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Geology

▲ Geostatistical resource estimation for the Poura narrow-vein gold deposit

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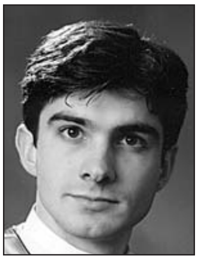
ABSTRACT

A case study for the application of a novel geostatistical technique for resource estimation of a narrow steeply dipping, gold-silver mineralized quartz vein deposit is presented. The technique is novel in two respects. First, mineral grades are kriged directly rather via the accumulation method more often applied to vein deposits and, second, a modified 2D ordinary kriging algorithm is used that allows the calculation of a single grade and variance for irregular shaped blocks of varying sizes. The objective of this investigation was to evaluate the suitability of this novel geostatistical technique for resource estimation of the Poura mine deposit and, if appropriate, to lay a firm foundation for future geostatistical work at the mine.

The reserve estimation concentrated on the remnant ore blocks and pillars in both underground and surface workings. The data, which was collected in 2D coordinates with grade and vein thickness values, was first analyzed statistically and used to compute experimental semi-variograms. Appropriate semi-variogram models were fitted and various aspects of the estimation technique were evaluated using cross-validation error analysis, with acceptable results. A block kriging computer program called Krige2D was developed to implement the modified 2D kriging algorithm and calculations. Production data were not available to evaluate the computed block resources, but they were compared with a previous resource data determined using an arithmetic approach. The geostatistical technique estimated slightly higher grades but lower overall tonnages as compared to the earlier arithmetic estimates.

Introduction

The Poura mine in Burkina Faso, West Africa, has mined a narrow-vein gold deposit using open pit and underground mining methods since the early 1980s. In 1998, a feasibility study was conducted for extraction of the remaining lower grade ore blocks and remnant pillars in the underground mine. The resource estimation procedure for that study involved trimming high-grade outliers and averaging the resulting arithmetic and logarithmic means of samples assigned to each block. Although this methodology was somewhat calibrated from historical production data, there was concern about the accuracy of this estimation procedure and the resulting impact on the estimated resources. In recent years, geostatistical methods have become more widely accepted and routinely applied for resource estimation, although some problems in the application of these methods to narrow-vein and precious metal deposits are recognized (Sinclair and Deraisme, 1974; Deutsh, 1989; Fytas et al., 1990; Dominy et al., 1997). The strength of these geostatistical methods is that they do not make *a priori* assumptions regarding the spatial relationships between mineral grades, vein thickness, etc. in a deposit, but instead determine these parameters independently through semi-variogram analysis. The objective of the study presented here was to investigate geostatistical methods for the resource estimation of this deposit and to make recommendations regarding the potential for further geostatistical work at the mine.



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Background

The Poura mine is located in the Mouhoun Province of southwestern Burkina Faso, about 180 km southwest of the capital Ouagadougou (Fig. 1). It is situated in the centre of the Proterozoic age, Boromo-Goren greenstone belt (Robinson, 1996). The mine's footwall consists of volcaniclastic rocks while detrital sedimentary formations comprize the hanging wall. The deposit consists predominantly of three steeply dipping quartz veins, of which the Filon Plaine is the most economically important and the focus of the most recent production. It has a strike length of more than 2 km, an average thickness of 2 m, and continues to a depth of at least 400 m. The ore is vein quartz with silver-bearing native gold and a minor percentage of polymetallic sulphides. Gold mineralization is concentrated in plunging ore shoots and is enriched in the oxidized zone that extends from surface to approximately 100 m depth.

Artisanal miners exploited the Poura deposit long before a modern underground mine was established in 1961. Operations ceased in 1966 for economic reasons after 5600 kg of gold had been produced from 420 000 t of ore. Reconnaissance work in the late 1970s revealed 1.6 Mt of surface and underground ore with an average gold grade of 13.5 g/t. Open pit mining started in 1981 and two parallel declines were started to exploit the underground resources. The mine exchanged owners several times since then, eventually being acquired by Sahelian International Goldfields, the project's current owner, in 1997. Sahelian continued underground exploration, rehabilitated the surface facilities, and commissioned the 1998 resource estimate and feasibility study referred to earlier.

Fig. 1. Burkina Faso, West Africa.

