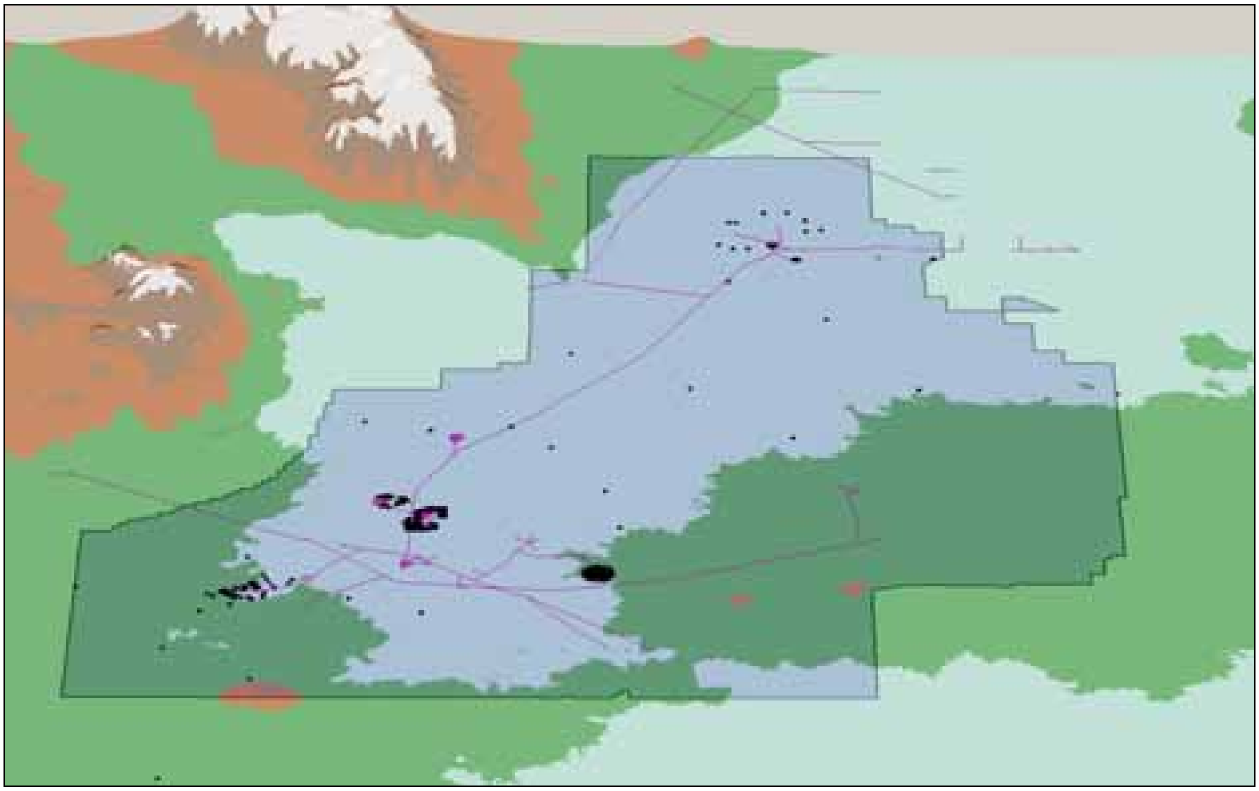

Figure 2. Black dots indicate locations of Cs-137 monitoring points at INL.

FIELD MEASUREMENTS

The system used for this field measurement effort consisted of 65 and 70% efficient (relative to a 3 × 3-in. sodium iodide detector at an energy of 1,332 keV) n-type high-purity germanium detectors mounted 1 m 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 m) facilitated an uncollimated field of view approximately 20 m in diameter. Figure 3 shows a typical field setup for the in situ germanium detector systems.

Figure 3. High-purity germanium detector used to measure Cs-137 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 gamma-ray emitting radionuclide can be derived from the peak count rate using parameters that describe the soil characteristics (density, percent soil moisture, etc.) and the depth profile of the Cs-137. 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 INL and other US-DOE 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 290 measured points.

EXPLORATORY DATA ANALYSIS

Figures 4 and 5 show simple post plots of the Cs-137 values above and below the 0.23 pCi/g limit. Note that most of the points are clustered near existing INL facilities. Further, most of the locations that exceed the Cs-137 risk-based concentration of 0.23 pCi/g are concentrated near two facilities, specifically the Auxiliary Reactor Area (ARA) and Idaho Nuclear Technology and Engineering Center (INTEC).

