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Examination of methods for evaluating remining a mine waste site. Part I. Geostatistical characterization methodology[1]

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Abstract

Comprehensive characterization of the distribution and metal content of mine wastes is a crucial component of any project which aims at selective remediation as a function of minimization of cost and risk. Knowledge of the existence of structures and horizons within the sediments is critical to remediation since metal concentrations can vary significantly both within and between groupings of wastes and sediments. The exploratory techniques for structural and statistical analyses of the wastes as presented herein were used to identify population domains between observed waste/sediment classes and by locality within waste/sediment classes. Analysis of Variance (ANOVA) of split spoon samples extracted from the wastes proved to be effective in identifying population domains within the various observed waste/sediment classes. Variography identified the nature and continuity of variability in metal concentrations. Metal concentrations in mine and mill waste may vary rapidly over distance. For this reason, exploratory variogram analysis was used to relate estimation variance to sampling grid design and orientation. Where the deposition of mine wastes is influenced by fluvial processes, gravity separation can take place across areas that are sometimes flooded. This process produces drift in metal concentrations and can complicate the characterization of water deposited or reworked waste/sediment sites. Contaminant levels in mine and mill wastes are controlled by forces that can be very local in nature. As a result, the covariance structure can be non-stationary over relatively short distances. A methodology is presented herein for checking covariance stationarity.

1. Introduction

This paper is the first of two papers that characterize a portion of the Kellogg mine waste Superfund Site near Kellogg, Idaho. The second paper will focus on using the characterization procedures described herein as a means of evaluating alternative remediation schemes for mine waste cleanup.

The Kellogg mine waste Superfund Site occupies approximately 54 km^2 within the Coeur d'Alene mining district of north Idaho. Part of it is situated within the floodplain of South Fork of the Coeur d'Alene River (Fig. 1). The Superfund Site is the result of 100 years of controlled and uncontrolled disposal of mining, milling, and smelting wastes. Mining began in the district in the late 1880s with the discovery of silver at what is now the Bunker Hill mine. Over 20 lead, zinc, and silver mines have operated within the district. Owing to the

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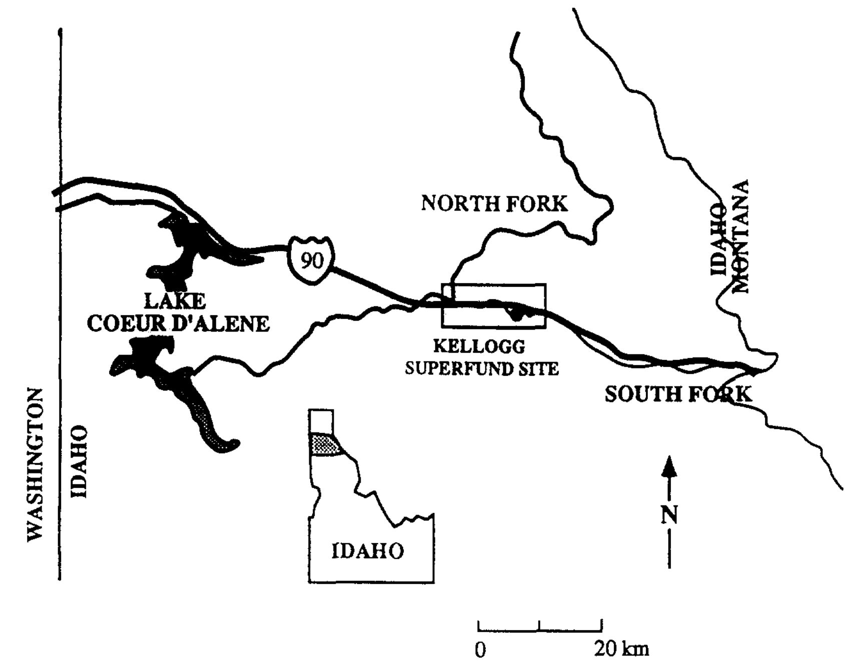

Fig. 1. Location of the Kellogg Superfund site (boundary of the site; after Dames and Moore, 1987).

steep topography and relatively small amounts of level land within the district, mine and mill wastes were discarded predominantly into the South Fork of the Coeur d'Alene River.

