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Estimation of lignite reserve in the Kalburcayiri field, Kangal basin, Sivas, Turkey

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Abstract

This paper addresses a case study on global estimation of lignite reserve in the Kalburcayiri field from the Sivas–Kangal basin, which is one of the most productive lignite basins in eastern Anatolia, Turkey. The two lignite seams, which were developed in a fresh-water lacustrine depositional environment during the Pliocene time, are currently being exploited in the Kalburcayiri open-cast mine for feed coal to a power plant with 300-MW capacity. Tonnage, thickness and quality parameters (ash yield, total sulphur content, and calorific value) of the lignite are variables considered in this study. The global estimates of these variables together with 95% confidence limits are obtained using the approximation principle of global estimation. A random stratified grid is fitted to available boreholes; the variograms for thickness and lignite quality parameters are estimated and modeled. The models are used in calculating estimation error variances that will later be used in constructing 95% confidence intervals for the true values. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Lignite; Geostatistics; Variogram; Global estimation; Error variance

1. Introduction

Coal reserves are those parts of resources for which sufficient information is available to enable prefeasibility study and for which such planning has been undertaken. Global estimation of coal reserves refers to estimates for tonnage and averages of coal quality parameters (ash yield, total sulphur content, and calorific value) over an entire coal deposit and measures for the accuracy of these estimates. Such estimates are useful in making decisions about opening up new coal mines, or in planning future investment for operating mines.

The total coal reserves of Turkey are estimated to be in the order of 8.4 Gt lignite and 1.1 Gt bituminous coal. Total annual lignite production is about 65.2 Mt, of which 80% is consumed for electrical generation in coal-fired power plants (Altas et al., 1998). The coal-fired power plants are widely distributed in Turkey, with the majority in the west.

The Sivas–Kangal basin, which is one of the most productive lignite basins in eastern Anatolia, includes three lignite fields: Hamal, Kalburcayiri, and Etyemez (see Fig. 1). Two lignite seams, the subject of this study, are currently being exploited in an open-cast mine in the Kalburcayiri field for feed coal

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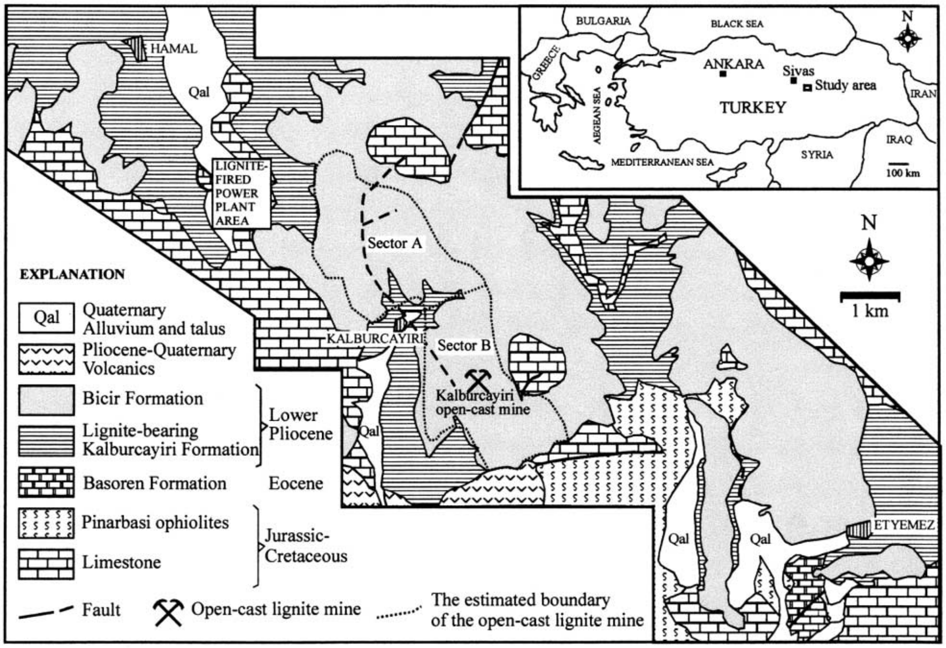