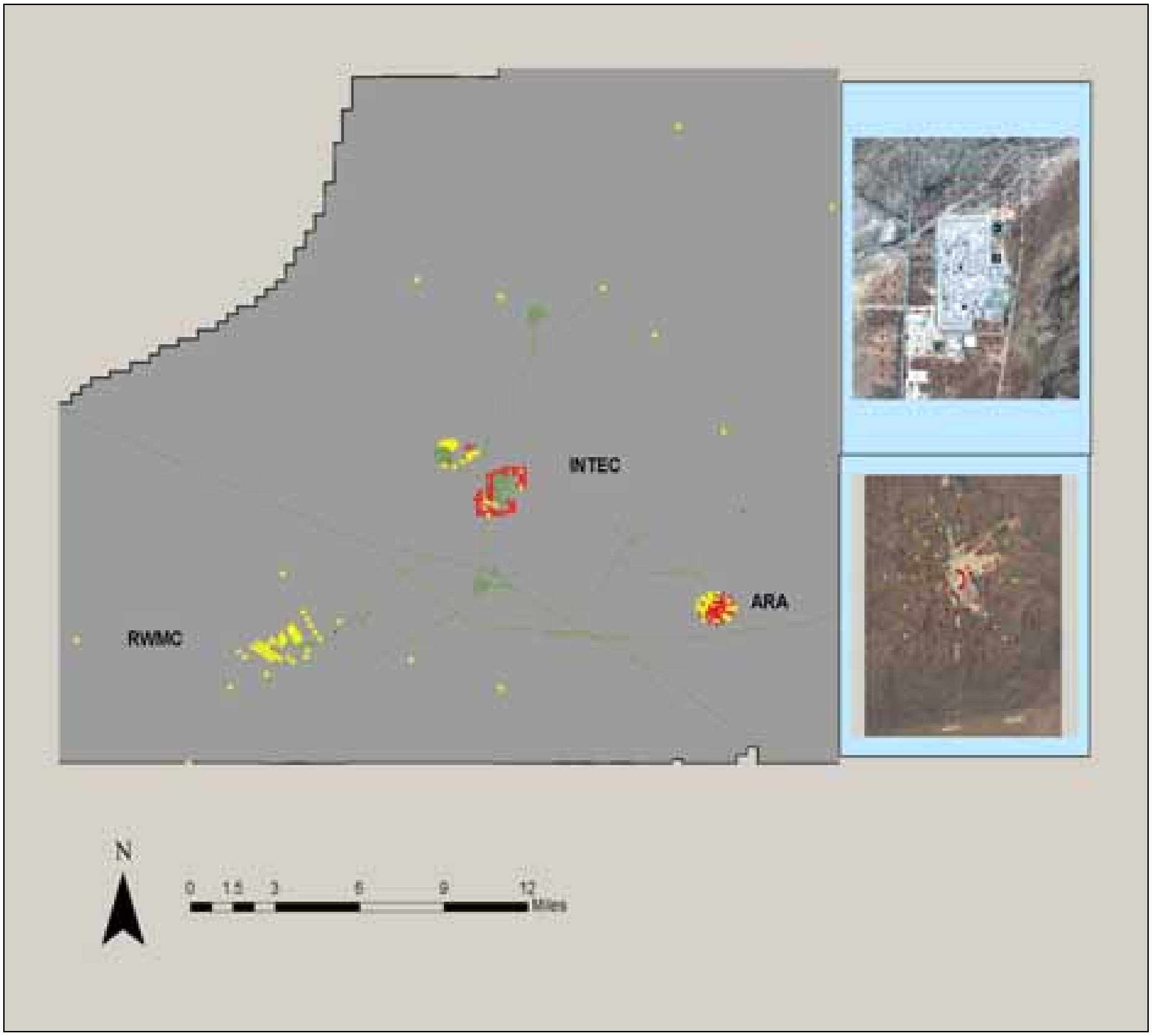

Figure 4. South area of INL showing Cs-137 <0.23 pCi/g (yellow) and >0.23 pCi/g (red). (RWMC = Radioactive Waste Management Complex.)

pCi/g.

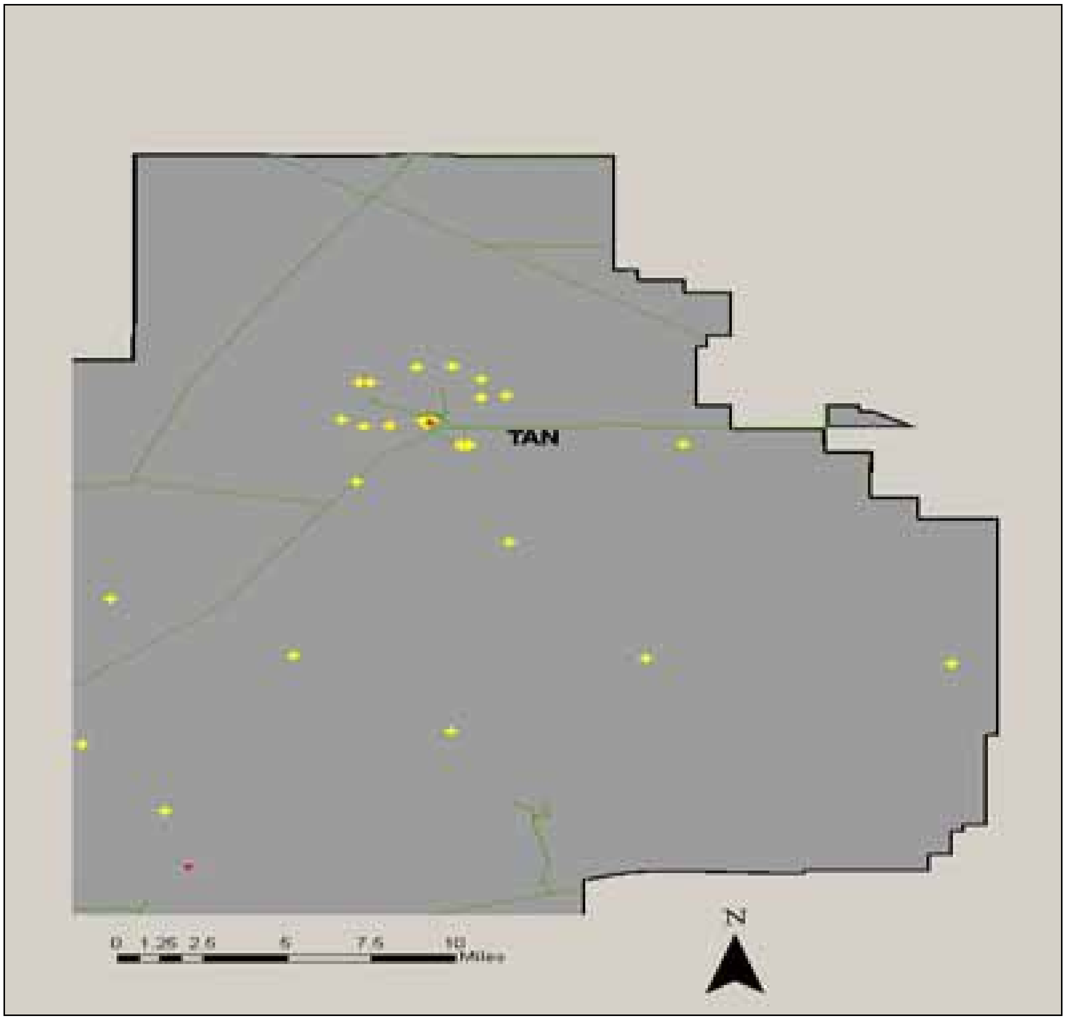

Figure 5. North area of INL showing Cs137 <0.23 pCi/g (yellow) and >0.23 pCi/g (red). (TAN = Test Area North.)