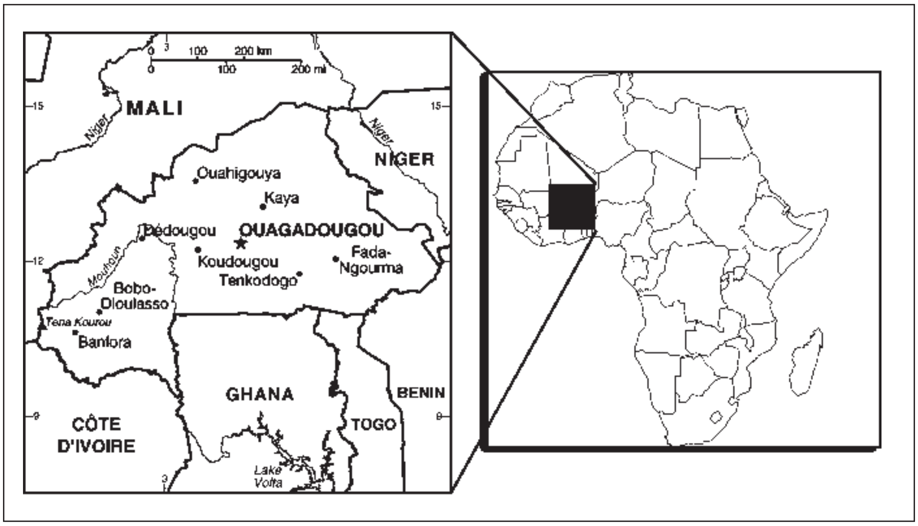
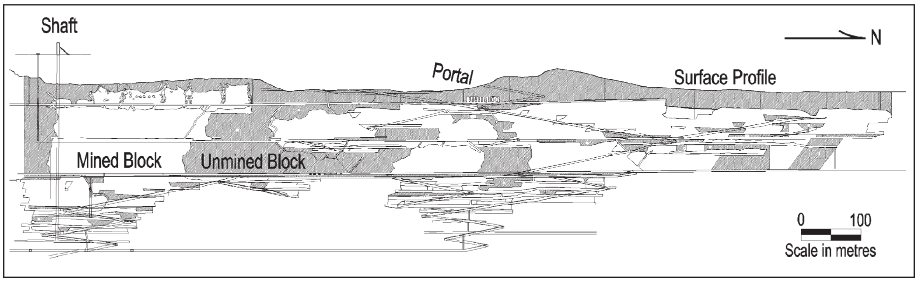


Fig. 2. Longitudinal section of the Poura mine.



Data and Statistical Analyses

The dataset consisted of over 3000 samples taken mostly from channel sampling with some diamond drilling, each reporting gold grade and vein thickness that were taken throughout the underground workings (Fig. 2). Channel samples were taken on an approximate 1 m spacing. No grades for silver in the samples were reported. After discarding samples with missing assays or location coordinates, 3245 good samples were finally used for the analyses. Figure 3 presents a section detailing a typical subset of this data showing the predominantly horizontal sampling orientation along strike. No information was available as to the type of assaying process used for some of the older samples because of differing company policies on metallurgical procedures, but at the time of this study, fire assay was the procedure being used in the mine.

Frequency histograms of the grade, thickness and accumulation (grade x thickness) data are given in Figure 4 and summary statistics for these distributions are given in Table 1. Grade and accumulation show approximately lognormal distributions with a high degree of skewness toward lower values. Upon initial examination, vein thickness appears to have two modes at approximately 1.0 m and 2.5 m signifying a multiple population (Clark and Garnett, 1974; Journel and Huijbregts, 1978; Frempong and Clark, 1996), however, the corresponding cumulative frequency distribution lacks the clear S shape and break point needed to substantiate this conclusion. It is more likely that the large histogram spikes observed at approximate multiples of 0.5 m are due to measurement rounding during sampling, there-

Fig. 3. Representative section showing location of samples.

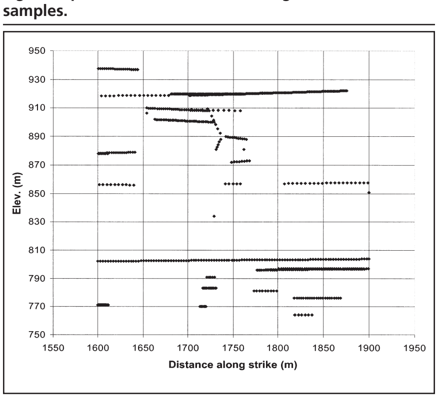


Fig. 4. Histograms of gold grade, vein thickness and accumulation for the Poura samples.

