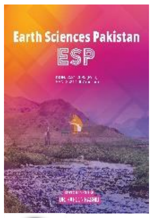
ZIBELINE INTERNATIONAL™ PUBLISHING
ISSN: 2521-2893 (Print)
ISSN: 2521-2907 (Online)
CODEN: ESPADC

Earth Sciences Pakistan (ESP)

DOI: http://doi.org/10.26480/esp.01.2025.20.25



CrossMark

RESEARCH ARTICLE

A GEOSTATISTICAL APPROACH TO ALLUVIAL GOLD DEPOSIT ESTIMATION AT THE KIBI GOLD DISTRICT, GHANA

Blestmond A. Brako[a]*, Seidu Abubakari[a], Daniel O. B. Nuamah[a], Amadu Charles Casmed[b], Gordon Foli[a], Simon K.Y. Gawu[a]

[a] *Kwame Nkrumah University of Science and Technology, Kumasi*
[b] *C. K. Tedam University of Technology and Applied Sciences, Earth Science Department*
**Corresponding Author Email: ablestmond@gmail.com*

ARTICLE DETAILS

Article History:

Received 19 March 2025
Revised 22 April 2025
Accepted 26 April 2025
Available online 16 May 2025

ABSTRACT

This research compares ordinary kriging (OK) and inverse distance weighting (IDW) techniques in the estimation of volume, tonnage, average grade, and ounces of gold within the alluvial gold deposit located in the northern part of the Kibi-Winneba gold belt, Ghana, to ascertain the technique that yields results that align more closely with actual production values. The deposit contains fine nuggets of gold in gravel profiles covered by sharply contrasted overburden materials. Overburden and gravel layers from 219 hand-dug pits were logged, while the gravel portions were sampled and assayed by washing to determine the gold grade of each pit. Implicit modelling of the deposit using wireframes was carried out in Datamine Studio RM software. The block model and resource estimates were compared and accurately reflected the input sample grade. At a cutoff grade of 0.4 g/m^3, the resource has 12.453 million cubic metres of auriferous gravel at an average grade of 0.51 g/m^3. This is expected to produce about 204238 ounces of gold after mining and extraction. Different block models and resource estimates using the inverse distance weighting (IDW) approach were used to compare the OK estimate. The IDW^2 correlated well with the OK model. Hence, a resource estimate was generated using the IDW^2 and the difference in the expected ounces of gold was calculated to be 2.02% lower than that of the OK estimate.

KEYWORDS

Geostatistics, Kibi gold belt, Ordinary kriging, Alluvial gold deposit, Inverse distance weighting

1. INTRODUCTION

Alluvial gold deposits occur in several favorable geographic locations in Ghana underlain by Birimian metasedimentary and metavolcanic rocks (Nkrumah et al., 2019). The amount of small-scale gold mining, primarily of alluvial deposits, had increased tremendously, especially in places like the Atewa range, where substantial alluvial resources are known. Over the years, the exploitation of alluvial gold deposits in Ghana was done using artisanal methods. However, significant increases in gold output in recent times were largely as a result of the proliferation of technological advancements in mechanization and Ghanaian initiatives to boost investment in the mining sector (Awudu, 1994). Estimating alluvial gold resources/reserves, which form the basis for economic decisions, is an important step in a feasibility study of any mining project (Rossi and Deutsch, 2013). Mining requires huge capital for development and understanding the risk involved is crucial. The estimated amount of saleable gold contained in the resource must demonstrate a positive net present value and its eventual extraction could be reasonably justified at a profit. The degree of confidence in the deposit estimation must be reported to investors and their advisers.

Ordinary kriging (OK) and inverse distance weighting (IDW) are the two most commonly used gold resource estimation methods (Novak et al., 2017). The IDW is a convenient and straightforward method that is applied to evaluate mineral resources in hard rock and alluvial environments. Many alluvial mining companies operating within the Kibi mining district, a major alluvial gold geographic zone located within the Kibi-Winneba gold belt (Figure 1) at the south-eastern end of the Birimian terrain in Ghana, use the IDW method. The IDW has some advantages over other conventional methods of resource estimation (Absalov, 2016). However, a few drawbacks such as the following are associated with it: There is no accounting for dealing with clusters and if clusters are present, the estimate will be biased towards the cluster grade; there is no accounting for anisotropy; and the determination of power for estimation (e.g., p= 0, 1, 2, 3, etc.) is generally arbitrary (Yamamoto, 2000; Glacken and Snowden, 2001). The IDW does not account for the nugget effect, which is probably more prominent in an alluvial environment. Hence, at Kibi Goldfield Limited (KGL), a factor of 0.925 is multiplied by the raw ounces of gold calculated using the IDW to account for the nugget effect. These drawbacks affect the accuracy of resource estimates of companies using the IDW method, including KGL. Agyemang (2020) noted that reconciliation studies of production results against resource/reserve estimates carried out at Aburi Goldfields to assess the accuracy and reliability of IDW estimates for a period spanning January to August 2013 indicate that an estimated reserve of 297668 m3 of auriferous gravel at a grade of 0.5 g/m3, a total of 3819.8 raw ounces of processed gold were produced against an estimated reserve estimate of 4785.7 ounces of gold. The difference between the estimated and actual ounces of gold produced was 965.9, constituting 20.2%. This difference may be considered too high and, as such, may constitute overestimation. Therefore, finding an alternative resource estimation method that addresses some of the drawbacks associated with the IDW and helps improve the accuracy and reliability is very appropriate. Ordinary Kriging is the best linear unbiased estimator (Matheron, 1971) used to estimate gold resources in deep-seated rock environments, where the parameters for estimation are well-defined and mineralisation is associated with the bedrock. The method uses borehole data to estimate a mineral deposit. OK is based on variography rather than being arbitrary; the weights reflect better the anisotropy of spatial grade distribution compared to inverse distance weighting; the