The mean Cs-137 concentration for the year 2006 data set was 0.95 +/- 2.19 pCi/g. Further examination of the data using a histogram showed that the data were highly skewed (skewness =4.4, kurtosis =25.4). Use of some geostatistical models is improved if the data are normally distributed. In particular, prediction maps using disjunctive kriging assume that the data comes from a normal distribution. As such, a normal score transform was performed on the data set prior the generation of the disjunctive kriging surface.

GENERATION OF PREDICTION AND PROBABILITY SURFACES

The extent of the INL property makes it impractical to measure enough locations to test whether the current monitoring program is adequate. As such, kriging and varicography methods within the Geostatistical Analyst in ArcGIS were used, along with the measured Cs-137 concentrations, to predict Cs-137 concentrations at unmeasured locations. Varicography and kriging were also used to generate probability surfaces showing where Cs-137 concentrations might exceed 0.23 pCi/g.

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 or 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, kriging is used 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. This was accomplished using the standard variogram technique. 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 (quantified 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 quantifies the spatial autocorrelation in the Cs-137 data. For this work, a spherical model with a range of 35,181 m 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 35,200 m, beyond which there is no longer spatial dependence in the Cs-137 values. The sill is equivalent to the variance of the data set, 4.79 pCi/g^2. Figure 6 shows the variogram of the Cs-137 data from 2006. The best estimate fit for this data is a spherical function written as:

$$\gamma = 0.931\text{Spherical}_{35181}+0.07*\text{Nugget} \qquad (2)$$

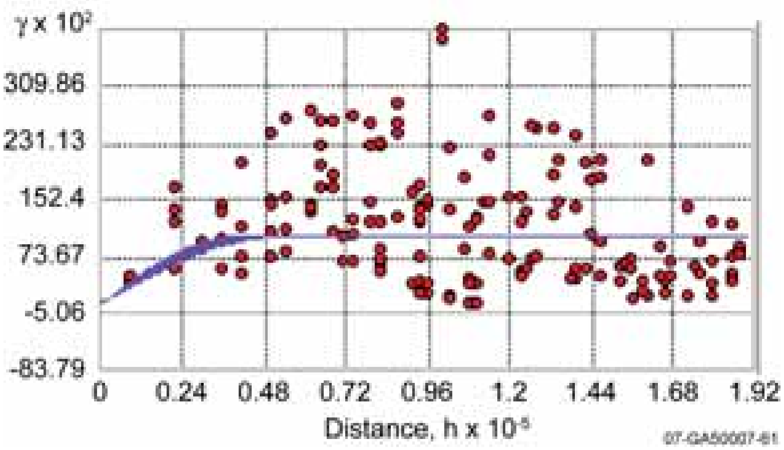

Figure 6. Variogram and best estimated function for CS-137 data. The distance is in meters.

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: The kriging weights for the measured values predictions were calculated over a finely spaced grid of locations. For this work, three of the many available types of kriging were used: ordinary, universal, and disjunctive.

In ordinary kriging, the weight depends on a fitted model to the measured points, the distance to the prediction location, and the spatial relationships among the measured values around the prediction location.

Ordinary kriging is the most general and widely used of the kriging methods and is the default in geostatistical analyst. It assumes the constant mean is unknown.

Universal Kriging assumes that there is an overriding trend in the data and that it can be modeled by a deterministic function, such as a polynomial. This trend is subtracted from the original measured points, and the autocorrelation is modeled from the remaining random errors. Once the model is fit to the random errors and before making a prediction, the trend is added back to the predictions to give meaningful results. Universal Kriging was evaluated for this data, because there are southwest-to-northeast wind gradients across INL that can transport Cs-137 contamination and possibly establish a trend in the data.

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. As shown previously in Figures 2, 4, and 5, the measurement locations have relatively high densities near some INL facilities, namely, RWMC, TAN, INTEC and ARA, with respect to the rest of the INL. 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.

At INL, there is a strong southwest-to-northeast wind gradient that 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. The maps in Figures 7 through 9 show the ordinary, universal, and disjunctive kriging prediction surface results, respectively, and Figure 10 shows the disjunctive kriging probability surface. These maps 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 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 value.