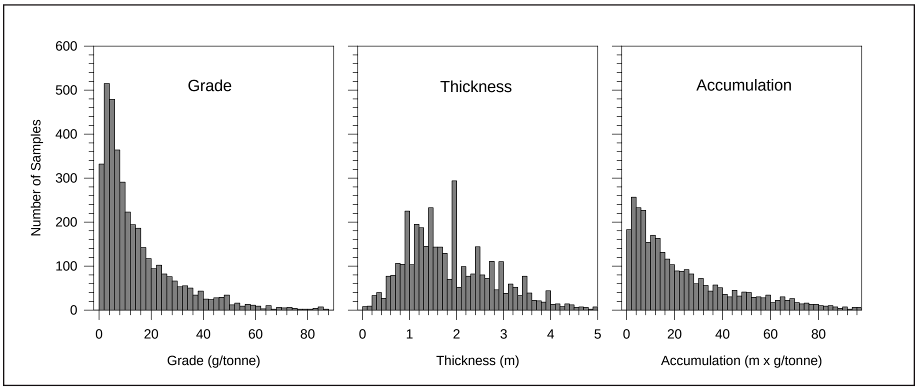


Table 1. Descriptive statistics of sample data

Parameter	Gold Grade (g/t)	Vein Thickness (m)	Accumulation (m x g/t)
Number	3245	3245	3245
Minimum	0.03	0.10	0.01
Maximum	172.20	7.4	430
Mean	15.75	1.92	30.48
Standard deviation	16.78	1.00	38.39
Variance	281.50	0.99	1551.42
Skewness	2.517	0.921	3.494
Mode	50	2	4.5
Coefficient of variation	1.06	0.52	1.29

fore, the vein thickness distribution is interpreted to show a single population slightly skewed toward lower values.

There was no observed systematic variation between mean sample value and sample position throughout the deposit, so no corrections were required to correct for drift during subsequent kriging. Also, declusterizing treatment to regularize the data was not needed due to the uniformity of the sampling and the regular sample spacing.

Semi-variogram Modelling

Semi-variogram modelling was conducted on the various resource data using commercial mine planning software and standard formulae (Journel and Huijbregts, 1978). After considering the sampling distance and spatial distribution of the data, a lag interval of 2.0 ± 1.0 m was used. Experimental semi-variograms were computed along several vectors including strike, dip, and at several intermediate orientations. For all variables, the experimental semi-variograms along strike showed clear structural relationships (Fig. 5) while semi-variograms along the other orientations were considerably more noisy with no clear structural relationship. There was no identified geological or mineralogical basis for the poor quality of the experimental semi-variograms in the non-strike vector orientations, therefore, the most obvious conclusion is these results were based on the general sparseness of sample data along these orientations due to the nature of the sampling program (Fig. 3). For the remainder of the geostatistical work, semi-variogram isotropy was assumed with the semi-variogram data along strike representing the semi-variogram data at all other orientations. However, this assumption was based more on the lack of data rather than any underlying deposit characteristics since, in fact, anisotropy is often observed during mineral resource evaluation (Goovaerts, 1997). This limitation of applying semi-variogram analysis to existing sample datasets has been long recognized (Sinclair and Deraisme, 1974) and this issue will be addressed in the "Recommendations" section of this paper.

The experimental semi-variograms of vein thickness and accumulation were fitted with spherical semi-variogram models while the experimental semi-variogram for grade was fitted with a linear transitive model (Fig. 5). This linear transitive model is not frequently used in geostatistics practice but was selected since it fitted the experimental data better than other single or nested composite models than were examined.