Fig. 1. Simplified geological map of the Kangal lignite basin (modified after Utku, 1976; Narin and Kavusan, 1993).

to a power plant with 300-MW capacity. The Kangal coal-fired plant annually consumes about 3.6 Mt run-of-mine lignite produced from the large-scale open-cast Kalburcayiri lignite mine. A new unit with 165-MW capacity and a flue gas desulphurisation system has been recently installed. Once the new unit comes on stream, annual total lignite consumption will reach about 5.5 Mt (Gayer et al., 2000; Karayigit et al., 2001). Plans are underway to construct another boiler; the decision will entirely depend on a reassessment of the global coal reserve estimates for the Kalburcayiri lignite field.

The purpose of the paper is to globally estimate the lignite reserves in the Kalburcayiri field in order to provide mine planners and decision makers with reliable information. One such attempt in this direction was made by Sen and Sarac (2000) who used kriging as the estimation technique and kriging variance as a measure of its accuracy. However, as pointed out by Journel and Huijbregts (1981), kriging is not an appropriate tool for global estimation over great distances; it is difficult to calculate the kriging variance due to cross-covariances. In this paper, a relatively simpler approach is considered: fit a random stratified grid (RSG) to available samples, estimate global averages by means of individual panel values, and assess accuracy of the estimates by global error variance. Assessing the accuracy is more difficult than estimating the global quantity. In this study, the global error variance is estimated by using approximation principle (Journel and Huijbregts, 1981), which is based on combining elementary errors that come from the same estimation configuration. In the literature, other techniques for the estimation of the global error variance are suggested. Among them are block-kriging shortcut (Crozel and David, 1985) and global kriging. At the feasibility stage, a simpler method is required and these methods are too complex to use at this stage. In addition, the predictive performances of these methods are not very well known. Indeed, Hansen et al. (1990) give the upper and lower bounds for global error variance of block-kriging shortcut for regular and random stratified grids, and based on the results obtained from a simulated field, they conclude that the estimates of these bounds are consistent with actual global estimation variance. However, using a real data set Isaaks and Srivastava (1989, pp. 521–513) have shown that the predicted error variance is considerably greater than the actual error variance. In addition to this shortcoming, both methods require covariance values for distances which are up to the dimensions of the global area and as pointed out by Buxton (1986), in practice, the covariance function cannot be estimated reliably for these distances. To the authors' knowledge, this is the first time that the approximation technique is applied to the evaluation of a lignite deposit. Although this method was basically developed for the evaluation of stratiform deposits and has found some applications in metal mines (e.g., Royle, 1977; Journel and Huijbregts, 1981; Dowd and Milton, 1987; Buxton, 1988; Wellmer, 1998), it is surprising that so far no such study has been undertaken for lignite deposits.

The paper deals first with estimation variance and confidence intervals for reporting the reliability of the estimates. In addition to knowing the global estimates, it is important to know the accuracy of the estimates. In this study, the accuracy of the estimates is assessed through estimation variance. Following a description of the RSG, estimation variances for tonnage, thickness, and the lignite quality parameters will be discussed. In the final section of the study, the Kalburcayiri lignite field and data used in the estimation are introduced. After inferring the variograms for thickness and lignite quality parameters, the global reserves together with a 95% confidence interval are estimated. Estimations are carried out for the upper and lower seams in the Kalburcayiri field.

2. Estimation variance and confidence interval

Whenever an unknown value is estimated, an error is made. It is, of course, impossible to know this error. However, geostatistical theory shows that the variance of the distribution of the errors (estimation variance) can be calculated in terms of a variogram. The variance of the distribution is a good measure of the spread of the global error distribution and thus gives an idea of the accuracy of the global estimate. A large estimation variance relative to the estimate implies a poor estimate. The probability of such an estimate being far from reality is high. Conversely, a low estimation variance indicates an estimate close to reality. Though estimation variance can be useful in reporting the reliability of estimates, it is not useful for decisions that require an absolute indication of the magnitude of the error. One way around this problem would be to use confidence intervals. If one assumes that estimation errors follow a Gaussian (normal) distribution with zero mean and a variance equal to estimation variance, the confidence intervals can be constructed depending on the estimation process. As pointed out by Isaaks and Srivastava (1989, pp. 504), global distributions of errors, even for very skewed data, do tend to be symmetric. This does not mean, however, that they are necessarily well modeled by a normal distribution. Unfortunately, there has been very little work on alternative models, and a 95% confidence interval will likely remain a standard for reporting uncertainty. The second assumption is most critical; variance of the error distribution may not be well predicted by estimation variance and, thus, is heavily dependent on the estimation method used. Fortunately, Buxton (1985), testing a wide variety of estimation scenarios, shows that estimation variance obtained by using the approximation principle is an accurate estimator of the actual error variance.