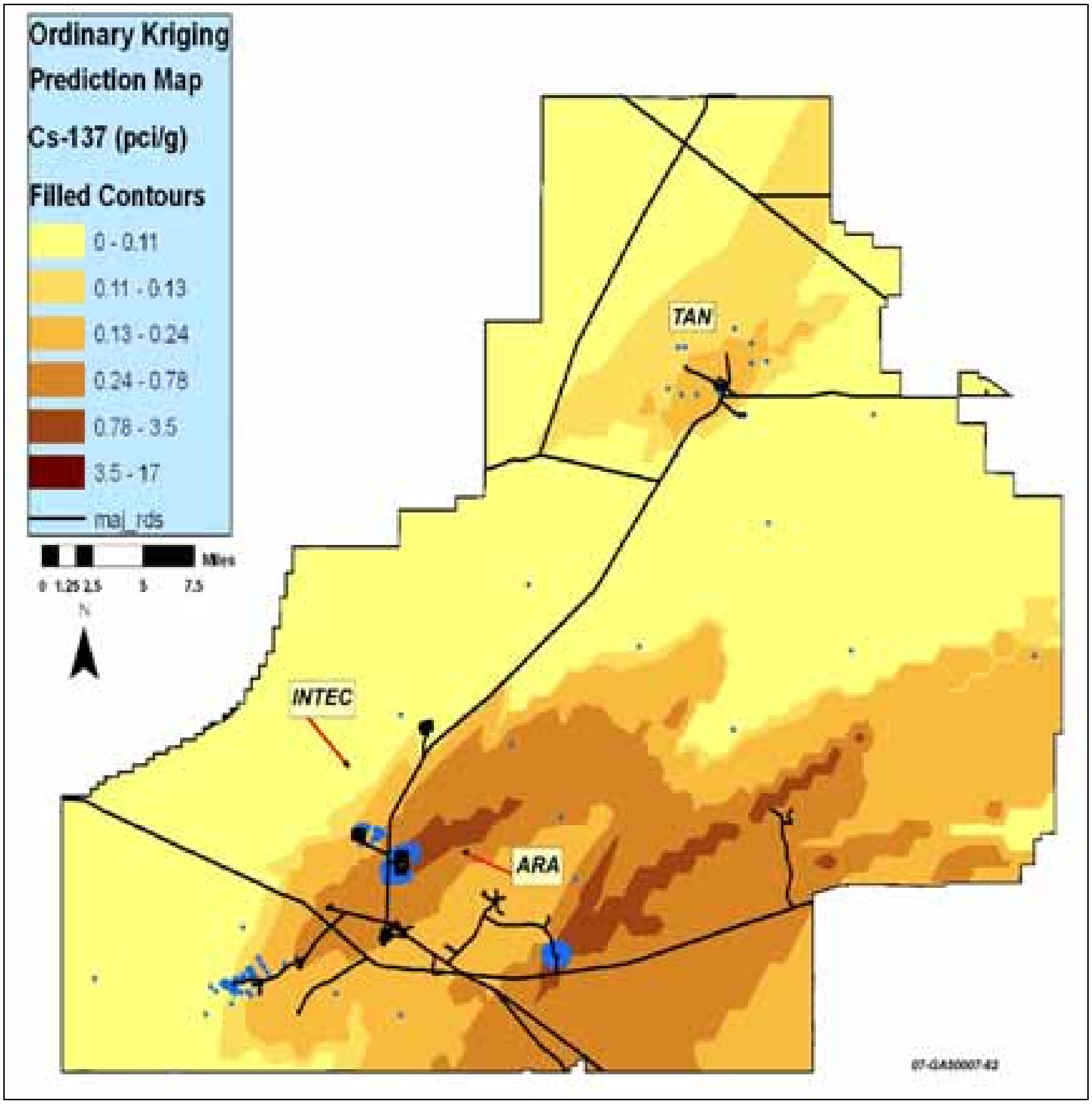

Figure 7. Ordinary kriging prediction surface using anisotropic adjustment. Note the high density of measurement locations near the ARA and INTEC facilities.