Kriging Methodology and Implementation

Selection of Kriging Method

Several forms of kriging are available including ordinary, universal, lognormal, outlier restricted, indicator, probability, multi-gaussian and disjunctive kriging (Dagbert and David, 1976; Journel, 1983; Verly, 1983; Verly and Sullivan, 1985; Kim et al, 1987; Armstrong and Boufassa, 1988; Arik, 1992). Of these various kriging forms, ordinary kriging is the most straightforward to implement since it is the only method that can compute point or block values directly from the semi-variogram (or co-variogram) relationship without having to provide additional qualifying data or pre- or post-manipulation of the sample data or kriging results. Several authors (Fytas et al., 1990; Dominy et al., 1997) have stated that for grade distributions with a coefficient of variation of less than about 1.5, meaningful semi-variograms can be produced. Fytas et al. (1990) also stated that parametric geostatistics like ordinary kriging perform well in deposits with a coefficient of variation around one or less. From Table 1, both gold grade and vein thickness have coefficients of variation that met this criteria and the coefficient for accumulation is only slightly higher at 1.29. Therefore, ordinary kriging was selected as the estimation method to evaluate in this investigation.

Accumulation vs Grade Approach

It is common practice for resource estimation in narrow-vein deposits to conduct kriging on accumulation and vein thickness independently and then estimate block grades by dividing the kriged values of accumulation by the kriged values of vein thickness rather than directly kriging grades. This practice is based on the frequent observation that grade distributions are highly erratic and do not produce stable semi-variograms or reliable kriging results. However, as shown in Figure 5 and Table 1, grade distributions for the Poura deposit are not too skewed and the data did produce a reasonable semi-variogram. Therefore, it was decided to evaluate the suitability of both the direct grade estimation practice and the indirect accumulation method for the Poura deposit. This evaluation is described in the next section.

Kriging Cross-validation

The suitability of the ordinary kriging method for the Poura deposit as well as the significance of direct grade estimation versus the accumulation method were evaluated using standard cross-validation methods and analysis of the resulting error statistics. These statistics were determined by using the developed semi-variograms and the point estimation algorithm for ordinary kriging to compute the kriged value at each sample location. The error between the actual and kriged values at each sample location was calculated as the difference between the two and the distribution of errors for all sample locations was examined through the development of a histogram. For these kriging estimates, a search sphere with a radius of

Fig. 5. Experimental and modelled semi-variograms for gold grade, vein thickness and accumulation for search azimuth along strike ± 22.5 degrees.

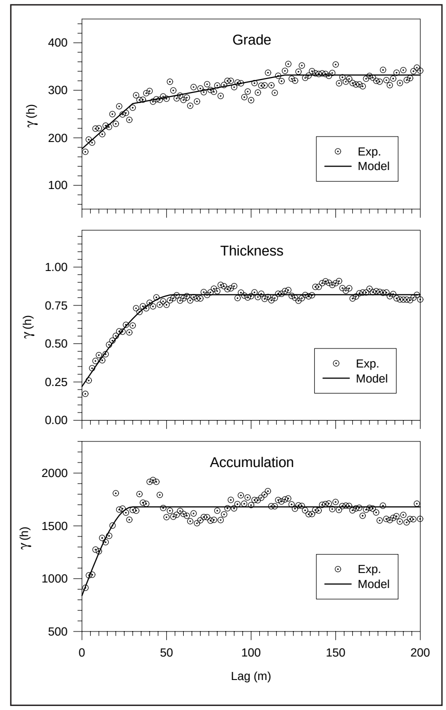


Fig. 6. Histograms of cross-validation errors for gold grade, vein thickness and accumulation. Errors computed as the kriged value minus the measured sample value.