The United States Environmental Protection Agency (EPA) has sub-divided the Superfund site into two broad areas that reflect different site characteristics. The first area is termed the "Populated Areas"; it is the primary focus of current EPA study. The second area is termed the "Unpopulated Areas". Risk assessments completed by the EPA suggest that the major possible threat to human health is by ingestion of airborne tailings and smelter wastes that originate from the unpopulated areas (Dames and Moore, 1987). Elevated levels of lead found in the blood of children that live within the populated area attest to the immediate need for remedial action (Idaho Department of Health and Welfare, 1976). Remedial response in the form of removing the lawns from contaminated households has been initiated. Only limited remedial endeavors have been initiated for the unpopulated areas, except for a revegetation experiment conducted by the United States Bureau of Land Management (BLM) on a 40-acre site on Smelterville Flats, the site of this study.

Smelterville Flats occupies approximately 13 km^2 within the "Unpopulated Areas" portion of the Superfund site (Fig. 2). The site is located downstream from the aforementioned mines and has received mine and mill wastes intermittently for approximately 100 years. Such wastes contain various heavy metals; they are also a source of airborne particulates. Norton (1980), Swope (1990), Towatana (1990), Ralston and Kunkel (1989), and Adams (1989), have demonstrated that such wastes have also degraded the quality of water within the underlying aquifers (Fig. 3).

Reclamation of Smelterville Flats is imperative if the objectives of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) are to be met. Typical reclamation procedures for such wastes include: (1) removing and relocating the wastes to an engineered disposal facility that must be located within the boundaries of the Superfund Site; (2) stabilizing the wastes in situ using chemical or biochemical approaches;

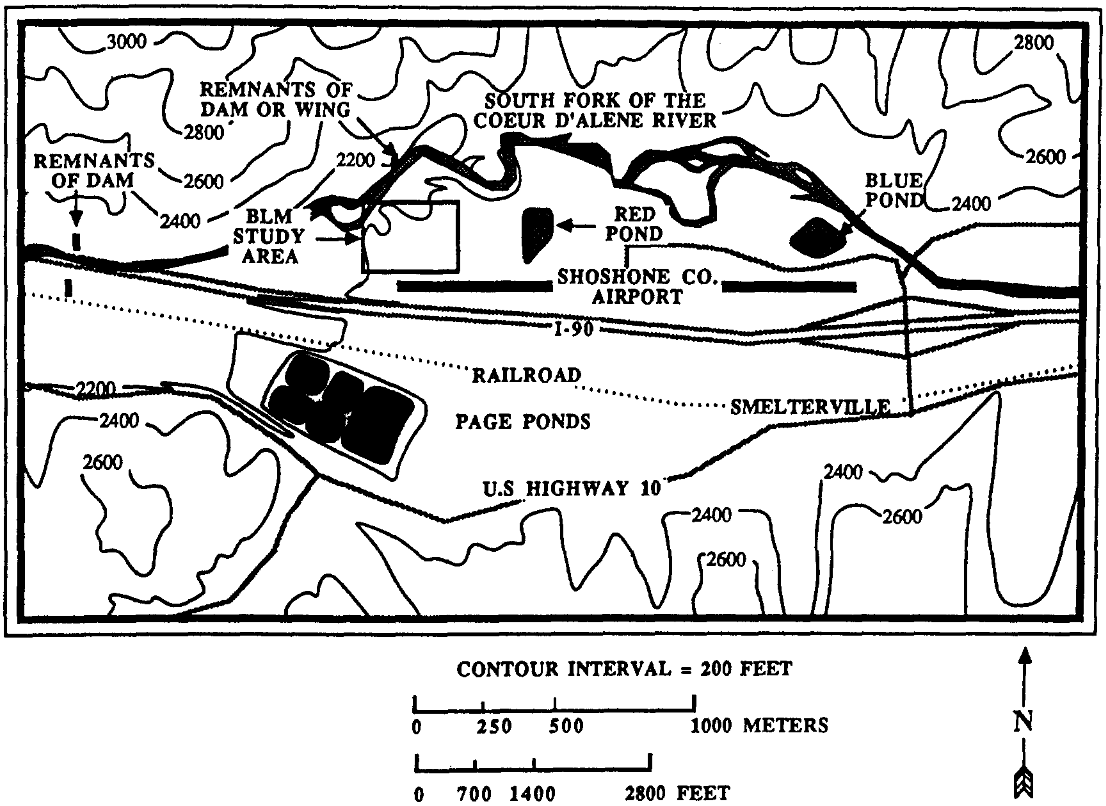

Fig. 2. Location of the BLM study area and current land use. Topography from EPA (1987). Land use from Norton (1980). BLM site location from Adams (1989).