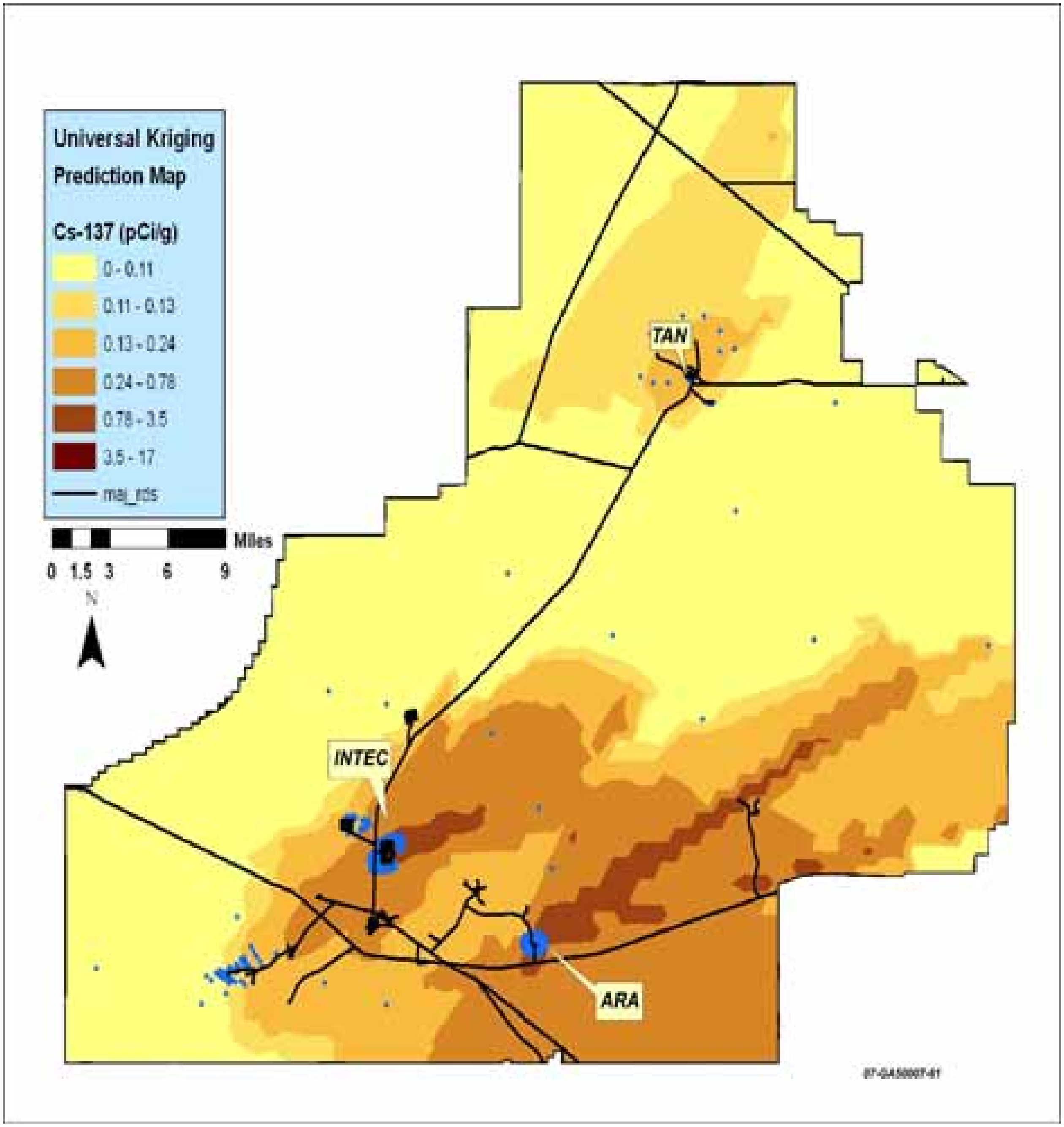

Figure 8. Universal kriging rediction surface using anisotropic adjustment. Note the high density of measurement locations near the ARA and INTEC facilities.

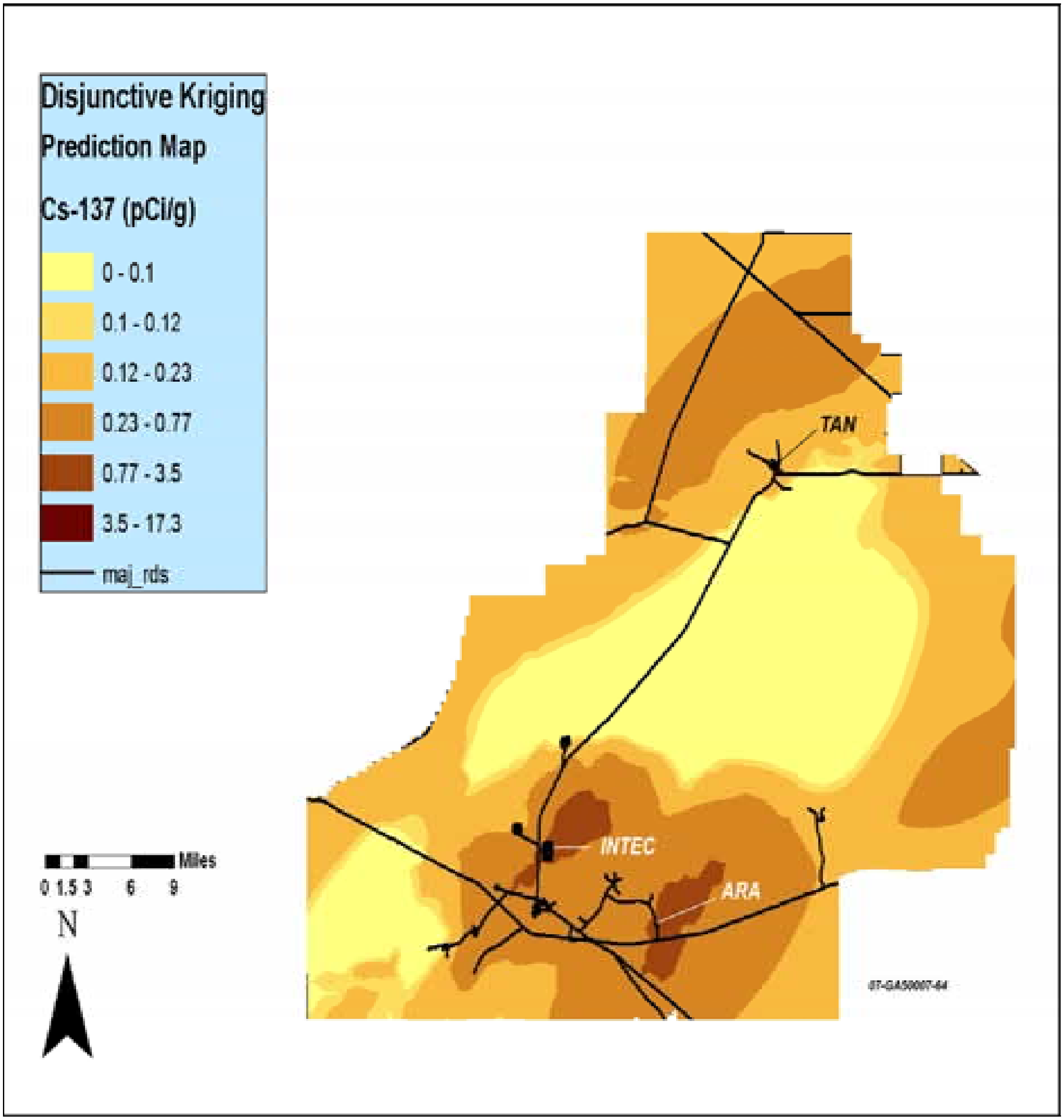

Figure 9. Disjunctive kriging prediction surface using normal score transformation and anisotropic adjustment.