Quick Response Code	Access this article online	
	Website: www.earthsciencespakistan.com	**DOI:** 10.26480/esp.01.2025.20.25

Cite the Article: Blestmond A. Brako, Seidu Abubakari, Daniel O. B. Nuamah, Amadu Charles Casmed, Gordon Foli, Simon K.Y. Gawu (2025). A Geostatistical Approach to Alluvial Gold Deposit Estimation at The Kibi Gold District, Ghana. *Earth Sciences Pakistan, 9(1): 20-25.*

interpolation weights assigned to the data are calculated in a way that they minimize the variance of the estimation error; and the quality of the estimate can easily be assessed by calculating the kriging efficiency and slope of regression for each block (Yamamoto, 2000).

Unlike hard rock, some significant challenges facing the alluvial gold mining industry are the poor characterisation of gravel and overburden thicknesses, gravel grade and deposit structure (Griffith, 1960). This leads to inconsistencies in exploration strategy, evaluation methods, mining procedures, ore dilution and poor reconciliation (Oman, 1977). Bookstein (2013) suggested that there must be a relatively large sample size because most of the deposits are composed of different sizes of gravel, which makes it very difficult to obtain a representative sample. Also, higher values of gold within certain areas distort the resource calculation. In addition, the values of gold recorded must be observed and noted with items associated with gravels, such as the boulder sizes, the volume of clay, bedrock conditions, and any other physical properties that may impact the mining and processing of the ore. Foli et al. (2020) recommended the appraisal of metallurgical data and grain size consideration to add an extra dimension to improve alluvial mining operations. Dzigdodi-Adjimah and Gawu (1994) also suggested that every deposit needs to be evaluated on a site-specific basis to ensure effective data collection and mining. This study compares ordinary kriging and inverse distance weighting techniques to estimate the volume, tonnage and ounces of gold within the auriferous gravel of an alluvial gold deposit to ascertain the technique that yields results that align more closely with actual production values.

1.1 Geology and gold mineralization of the Kibi gold district

The study was conducted at Saamang on the eastern flank of the Atewa range forest reserve in the Kibi gold district at the northern part of the Kibi–Winneba belt, which is truncated at the north by the Voltaian scarp. The geology of the Kibi-Winneba belt consists of a tightly folded, slightly overturned, north-north-east trending syncline featuring a variety of metavolcanic, mafic intrusions, and metasediments (Griffis, 2002). The western margin of the belt is dominated by steeply dipping, highly deformed, and fractured metasediments, often with extensive bands of graphite. These are flanked by metavolcanic flows (mafic to intermediate) and metavolcanic clasts with interbedded metasediments (Griffis, 2002). The Atewa range comprises greenstone suites such as phyllites, andesites, altered basalts, meta-tuffs, cherts, metagreywacke, and epidiorite, while the metasedimentary rocks are predominantly greywacke, argillite, and phyllite (Griffis, 1998; Griffis et al., 2002). Griffis et al. (1989) reveals that the Kibi area is covered by a thick sequence of alluvial deposits with several cross-cutting structures observed along the flanks of the Atewa range.

In the Kibi gold district, fast-flowing streams and rivers form alluvial fans moving into lower valleys and onto adjacent plains, producing blanket-like auriferous gravel units (Smith et al., 2012). The gravel layer is composed of varying shapes and sizes of cobbles, pebbles, boulders, sand and silt in a clay matrix. The sizes of gold grains in these deposits reduce downstream due to a decrease in the energy of deposition. The fine gold particles are generally flaky, but the coarse grains are generally irregular and sub-rounded (Smith et al., 2012). However, re-eroded lateritic capping from the paleoplacer deposits at the Atewa range contains a small percentage of well-rounded and worn-out gold (Griffis et al., 1991).