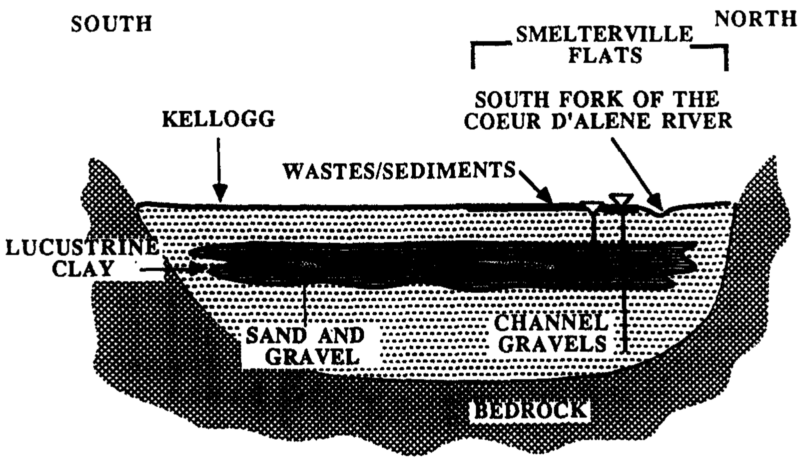

Fig. 3. Generalized transverse cross-section of the valley beneath Smelterville Flats (after Dames and Moore, 1987).

and (3) selective in situ leaching or remining and re-processing of the wastes. Removing such wastes at Smelterville Flats and subsequently relocating them is an option; however, constructing an environmentally sound disposal area would be very costly because land that is suitable for long-term containment is not available within the Superfund site. A major portion of the Superfund site is located within the 100-year floodplain. The details of the hydrological aspects of the Superfund site are discussed by Williams, 1993 (Vol. III).

The principal goal of this first paper is to present the geostatistical techniques used for the characterization of the mine and mill wastes on the 40-acre tract of BLM-administered land on the Smelterville Flats portion of the Bunker Hill Superfund Site. Soil contaminant characterization was done as a prerequisite to possible remedial in situ leaching or mining of the wastes. It has significant influence on the economics and risk associated with either removal and burial of tailings or their stabilization or their remining. Characterization included: (1) examination of the many waste and sediment types so as to define statistically unique waste types for purposes of sampling and spatial modeling of structures and metal concentrations; (2) exploratory variogram analysis in order to establish sampling grid design as a function of estimation error; (3) evaluation of sampling size and preparation prior to assay; and (4) evaluation of covariance stationarity.

Examination of the literature and contact with professionals has made it apparent that very little research has been conducted in the area of geostatistical characterization of mine and mill wastes. Many of the findings reported herein constitute a first application of geostatistical analysis in this field. Some of these results represent new developments in geostatistical modeling. No previous researcher of such wastes has developed a statistically based approach for the testing of covariance stationarity. Likewise, the use of indicator kriging and engineering cost models suggests a quantitative approach to risk analysis and project evaluation that should be implemented if the limited budgets currently available for mine waste remediation are to be spent efficiently.

The experience gained in this project has shown that many complications are inherent in the site characterization of mine and mill wastes. These complications must be accommodated using detailed data analysis and spatial modeling techniques. The relatively modest effort summarized in this paper presents guidelines and precautionary advice to those who will be involved in the evaluation of other mine and mill waste sites.

2. Exploratory analysis

The initial stage of this project focussed on the data acquired by Swanson (1992) on the characteristics of the sediments in the Flats and their influence on metal levels in surface water recharge. The main objective of this sub-site study was to determine the optimal sample grid spacing and sample collection protocol for a larger area.