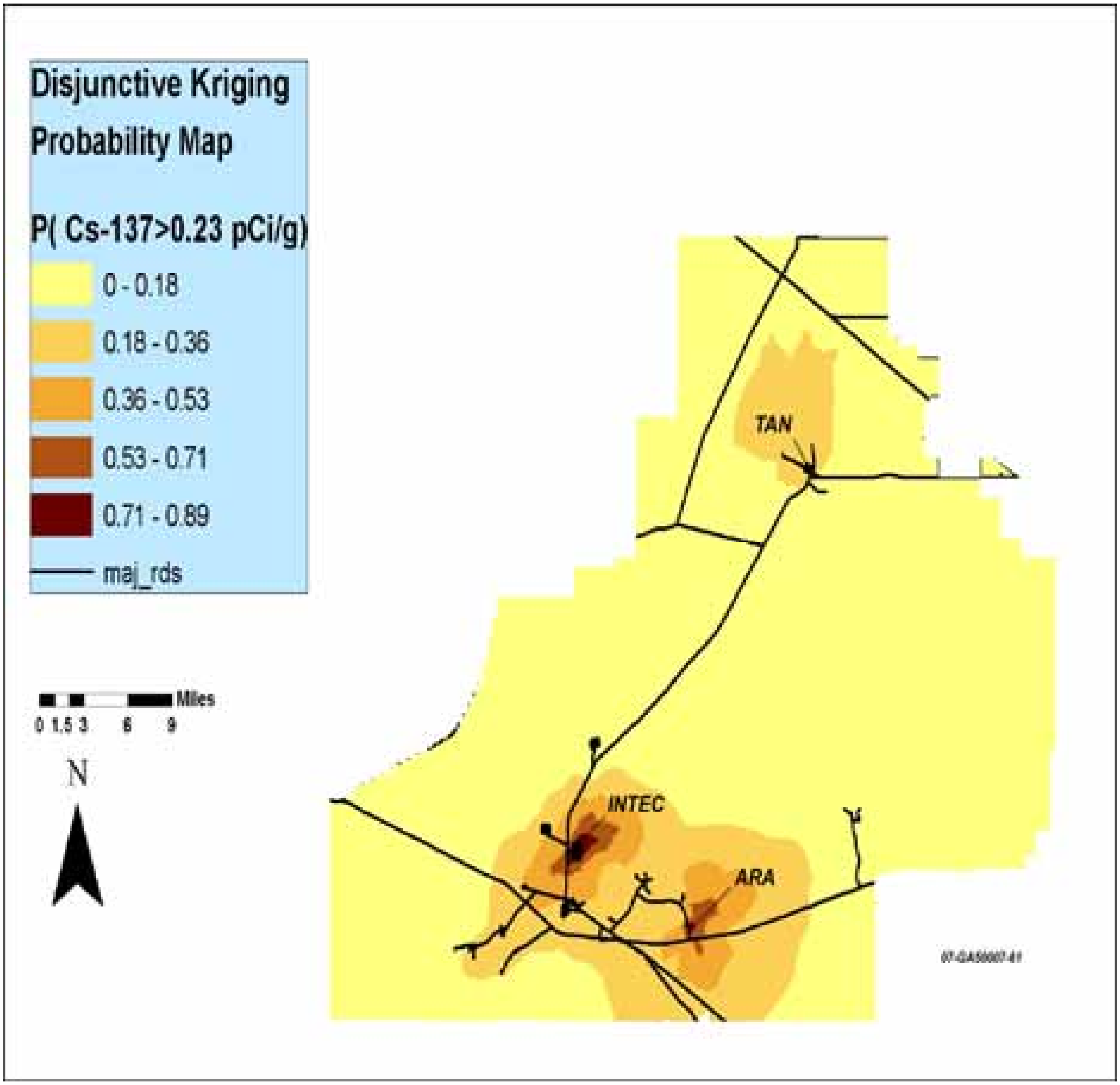

Figure 10. Disjunctive kriging probability surface using anisotropic adjustment. On the surface there is a probability that Cs-137 exceeds 0.23 pCi/g.

The prediction results for several iterations of ordinary, disjunctive, and universal kriging were compared using the standard cross-validation technique in geostatistical analyst. Cross validation yields several statistics that serve as diagnostics that indicate whether a given model provides a reasonable prediction from the given data. Cross validation is performed in geostatistical analyst by removing a data point and using the rest of the data to predict the value of the removed point. This is repeated for each value in the data set.

Table 1 shows that all the predictions are unbiased (centered on the true values because the mean prediction errors are all near zero. The geostatistical analyst was also used to assess the model uncertainties (i.e., prediction standard errors). The average standard errors are close to the root-mean-squared prediction errors, unless the data were transformed. Because the average standard errors are near the root-mean-squared prediction errors, the models based on nontransformed values correctly estimated the variability of the Cs-137 predictions. The ratio of the root-mean-square errors to the average standard error should be close to 1.0 if the average standard errors are valid. In general, ordinary, universal, and disjunctive kriging produced valid prediction surfaces. Due to the declustering capability and low mean prediction error, the disjunctive prediction model was used for comparison to meteorological data described below.

Table 1. Cross validation results from six prediction surfaces for Cs-137 data.

TYPE	ORDIN. DEFAULTS	ORDINARY ANISOTROPY	DISJUNCTIVE ANISOTROPY	UNIVERSAL ANISOTROPY	IDEAL
TRANSFORM	NONE	NONE	NORMAL SCORE	NONE	
MEAN PRED ERROR	-0.03	-0.01	0.03	-0.03	0
ROOT MEAN SQUARE ERROR	1.79	0.18	1.77	1.78	SMALL
AVG STD ERROR	1.94	0.19	0.76	1.72	=RMS
RMS STD ERROR	0.95	0.94	2.3	1.07	1

COMPARISON TO METEOROLOGICAL DATA

INL maintains a database of windrose plots for INL facilities. Windrose maps were georeferenced to meteorological measurement stations at the INTEC, ARA, and TAN sites, as shown in Figures 11 and 12. The windroses coincide with the anisotropic prediction surfaces. The agreement in these measurements validates the anisotropic assumptions and indicates that areas to the northeast of these three sites require additional Cs-137 measurements to further validate, or refute, the prediction surfaces. Additionally, there are areas southeast of ARA and small areas southwest of both INTEC and ARA that require additional measurements. Figure 13 shows hatched polygons drawn over the areas of higher Cs-137 predictions along the strongest wind vectors. These areas represent about 235 mi^2 that need to be measured for Cs-137. Based on the existing sample/area ratio, approximately 12 more measurements would be required to assess the Cs-137 concentrations in these areas.