A confidence interval consists of a minimum value, a maximum value, and a probability that the unknown value falls within this range (Eq. (1)).

$$\Pr\left[z^{*} - z_{\alpha/2}\sigma_{\mathrm{E}} < z < z^{*} + z_{\alpha/2}\sigma_{\mathrm{E}} \right] = 1 - \alpha \qquad (1)$$

where z^{*} is the estimated value, σ_{E} standard deviation of estimation error, α a confidence level, and $z_{\alpha/2}$ the z value leaving an area of $\alpha/2$ to the right under a normal density function curve. For example, the most traditional 95% confidence interval for an actual value z estimated by z^{*} is given as follows:

$$\Pr\left[z^{*} - 1.96\sigma_{\mathrm{E}} < z < z^{*} + 1.96\sigma_{\mathrm{E}} \right] = 0.95 \qquad (2)$$

3. The sampling grid

In the approach followed here, it is assumed that the basic data are obtained from boreholes on a regular or irregular grid and a random stratified grid (RSG) can be fitted to the sample points (Fig. 2). Although we recognize that under certain conditions there can be more efficient sampling schemes (Ripley, 1982), the assumption is justified here based on the fact that a random stratified (or uniformly random) sampling grid is a common feature of field

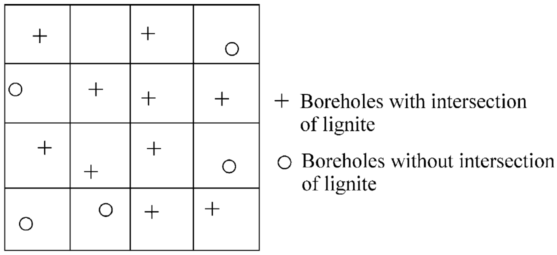

Fig. 2. A random stratified sampling grid.

problems. When the sampling grid is taken to be uniformly random, the grid mesh is regular: all grid panels have the same shape and size. To fit an RSG to the intersections of the boreholes with coal, the size and orientation of the grid are adjusted so that, as far as possible, one sample lies within each grid panel. The area of one RSG panel is roughly obtained by dividing the area of interest by the number of samples it contains. The ratio of lengths of the RSG panel sides is best obtained by an examination of the sampling pattern. If this seems uniform, a square RSG is probably the best. Otherwise, if samples were taken along lines and the distances between the lines are greater than the intervals between samples, a rectangular grid with sides equal to the mean sampling interval and mean line interval could be tried. Although the aim is to have each of the RSG panels occupied by a single sample, inevitably, some panels will contain two or more samples and some none. Where two or more samples occur in an RSG panel, the panel is given the mean value of its samples and treated as though only one sample with this mean value was available in it. Where RSG panels without any samples in them lie within the deposit, surrounded by apparently payable panels, and where there is no reason to suppose that coal does not continue through them, they are included in reserves (Royle, 1977).

4. Tonnage estimation and relative error variance

Three factors are required to estimate the tonnage of reserves (T):

- the area of the lignite deposit, S;
- the average thickness of the lignite deposit, m_t; and
- the average specific gravity of the lignite, m_d.