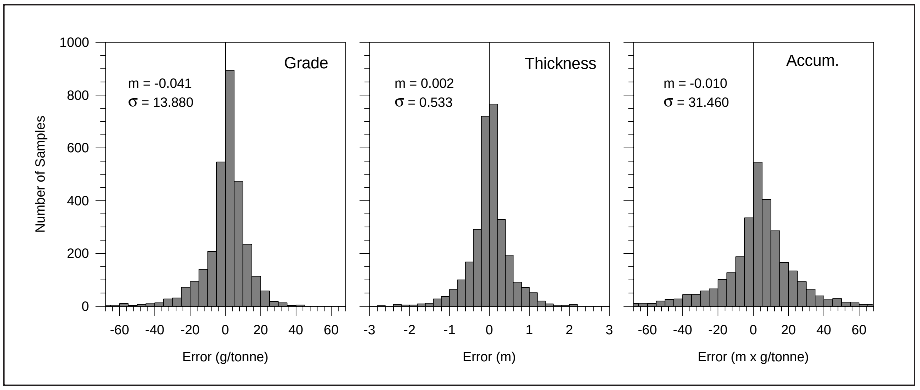
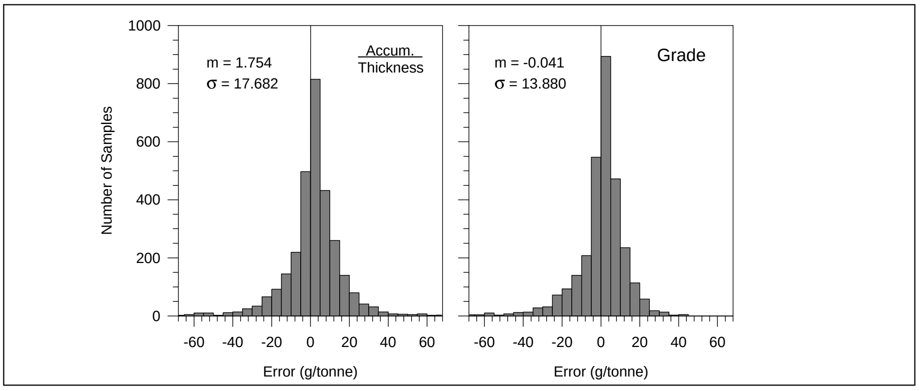


Fig. 7. Histogram of cross-validation errors for gold grade calculated by dividing kriged accumulation by kriged thickness (left) and by direct kriging of grade (right).



120 m was used based on the range of the grade semi-variogram.

Figure 6 presents the error histograms for vein thickness, grade and accumulation, respectively. The vein thickness histogram is uniformly distributed about zero error value indicating that the kriging results are unbiassed (i.e., the kriging procedure overestimates the vein thickness with the same approximate frequency and magnitude as it underestimates it). The grade and accumulation histograms are both slightly skewed toward positive error indicating that the kriging algorithm overestimates the grade or accumulation with a slightly greater frequency than underestimating it. This bias could have been corrected by iteratively determining an appropriate cutoff value for high-grade outliers, as per standard practices, but since the degree of bias shown was relatively small, it was considered acceptable and thus no treatment of outliers was conducted at this stage of the investigation. This issue will be addressed later in the "Recommendations" section of this paper.

To evaluate whether directly kriging grade or using the accumulation/thickness method is the most appropriate for the Poura deposit, a fourth error distribution was determined. This distribution describes the estimation errors for grades determined by subtracting the sampled grade value from the grade estimated at the sample location by dividing the kriged accumulation by the kriged vein thickness. Histograms presented in Figure 7 compare these errors to the error distribution for the direct grade estimation method (repeated from Figure 6). These distributions indicate that both methods have similar levels of bias and accuracy and, in fact, the direct grade estimation method is slightly less biassed (with a mean error value closer to zero) and more accurate (with a lower standard deviation). Therefore, directly kriging grade was the method adopted for block kriging.

Table 2. Block kriging statistics

Parameter	Grade (g/t)	Vein Thickness (m)
Minimum grade	4.67	0.77
Maximum grade	36.28	3.81
Mean	14.85	1.86
Dispersion variance	58.35	

Block Kriging Implementation — Krige2D

As shown in Figure 3, most of the sample data was recorded in the stopes and mine openings bounding the ore blocks and pillars of interest. The arithmetic resource estimation procedure used for the 1998 feasibility study utilized only those samples located adjacent to each block in the resource calculation for that block. As well, many of the blocks were irregular in shape and the standard rectangular block array used by most commercial mine planning software was considered too coarse to accurately map the irregular boundaries of many of these blocks. Given these considerations, a custom block kriging program Krige2D (Roy, 2000) was developed which employed two primary features:

1. Each block was defined as a 2D closed polygon consisting of straight-line segments coinciding with the block boundaries as indicated on mine sectional maps. The software then discretized an internal grid of 1 m by 1 m points to get uniform coverage of the block interior.

2. The subset of samples used for kriging was limited to the those samples which bounded the block or were otherwise assigned to the block due to close proximity. Thus, no searching sphere or ellipsoid was used to determine those samples which fell within the volume of influence of the block.