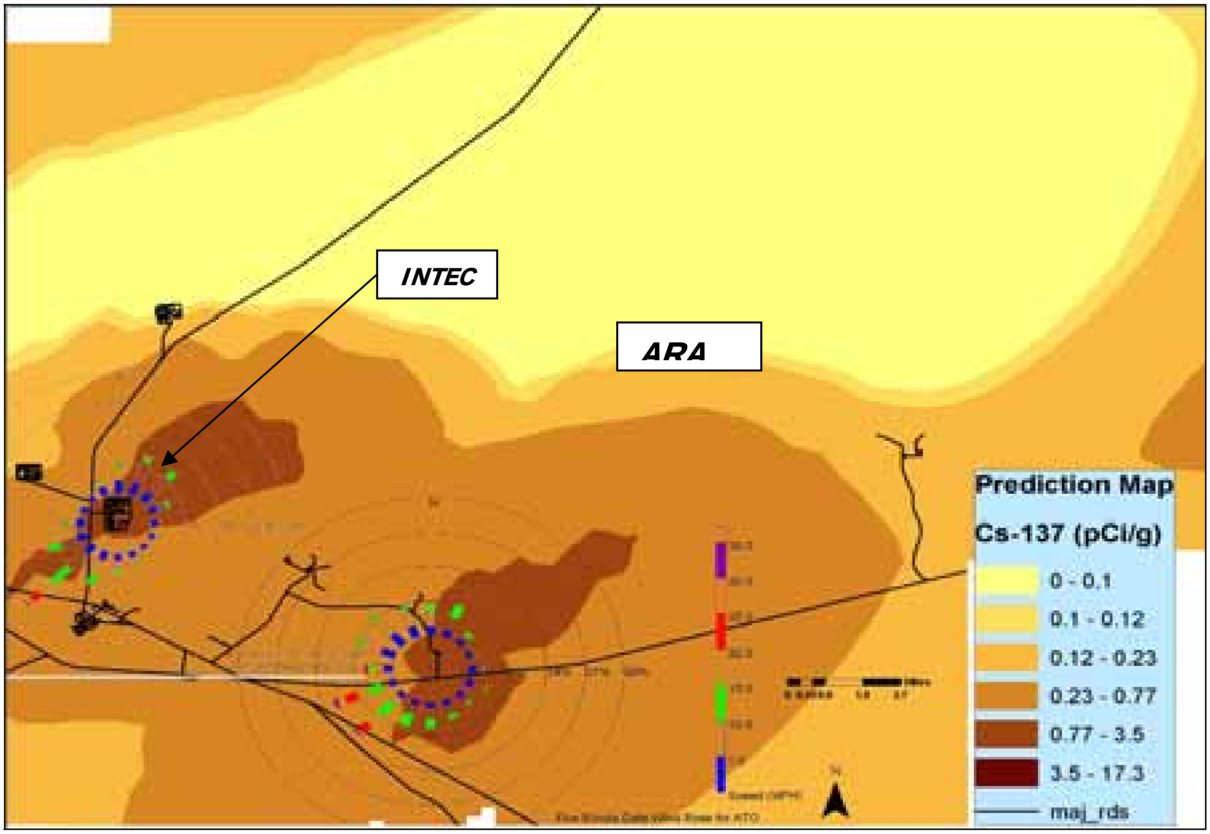

Figure 11. Disjunctive kriging prediction surface using anisotropic adjustment with georeferenced windrose over INTEC and ARA facilities.