Of Swanson's 254 original soil/waste samples, seventeen visually identifiable strata were quantified. In order to develop a sampling procedure for subsequent large-scale sampling and mapping of contaminants, the significance of these strata with respect to the distribution of Pb, Zn and Cd had to be determined. It should be noted that about 80% of the assay values for Pb and Zn exceeded 1%.

2.1. *Review of preliminary data*

In order to take advantage of early studies at the site, the experimental sampling grid developed herein incorporated soil assays taken from a small study site delineated by Swanson (1992). This analytical information was used as the basis for expanding a sampling grid across the rest of the study area and as a guide to a sampling protocol. Swanson's (1992) sampling procedure called for separate samples of every visually distinct sediment type to the bottom of the wastes (top of natural sediments). These visually distinct mine waste categories are described in detail by Swanson (1992).

Using this procedure, Swanson (1992) distinguished 17 waste/sediment types. Subsequent ANOVA for these classes of wastes identified two primary groupings: coarser yellow and orange to brown sediments versus a dark clay-like sediment with low permeability that was significantly higher in metal concentrations. Based on the supposed origin of the wastes, these two waste type groupings have been referred to as jig tailings and flotation slimes, respectively. Since jig tailings generally were found to be contiguous and shallower than flotation slimes, most locations required only two samples: one for each category of mine wastes. Therefore, additional samples taken to expand the sample grid followed a different procedure in which a single sample was collected for each of the two horizons, except in the case where jig tailings and flotation slimes were embedded in each other. For details of this approach see Smith and Swanson (1992).

2.2. Sampling protocol

Based on the considerations outlined above, the following sampling protocol was developed.

(1) Sample length was based on a practical volume which could be bagged, dried and sent for lab analysis, approximately 24″.

(2) The entire core was bagged at the sampling site, returned to the lab, air dried and then split to provide a representative sample for shipment and assay.

(3) In zones where the sediment interval being sampled was thinner than two sample intervals, only one sample was taken.

(4) Every sample was located at least 6″ below the surface to avoid contamination by fugitive dust; the samples did not extend into the oxidized zone between the jig tailings and the flotation slimes or include any organic layers.

(5) Multiple samples of the same sediment type in the same hole were individually assayed but, for purposes of point kriging, all samples in the same hole in that sediment type were regularized by length to a single value.

(6) Samples were collected in cloth bags, air dried, split and assayed for lead and zinc.

(7) Sample size considerations are presented in detail by Williams (1993) (Vol. III).

2.3. Spatial analysis for the sub-site study

The main objective of the sub-site study was to determine the optimal sample grid design and sample collection protocol for the larger (40 acre) study area. This objective was accomplished following the completion of sampling and assaying by using variography to determine the relationships between grid design and the global estimation error using ordinary kriging. The experimental variograms from the sub-study site were also used to evaluate the presence of any directional anisotropy in the spatial variance of metal concentration.

2.4. Establishing the experimental variogram

The spatial configuration of the exploratory sampling campaign should facilitate the establishment of the experimental variogram which in turn is used to establish a grid spacing and orientation for any continued sampling in the locality. For this reason, the initial sampling campaign was carried out on two intersecting transects oriented at 90° to each other and oriented with one of the axes parallel to the expected direction of deposition, in this case the river bank. Sampling on the transect was conducted in successive stages with attempts to establish the experimental variogram between each stage. Eventually, as the length of the transects and the size of the data set increased, a stable variogram emerged. Initially, the sample spacing on the transects was close enough to capture the short-scale variability of metal concentrations and sediment structures. As transect length increased, a stable sill was found. Transect length must reach about twice the range of correlation before a stable sill can be established. If the experimental variogram is unstable, additional in-fill sampling in the four quadrants delineated by the transects can be used for better variogram definition. In-fill sample spacing need not be any closer than the smallest lag interval that displays erratic behavior. It is essential that the variogram program being used must have the capability of providing the individual variogram values at each lag distance used in calculating the experimental variogram. Outliers can affect strongly the appearance of the experimental variogram, thereby making it very difficult to interpret the underlying covariance structure correctly. Lag histograms and *h*-scatter plots are indispensable tools in exploratory variogram data analysis. They should be used along with ANOVA and other exploratory techniques to identify outliers and mixed population domains.