$$T = S \times m_t \times m_d \tag{3}$$

The accuracy of this estimate can be obtained from the Eq. (4) for the relative estimation variance of the tonnage:

$$\frac{\sigma_T^2}{T^2} = \frac{\sigma_S^2}{S^2} + \frac{\sigma_{m_t}^2}{m_t^2} + \frac{\sigma_{m_d}^2}{m_d^2} \tag{4}$$

where σ_S^2/S^2, $\sigma_{m_t}^2/m_t^2$ and $\sigma_{m_d}^2/m_d^2$ are the relative estimation variances, respectively, for the surface area, the average thickness and the average specific gravity. As no data are available for specific gravity calculations, the term $\sigma_{m_d}^2/m_d^2$ is taken as zero and all tonnage calculations are calculated using a standard average specific gravity. The relative estimation variance is then:

$$\frac{\sigma_T^2}{T^2} = \frac{\sigma_S^2}{S^2} + \frac{\sigma_{m_t}^2}{m_t^2} \tag{5}$$

Table 1
Basic statistic parameters for the upper and lower seams in the Kalburcayiri field from the Kangal basin

	Upper seam				Lower seam			
	t	$t \times$ cal	$t \times$ ash	$t \times s$	t	$t \times$ cal	$t \times$ ash	$t \times s$
Number of data	163	157	124	79	158	151	124	80
Mean	7.05	9163	159.7	16.80	6.37	8465	169	16.99
Variance	17.13	4.0 × 10e + 7	7797	76.38	11.87	2.9 × 10e + 7	7152	48.95
r	–	0.94	0.85	0.91	–	0.92	0.88	0.92

Abbreviations: t = thickness, $t \times$ cal = accumulation for calorific value, $t \times$ ash = accumulation for ash, $t \times s$ = accumulation for total sulphur, r = correlation coefficient between thickness and accumulation.

4.1. Area estimation error

The estimated area of the reserves is equal to the size of an RSG panel multiplied by the number of positive panels within which the lignite deposit is intersected. The relative error variance for this estimation is given by

$$\frac{\sigma_S^2}{S^2} = \frac{1}{n^2}\left(\frac{N_1}{6} + 0.0609\frac{N_2^2}{N_1}\right), N_2 \geq N_1 \qquad (6)$$

where n is the number of positive grid panels, N_1 half the number of positive grid panel sides around the perimeter of the lignite surface parallel to one axis of the RSG, and N_2 half the number of positive grid panel sides parallel to the other axis of the RSG (Journel and Huijbregts, 1981).

4.2. Average thickness estimation error

The average thickness is estimated by the mean of the thickness of positive panels. The estimation variance for the average thickness of the lignite deposit is obtained by dividing the error variance for a single panel, σ_p^2, by the number of the positive panels, n. The value of σ_p^2 depends on the location of the sample within the panel, the length of the grid panel side and the spatial variability of thickness. It is possible to express σ_p^2 in terms of these variables but the expressions are difficult and time consuming to use. Instead, the variance can be plotted as a graph. For example, Journel and Huijbregts (1981, p. 128) show values of error variance for a spherical variogram model when the sample is taken at random within an RSG panel.

If the boundary of the lignite deposit is not known and is estimated by the geometry of the panels intersecting lignite, an additional uncertainty is inserted into the estimated mean value. This is known as the edge effect and must be added to the error variance of the estimated mean. The edge effect is given by:

$$\frac{\sigma_S^2}{S^2}\mathrm{Var}(t)$$

where Var (t) is the variance of the thickness. In this case, the error variance for the estimated mean is equal to:

$$\sigma_{m_t}^2 = \frac{\sigma_p^2}{n} + \frac{\sigma_S^2}{S^2}\mathrm{Var}(t) \qquad (7)$$

5. Estimation variance for average lignite quality

Lignite quality variables (ash yield, total sulphur content, and calorific value) cannot be used directly in the global estimation because they are not defined on a constant support, i.e., they are not additive. In such cases, a new variable, accumulation, (i.e., the product of the thickness and the lignite quality variable) is defined. For example, if calorific value, cal, is considered to be the lignite quality variable, the corresponding quality accumulation, ac, is defined as:

$$\mathrm{ac} = \mathrm{cal} \times t \qquad (8)$$

The accumulations for other quality variables can be calculated in a similar manner. The mean accumulation of the entire lignite deposit is then estimated by the mean of the accumulations of each of the panels. Lignite quality estimates, m_q, can be obtained in an approximate manner by dividing the estimated mean accumulation, m_{ac}, by the estimated mean thickness, m_t:

$$m_q = m_{ac}/m_t \qquad (9)$$

The relative error variance of the estimated mean lignite quality is given by:

$$\frac{\sigma_{m_q}^2}{m_q^2} \approx \frac{\sigma_{m_{ac}}^2}{m_{ac}^2} + \frac{\sigma_{m_t}^2}{m_t^2} - 2r\frac{\sigma_{m_{ac}}}{m_{ac}}\frac{\sigma_{m_t}^2}{m_t^2} \qquad (10)$$

where r is the correlation coefficient between thickness and accumulation, and $\sigma_{m_{ac}}^2/m_{ac}^2$ is the relative error variance for the accumulation. This term can be calculated in a manner similar to that of the thickness estimation. Note that this is an approximation and that quality estimates can be obtained in this manner only under certain restrictive conditions. The most important of these conditions are:

- thickness estimates are sufficiently accurate (relative error less than 1),
- accumulation and thickness estimates are made from the same data configuration.

In practice, these conditions are only important for individual panel values and the effects of them not being met for global estimation are not significant (Dowd and Milton, 1987).

6. Geological background

The Kangal lignite basin was developed in a fresh-water lacustrine depositional environment during the Pliocene. Only limited geological investigations about this basin are available; some previous authors investigated coal geology, proximate analysis, and trace element contents of the lignite samples collected from boreholes and open-cast mines (e.g., Utku, 1976; Gokmen et al., 1993; Narin and Kavusan, 1993; Gayer et al., 2000; Karayigit et al., 2001). A geological map, simplified from Utku (1976) and

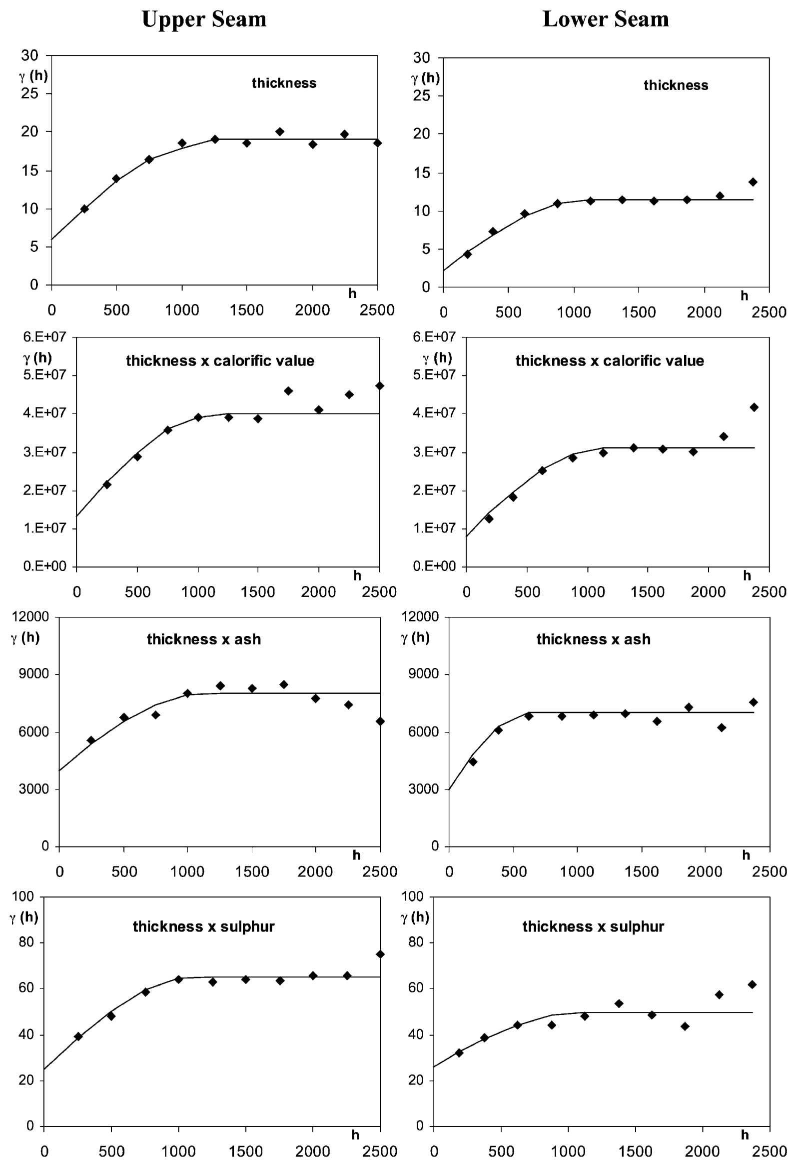

Fig. 3. Experimental and model variograms in the Kalburcayiri lignite field from the Kangal basin.