Once the block boundaries and the subset of samples were defined, the software conducted block kriging for each block as per standard algorithms (Journel and Huijbregts, 1978) and generated a single value of gold grade and vein thickness which could then be used to estimate the block resource (Table 2). It was presumed that the resource estimation on a whole block basis would also smooth some of the irregularity that might occur if smaller subblocks were used. This procedure would also facilitate better comparison with the block resources computed using the earlier arithmetic method since the same samples would have been used for each block.

Kriging Results

Block kriging using the Krige2D software was conducted for all the blocks of interest in the Poura deposit. The resource reported for each block was determined from the product of the kriged grade and thickness estimates for the block. Since no production data was available at the time of this work, it was not possible to evaluate the accuracy of the block resource estimates. Even if production data was available, the complications of concurrent production in multiple stopes and difficulties with material balances in the materials handling and mineral processing streams would have made accurate evaluation of the resource estimates difficult. However, the error statistics analyses described in the preceding section suggest that the results should be at most only slightly biassed with respect to grade overestimation and unbiassed with respect to vein thickness estimation.

For comparison, the block resources computed by kriging were compared with the arith-

Table 3. Comparison of estimation results

Block	Block Kriging Estimates			1998 Study Estimates		
	Grade (g/t)	Tonnage (t)	Resources (kg)	Grade (g/t)	Tonnage (t)	Resources (kg)
1	25.18	1975	49.73	14.78	1983	29.31
2	18.68	512	9.56	9.21	588	5.42
2A	6.77	2045	13.84	4.89	1753	8.57
3	20.21	1008	20.37	15.43	943	14.55
4	27.37	2518	68.92	17.46	2367	41.33
5	23.44	1261	29.56	18.55	1473	27.32
6	8.68	456	3.96	5.26	774	4.07
6A	12.83	137	1.76	9.48	147	1.39
7	13.87	1136	15.76	10.35	1377	14.25
8	9.72	8579	83.39	5.8	13903	80.64
9	8.85	10800	95.58	8.22	10482	86.16
10	22.48	1376	30.93	23.28	1926	44.84
10A	10.57	6356	67.18	8.55	5894	50.39

metic block resources computed during the 1998 feasibility study. Table 3 presents a representative list of blocks where the same subset of samples were used by both estimation techniques. As shown, the kriging method generally estimated higher grades with lower tonnages for the blocks and resulted in higher resource estimates for most blocks. Overall, for this subset of blocks, the kriging method estimated 5451 t less resource but 82.3 kg more gold than the arithmetic method. This pattern was repeated for all the other blocks which were compared for both methods.

Conclusions and Recommendations

From the work presented in this investigation, two primary conclusions can be drawn. First of all, from the cross-validation kriging error analysis it was shown that for the Poura deposit, the direct estimation of grade is as accurate and unbiassed (or even slightly better) than estimating grade via the accumulation/thickness approach. Whether or not this simplified resource estimation approach is suitable for other deposits remains to be evaluated. Secondly, the application of geostatistical methods to an existing sample dataset can be problematic, particularly when the spatial distribution of samples impedes the reliable development of directional semi-variograms and evaluating semi-variogram anisotropy. This reinforces the findings of earlier studies.

From these results, several recommendations can be made regarding further geostatistical work at the mine:

1. The sampling program should be modified to get better spatial distribution of samples, in particular, increased sample density along non-strike orientations. This would enable better evaluation of semi-variogram anisotropy. At a minimum, increased sampling along dip could enable the estimation of an approximate range along this orientation while relying on the good quality semi-variogram along strike to provide the sill values. As well, inclusion of silver assays in the sampling database would enable the evaluation of a potential linear relationship between gold and silver grades and subsequent estimation of silver resources via co-kriging.

2. When production is resumed, more detailed metal accounting should be employed. This will enable evaluation of the geostatistical block resource estimates which, in reality, is the only true measure of the accuracy of the estimation procedures.

3. Further work should be done on the treatment of high-grade outliers. As was suggested earlier in this paper, these outliers may be the root cause of the slight overestimation bias observed for both grade and accumulation. Further investigation of trimming these outliers or even adopting a more sophisticated kriging method designed to handle outliers (e.g., indicator kriging) is warranted. Improvements in reducing bias or increasing accuracy can be evaluated using the cross-validation methods utilized in this investigation.

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