Exploratory directional variograms for lead assay and thickness in the jig tailings are shown in Figs. 4 and 5. The global and east–west variograms are reasonably well behaved but, beyond a lag of 100′, gamma decreases. This result is a function of the size of the sampling grid which is roughly 100′ on a side. Since the variogram does not reach an identifiable stable sill before 100′, it became necessary to extend the sampling grid size until a clear sill was reached. Likewise, poor results in the north–south direction (180,0,25) may be a result of the availability of fewer lag pairs in that direction.

Directional variograms for azimuths of 45, 90 and 180° could not be used to infer the presence of anisotropy (significantly different spatial correlation as a function of direction). Also, variograms

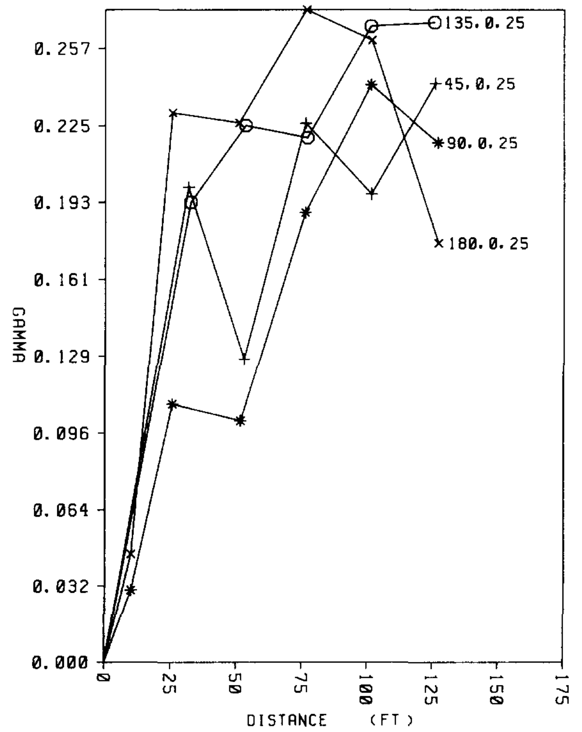

Fig. 4. Experimental directional variograms of lead assay in jig tailings.

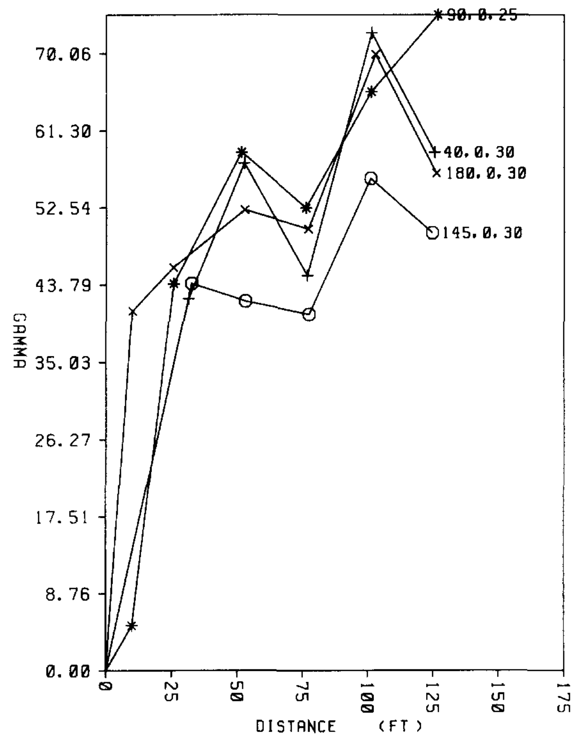

Fig. 5. Experimental directional and global variograms for the thickness of jig tailings.

for flotation slimes were even less well-behaved than for the jig tailings due to the more limited extent of the flotation slimes and the resulting decrease in information.