Table 2
Variogram parameters for the upper and lower seams in the Kalburcayiri field from the Kangal basin

	Upper seam			Lower seam		
	C_0	C	a	C_0	C	a
t	6	12	1100	2.2	9.3	1100
$t \times$ cal	$1.33 \times 10e + 7$	$2.63 \times 10e + 7$	1100	$8.00 \times 10e + 6$	$2.30 \times 10e + 7$	1100
$t \times$ ash	4000	4000	1100	3000	4000	600
$t \times s$	25	40	1100	26	24	1100

Abbreviations: t = thickness, $t \times$ cal = accumulation for calorific value, $t \times$ ash = accumulation for ash, $t \times s$ = accumulation for total sulphur.

Narin and Kavusan (1993), is presented in Fig. 1; also shown on this map is the boundary of the area of the Kalburcayiri open-cast mine for which Tercan (1998) applied probability kriging.

The Pre-Neogene (Jurassic–Cretaceous and Eocene) rocks form the basement. The Lower Pliocene rocks were subdivided into the Kalburcayiri and the Bicir formations. The former consists of two thick lignite seams, the upper and lower, which are associated with siltstone, claystone, and marl. The two seams are separated by about 20 m of tuffaceous sedimentary rocks in the Kalburcayiri field; this interburden varies from 4- to 26-m thick (Narin and Kavusan, 1993). In this study, the Kalburcayiri is divided into sectors A and B. The Bicir Formation composed of fossiliferous marl, clayey limestone and

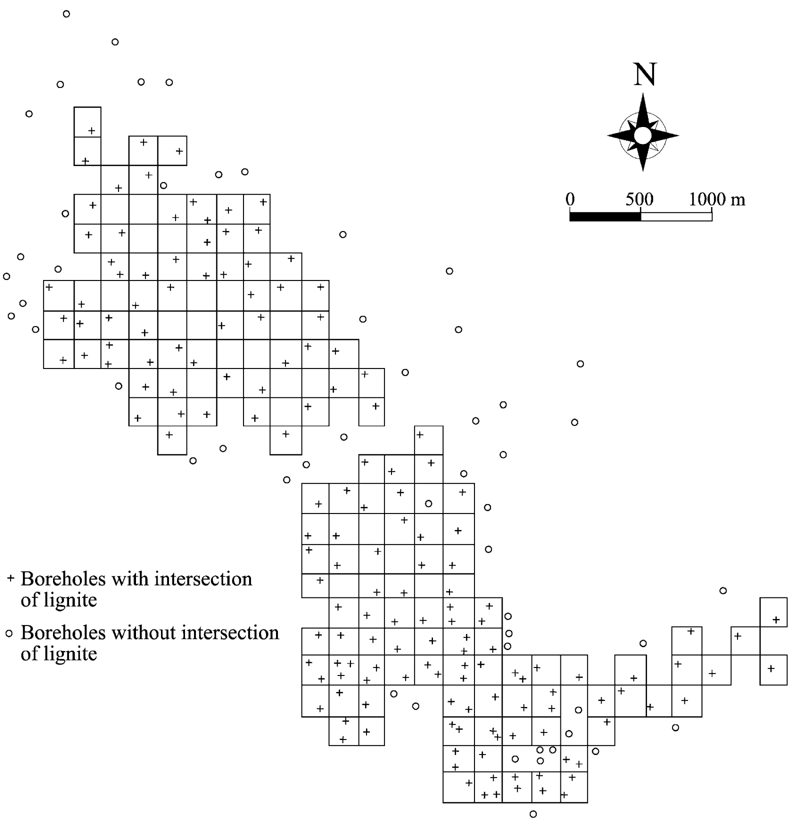

Fig. 4. Random stratified grid fitted to boreholes in the upper seam in the Kalburcayiri lignite field from the Kangal basin.