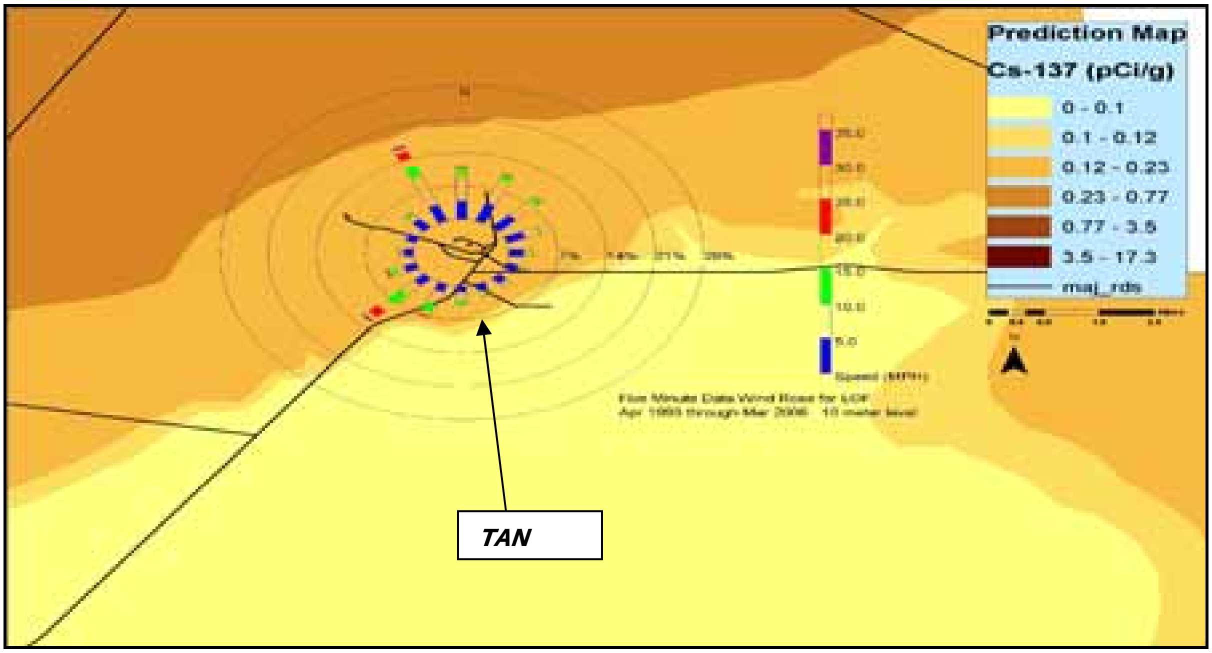

Figure 12. Disjunctive kriging prediction surface using anisotropic adjustment with georeferenced windrose over TAN facility.

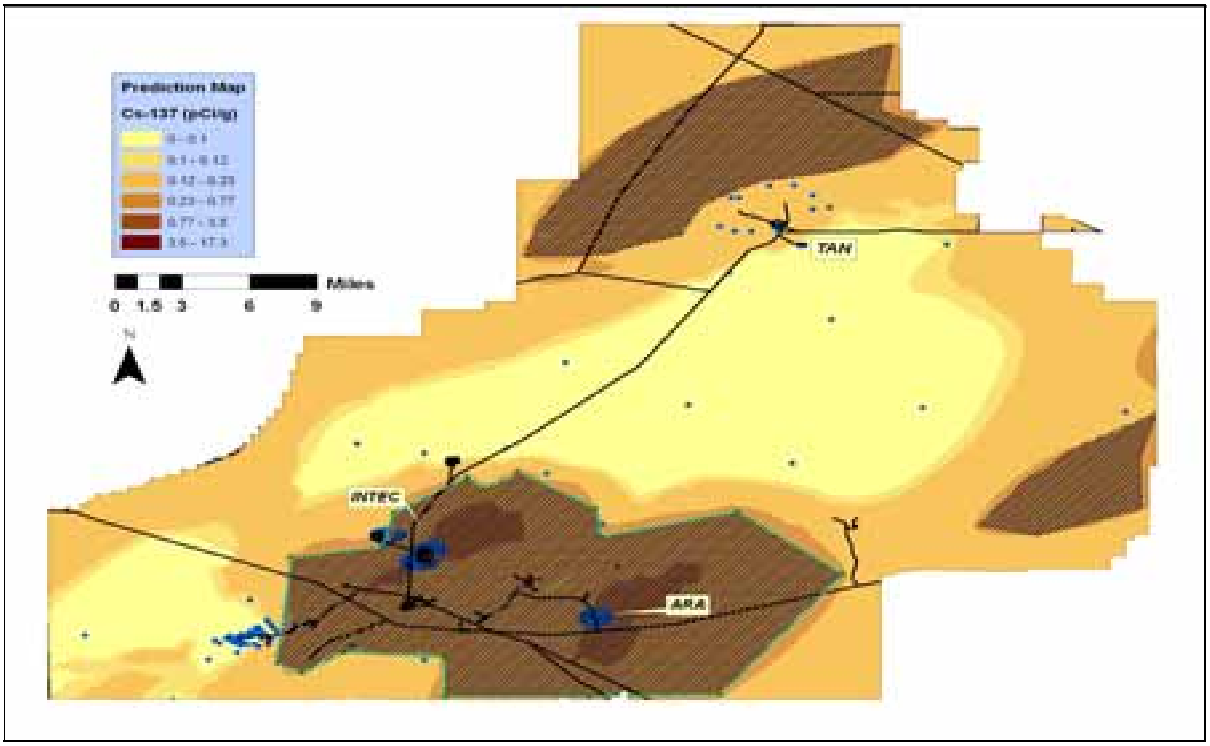

Figure 13. Locations (hatched areas) requiring additional Cs-137 measurements.

SUMMARY

INL conducted measurements for radioactive Cs-137 at 290 locations during 2006. These measurements were performed using in situ gamma spectroscopy. Reporting these measurements was necessary for satisfying US-DOE environmental monitoring requirements. Because INL is such a large site, geostatistical analysis was used to predict the Cs-137 values at unmeasured locations. Ordinary, universal, and disjunctive kriging models produced similar prediction and probability surfaces. The disjunctive kriging results 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 12 measurements are needed to augment the database and improve spatial coverage of these measurements. The use of ArcGIS geostatistical analyst provides a powerful tool for monitoring the Cs-137 concentrations at this site.

REFERENCES

1. Fromm, J. "Radionuclide Risk-Based Concentration Tables." Internal Memorandum to INEL Waste Area Group Managers. 1996.

2. Gogalak, C. "In situ methods for quantifying gamma-radiation levels and radionuclide concentrations." Proceedings of an Institute of Electrical and Electronics Engineers nuclear-science symposium. October 1981.

3. Miller, K.M. and Helfer, I.K. "In situ measurements of 137Cs inventory in natural terrain." Proceedings of the Eighteenth Midyear Topical Symposium of the Health Physics Society; 1985: 243-251.

4. Krivoruchko, K. and Gotway, C. "Creating Exposure Maps Using Kriging." www.esri.com/software/arctisextensions/geostatistical/research_papers.html.

5. Johnston, K., Ver Hoef, J.M., Krivoruchko, K., and Lucas, N., "Using ArcGIS Geostatistical Analyst." 2001.