2.5. Sample size

All of the estimation and subsequent mapping and volumetric calculations were based on data that were essentially point sample values, which in turn were used to estimate block or cell average grades for a point-centered volume. Recognizing that the volume of material which is estimated is far greater than the volume of the samples used in estimation leads to an appreciation of the importance of selecting and preparing a representative sample. Gy's basic sampling equation (Gy, 1979),

$$M = Cd^3/s^2$$

related the minimum required sample lot, M, to the diameter of the largest particles at 95% passing, d, the variance of the assay, s^2, and a sampling constant, C, which is specific to the material's characteristic shape, mineral liberation size, particle size range and mineralogical composition. The safety rule for non-gold ores (Gy, 1979) is:

$$M = 125\,000\, d^3$$

which, in the case of the coarser jig tailings in the study area, indicated that the initial sample lot should be roughly 1 kg. In the case of the finer flotation slimes, a 300-g sample was determined to be adequate.

2.6. Sampling grid design as a function of estimation error

Kriging is the preferred method for estimation since it is a statistically optimal method that provides an estimate of the mean square error (MSE). In kriging, the MSE is based on the sample variance, estimation weights and variogram model. Since both the sample variance and variogram model are determined directly from experimental data, the only variables are the kriging weights. These weights vary in value only as a function of grid spacing and design.

A square grid design was used at Smelterville Flats both for the statistically near optimal properties of estimation based on a rectangular design and for its simplicity. The model variogram for lead assay was used to derive an equation for kriging estimation error which was evaluated for lag distances from 20 to 100′. Based on these results, a grid spacing of 75′ was selected for continued sampling in order to provide a reasonably low estimation error without excessive sampling (see Smith (1992) or Williams (1993) for a more detailed discussion).

2.7. Summary of sampling

The expanded sampling grid covered an area of 1275 × 750′, with most of the area sampled on a 75′ rectangular grid. There are two areas with a higher sampling density: the old Swanson (1992) grid and a second small-scale grid to the southeast which was used to test assay variogram stationarity.

Four hundred and fifty-three samples were taken from 277 holes. These samples showed that mine waste thickness varies from several inches to more than 5′. Sampling holes were augured down to either river clay, gravel or the final organic layer underlying the mine wastes. A typical sample hole consists of jig tailings overlying flotation slimes with a sample taken from each horizon. In some locations, a transition zone occurs between the two sediment classes consisting of "blebs" of oxidized gray slimes in a matrix of red tailings. In this case, the mixed sediments were bagged in accordance with the dominant waste class. Detailed results of the sampling scheme are presented in Williams (1993) (Vol. III).

2.8. Global and spatial statistics

Lead and zinc assays were taken for samples located in both jig tails and flotation slimes. The maximum, minimum, average, standard deviation and variance for all data classes over the full extent of the study area are shown in Table 1.

3. Structural analysis of site

Following exploratory analysis on the small-scale Swanson site, a 75′ square sampling grid was extended across the remainder of the aforementioned 40-acre BLM study site. Four directional experimental variograms were generated for lead

Table 1
Summary of analyses (percentage by dry weight)

	Tails (n=257)		Flots (n=159)	
	PB	ZN	PB	ZN
Mean	2.3659	0.9090	3.8650	2.6435
S.D.	0.6727	0.3059	1.2060	0.7505
Variance	0.4525	0.1449	1.4545	0.5632
Maximum	5.34	3.69	6.96	4.10
Minimum	0.19	0.21	0.38	0.67
Range	5.15	3.48	6.58	3.43
Standard error	0.0420	0.0241	0.0956	0.0595

and zinc concentrations in the tails and slimes as shown by Williams (1993) (Vol. III) and as illustrated for lead in Fig. 6. The variograms imply a range in the north–south direction of about 250′ and nearly 300′ in the east–west direction at an azimuth of 30° as shown by the grid contour maps presented in Williams (1993) (Vol. III). This finding concurs with the original assumption that the general direction of river flow would produce a parallel depositional pattern, but that the apparent anisotropy is weak, perhaps reflecting the sluggish currents that may have existed during the period of initial deposition when the Flats was effectively a large sedimentation basin. Rose diagrams were plotted to help determine whether the anisotropy observed in the directional variograms is significant. The corresponding global variograms display increasing variance with distance without a definite sill. The variogram functions fitted to this expanded data set and used for estimation are presented in Williams (1993) (Vol. III).