limestones, and Narin and Kavusan (1993) noted that Pliocene/Quaternary volcanic rocks (andesite and basalt), pyroclastic rocks (tuff, lapilli tuff) occur to the southeast of Kalburcayiri. Basaltic lava flows are widespread beyond the study area (Utku, 1976). Quaternary deposits are represented by alluvium and talus. The Kalburcayiri and Bicir Formations in the Kangal basin lie nearly horizontal; dips range between 2° and 5°. A normal fault is developed within the Kalburcayiri Formation (Utku, 1976; Narin and Kavusan, 1993; Karayigit et al., 2001).

7. Data

The data used in this study are from the upper and lower seams. MTA (General Directorate of Mineral Research and Exploration of Turkey) drilled about 220 exploration and development holes in an irregularly pattern. Of these, 163 intersected the upper and 158 the lower. We evaluated thickness and accumulations for calorific value, ash yield and total sulphur content from this data set. The proximate analysis of core samples used in this study was determined by MTA. Basic statistics for thickness and accumulations are shown in Table 1. Note that the mean and variance of the thickness of the lower seam is less than that of the upper seam. This suggests that the lower seam has less variability. A descriptive statistical analysis of the sample data collected from boreholes in sectors A and B indicates that the lignite quality of sector A is relatively poorer than that of sector B. This is the case for both seams. For example, in the upper seam, while average calorific

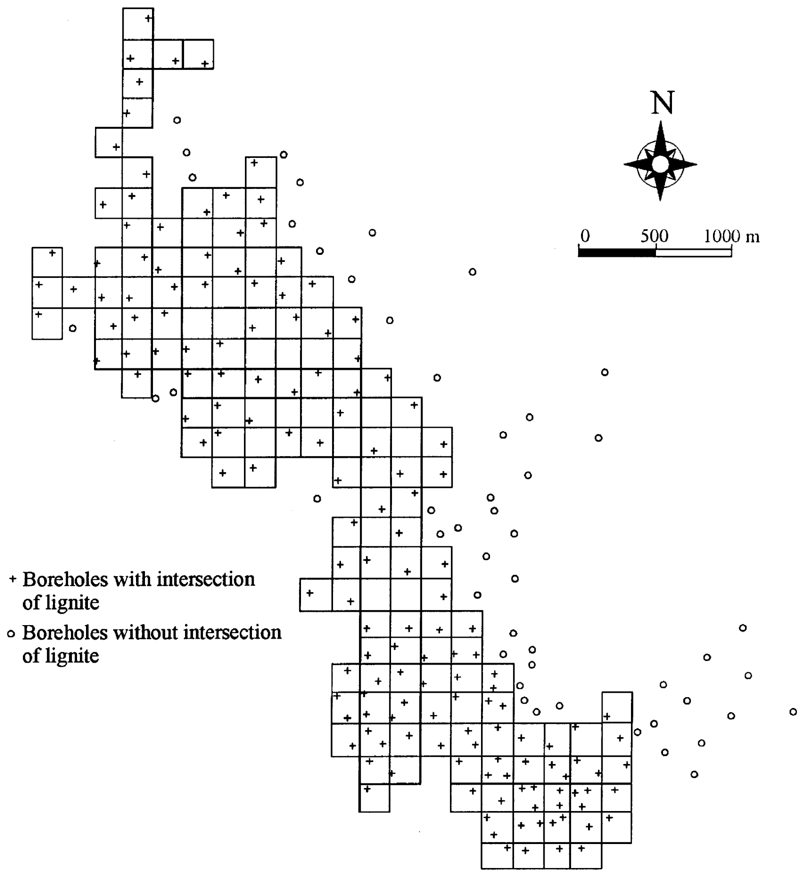

Fig. 5. Random stratified grid fitted to boreholes in the lower seam in the Kalburcayiri lignite field from the Kangal basin.

value and ash yield for sector A are, respectively, 1150 kcal/kg and 21.8% ash, these are 1394 kcal/kg and 20.6% ash in sector B. Similarly, in the lower seam, while average calorific value and ash yield of sector A are, respectively, 1271 kcal/kg and 24.4% ash, these are 1334 kcal/kg and 23.9% ash for sector B. We think that this pattern may be related to the proximity of sector B to the Pliocene/Quaternary volcanic rocks (andesite and basalt) located south of Kalburcayiri (Fig. 1).

8. Variogram analysis

The variogram is a geostatistical tool that characterizes the spatial variability of the variable considered. It is used in various procedures of resource and reserve evaluation. The variogram in this study is used to quantify the geological factors that affect the accuracy of estimates. Sample variograms for thickness and accumulations (calorific value × thickness, ash yield × thickness, and total sulphur content × thickness) for the two seams are calculated. Because no severe anisotropy is found, only an omnidirectional variogram is retained for modelling. The model variograms consist of one nugget effect and one spherical scheme:

$$\gamma(h) = C_0 + C\left[1.5(h/a) - 0.5(h/a)^3\right], \quad h < a$$
$$\gamma(h) = C_0 + C, \quad h > a$$
$$\gamma(h) = 0, \quad h = 0$$

where C_0, nugget effect or variance due to random or small scale structure; C, structural variance ($C_0 + C$ is sill or total variance); and a, range of influence. Fig. 3 shows experimental and model variograms. Table 2 gives model parameters for each variogram.

Except for the total variance, there is a remarkable similarity between the variograms of the upper and the lower seams. The same observation can also be made when thickness is compared with accumulation. This is an expected result since the correlation coefficient between thickness and accumulations is very high (Table 1).

9. Global estimation

Considering the principles given in Section 3, the unit grid was chosen to be square with a side length of 200 m; the RSG of 200 × 200 m was fitted to the two lignite seams (Figs. 4 and 5). This produced 158 RSG panels for the upper seam and 156 for the lower seam. Using Eqs. (2)–(10), the reserves for the two seams were globally estimated and the results summarised in Table 3. The fourth and last columns in Table 3 are confidence limits expressed as percentage of the estimate. This allows a comparison of the confidence intervals. The errors quoted in Table 3 indicate that the largest source of uncertainty among the variables is the thickness. Also note that the lower seam has shorter intervals than the upper seam. This is due to the low nugget variance associated with the thickness of the lower seam.

10. Conclusions

The reserve of the Kalburcayiri lignite field was globally estimated and the accuracy of the estimates

Table 3
Global reserve estimates for the upper and lower seams in the Kalburcayiri field from the Kangal basin

	Upper seam			Lower seam		
	Estimate	95% confidence limits (±)	% of estimate (±)	Estimate	95% confidence limits (±)	% of estimate (±)
Reserve (ton)	58 289 400	4 406 567	7.55	51 673 440	3 246 630	6.28
Surface area (m^2)	6 360 000	235 557	3.70	6 240 000	219 880	3.25
Thickness (m)	7.05	0.46	6.52	6.37	0.33	5.18
Calorific value (kcal/kg)	1299	33	2.55	1329	37	2.77
Ash yield (%)	22.65	0.83	3.67	26.53	0.78	2.93
Total S content (%)	2.38	0.07	2.77	2.67	0.05	2.08

assessed. The global estimations indicate that the field has a tonnage of 110 ± 7.7 Mt of lignite at a 95% confidence level. Although this may be enough for the three boiler units of the Kangal coal-fired power plant that consumes annually about 5.5 Mt of lignite, when an additional new boiler unit is constructed, it may be necessary to open up new lignite mines in the Hamal and/or Etyemez fields. The global mean values at a 95% confidence level over the whole field are estimated to be 1313 ± 35 for calorific value, $24.47 \pm 0.81\%$ for ash yield, and $2.52 \pm 0.06\%$ for sulfur content. Specifications of feed coal to the power plant seem to fall inside these interval estimates.

The magnitude of the confidence intervals varies depending on variable considered but the intervals are small enough to classify lignite reserve as proven. This study shows that the variogram, in particular its nugget parameter, is an important factor affecting the magnitude of the confidence intervals. Another factor that has a significant impact on the intervals is panel size. Although it is fixed in this study, it is expected that as the panel size increases, the confidence intervals get shorter. This is an area that requires further research.

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