Ordinary kriging was used for grid estimation, while MineSoft's Techbase grid contouring routine (MineSoft Ltd., 1993) was used for map generation. Williams (1993) (Vol. III) shows the contoured maps of the estimated grids for zinc and lead assay in the jig tails and slimes, respectively. Unfortunately, reproduction of them here is beyond the limits of the scale of this paper.

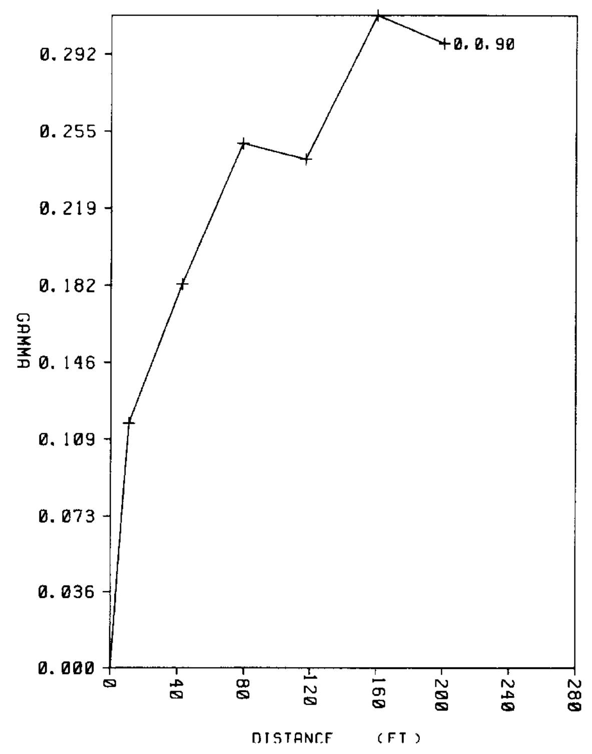

Fig. 6. Experimental variogram of Pb in tails.

4. Stationarity in mine wastes

Typically, a single experimental variogram is fitted to a single population of data; populations are distinguished by the variate being measured and by salient features such as rock or soil type. For each population, a single experimental variogram is fitted, modeled with a continuously differentiable function, and used to establish optimal weights for grid estimation. The obvious advantage of estimating a single experimental variogram is that the maximum possible number of data pairs over the greatest possible lag distance will occur. With more data over a greater area, one would expect the variogram to be more stable and to be a better approximation of the true, but unknowable, underlying variogram function.

Unfortunately, the assumption that a global variogram is equally valid for kriging estimation across all areas of the estimation grid creates a major problem regarding covariance stationarity. It may not be correct to assume that the structure of spatial covariance, as represented by the variogram, is essentially the same for all areas. If it is assumed mistakenly that stationarity does exist, the result will be poor estimation, and the statistically optimal advantages of kriging will be lost because the underlying assumption of the nature of the covariance structure will be incorrect. Therefore, the selection of weights for kriging will be more or less false for different areas of the grid being estimated.

4.1. Assay drift

Average metal concentrations or waste horizon thicknesses can change as a result of location. When deposition of mine wastes is influenced by fluvial pressures, changes in water velocities can result in preferential settling of the metal bearing minerals, resulting in drift in assay levels. Experimental variograms based on data which have a directional trend in magnitude will not have any sill. Instead, a non-transitional variogram will result. It will show increasing variance with distance to lags that correspond roughly to half the extent of the data set. This result may be explained by a strong long range of correlation, but for most cases mine wastes are of relatively small extent (Smelterville Flats being exceptionally large) and do not have the continuity that is expected of large scale structures. When a non-transitional variogram is encountered, the possibility of a non-stationary mean should be checked by fitting a trend surface to the raw data. If a first, or, at most, second, order trend surface provides a reasonable fit, then the residuals of the trend surface should be used to generate an experimental variogram. If the resulting residual variogram is not a pure nugget effect and does possess a range and sill, then either universal kriging or a combination of trend surfaces and residual kriging should be used (Smith and Li Renhao, 1993a, no. II).

4.2. Non-stationary covariance

Prior to this project, no research on methods used for checking the validity of the assumption of covariance stationarity relative to mine wastes has been published. Typically, the only check made of stationarity has been by visual examination of the variograms over a series of windows across the area to be estimated. When the underlying covariance structure is well behaved and the density and extent of the data set are sufficient for local estimation, then visual comparison is adequate; but in the case of noisy data, as is likely for younger, less stable deposits such as mine and mill wastes along stream channels, the variance between data pairs may be so great as to make a visual comparison of experimental variograms a hopeless task. In this case, a statistical approach that can compare the values used to construct experimental variograms from two potentially different populations is required.

Because the original assay data used to generate the experimental variogram as well as the variance values between different lags in the experimental variogram function are highly correlated, a multivariate *F*-test is used to test the assumption of covariance stationarity. This assumption is that experimental variograms generated for two different areas of the data set will be equivalent. The details of this analysis are presented in Williams (1993) (Vol. III) and Smith and Li Renhao (1993b) (no. I).

4.3. Results of the stationarity test

Covariance stationarity between two small areas was tested for lead assay.

The realizations of the variogram functions over two test areas were tested using the multivariate *F*-test as well as a joint T^2 of the overall means. Details of the results are shown in Williams (1993) (Vol. III). The test shows that the difference of the variograms or the covariances of lead content in jig tails between the two small test areas are not significant, whereas the covariance of lead in flotation slimes is significant. Results show greater mobility in the jig tails than in the flotation slimes. The method developed here discusses only the comparison of two areas; however for comparing more than two areas, the same procedure is equally valid.

4.4. Summary of the stationarity test

Based on the results of the multivariate stationarity test, it is apparent that a single variogram and kriged grid model can be used for the jig tails in the BLM 40-acre plot; but for the flotation slimes, it is necessary to select areas of local stationarity and estimate these grid cells using different variogram models. However, it should be noted that at least a few problems exist with applying this technique. One problem is that the subsets of the sample area may not have sufficient data. Another problem arises when the nugget effect accounts for the majority of the variance. In this case, the test for significance is weakened as the difference in the variance between the two populations becomes a smaller portion of the overall variance.

5. Summary

Characterization of lead and zinc concentrations in the mine and mill wastes at the 40-acre BLM site on Smelterville Flats began with an exploratory analysis of the metal content of each visually distinct sediment type observed in the mine and mill wastes on the Flats. Detailed logging of split spoon samples identified 17 visually distinct classes of sediments. The influence of sediment type on the variability of metal concentrations had to be established so that an efficient sampling protocol could be designed. The purpose of this sampling protocol is to simplify sampling and geostatistical analysis of the wastes without loss of explanatory power. ANOVA was used to identify those sediment classes which contained significantly different metal concentrations. This methodology was used to identify sediment types which had to be sampled individually and treated as separate population domains for subsequent statistical analysis.

Exploratory variogram analysis was based on an initial set of samples taken from two transects. In order to define the short-scale variability of metal concentrations and the structural continuity of the sediment types, samples were taken at 10′ intervals along the transects. Subsequent to transect sampling, infill sampling on a 25′ square grid was used to provide sufficient information for exploratory variogram generation.

The exploratory variograms were used to identify a sampling grid pattern spacing and orientation that would yield a reasonable estimation variance without an excessively dense sampling grid. Directional variogram analysis was used to check for covariance anisotropy as part of selecting sampling grid spacing and orientation.

Once the initial exploratory sampling area was completed, a second sampling grid was established to provide a check on covariance stationarity. If it were determined by comparison of the experimental variograms that the covariance structures in the two areas were significantly different, then it would be necessary to use local variograms during the estimation of the model of metal concentrations across the mine and mill wastes. Since no such statistical test of stationarity is reported in the geostatistical literature, a multivariate test was developed as part of this project.

Non-stationarity of the mean waste thickness of metal concentration can also result in a non-representative experimental variogram. Trend surfaces and varicography of the resulting residuals can be used to check for drift and for modeling when drift is present.

The second paper in this sequence of two papers will focus on using the characterization procedures described herein as a means of evaluating alternative remediation plans for mine waste cleanup.

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