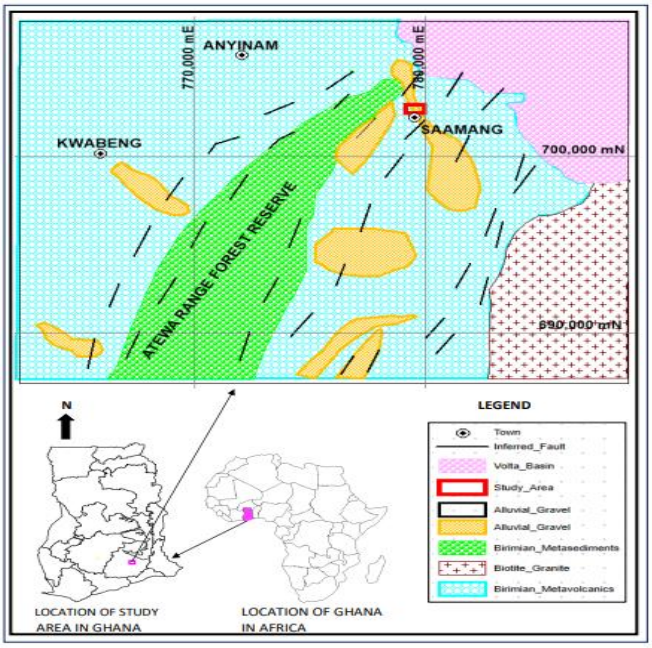


Figure 1: Geological map of southern Ghana showing alluvial gold deposits and the study area (modified after Kesse, 1985 and Agyemang, 2020)

2. Materials and Methods

2.1 Pitting and sampling

The project is 1800 m by 330 m along and across strike, respectively. The pitting followed a regular grid pattern in which cross lines were cut perpendicular to baselines. The baseline was cut in a northeast-southwest direction almost parallel to the Birim River, which flows through the project area and sample spacing of about 50 m both laterally was used. In all, two hundred and nineteen (219) hand-dug pits were used.

1m x 1m pits were hand-dug using chisels, pick axes and shovels to expose the overburden and gravel layers and the top of the weathered bedrock. The excavation was carefully done to ensure the pit walls were vertical, square, and safe. In cases where groundwater seeps into the pits, constant dewatering is done to avoid the caving in of the pit walls.

About 2 kg of samples at 0.5 m intervals were scooped from the four sides of each pit and well-mixed. Once the bedrock is reached, a 0.5 m thick sample is taken from the bedrock to check for gold that might have been leached into the gravel-bedrock interface. All the samples were piled individually on tarpaulins around the perimeter of the pit collar. A tape measure was used to measure the thickness of the overburden and gravel layers.

The samples were washed over a sluice box equipped with jute sack matting to generate alluvial gold concentrates, which were then oven-dried at 100°C. Magnetic fractions were separated using a bar magnet before recovering the gold (Clark, 2010; Mboudou et al., 2017). After washing each heap of material, the jute sacks used in the sluice box were removed and rinsed in a large washing bowl before the final panning to recover the free gold. The free gold was subsequently weighed and expressed in terms of the sample volume. The grade of gold recovered was expressed in g/m^3 and divided by a factor of 31.1035 to convert the value into ounces (Oz) (Rae et al., 2009).

2.2 Geological modelling

Geological modelling of the deposit was done in Datamine Studio RM software after importing the collar coordinates, downhole survey, lithology and assay data to create a desurveyed pit file. Three-dimensional lithological models of the overburden and gravel were created using the implicit geological modelling tool of the software. A surface elevation model showing the variation of elevations above sea level of the deposit was also created.

Statistical tools such as histograms, probability plots, and mean and

Cite the Article: Blestmond A. Brako, Seidu Abubakari, Daniel O. B. Nuamah, Amadu Charles Casmed, Gordon Foli, Simon K.Y. Gawu (2025). A Geostatistical Approach to Alluvial Gold Deposit Estimation at The Kibi Gold District, Ghana. *Earth Sciences Pakistan, 9(1): 20-25.*

variance plots were created to understand the grade distribution within the deposit, identify the presence of outliers for top-cutting analysis, and elimination, if any. The geostatistical analysis produced a series of directional experimental variograms whose parameters can be used to determine the kriging neighbourhood dimensions leading to the eventual resource estimation.

2.3 Ordinary Kriging

The geological nature of the orebody was first modeled,, after which the structures characterising the spatial variability of ore grades using variograms are examined (Kapageridis, 1999). The variogram is computed using Equation (1) (Bohling, 2005).

$$\gamma(h) \frac{1}{2N(h)} \sum_{\alpha=1}^{N(h)} [Z(u_{\alpha} + h) - Z(u_{\alpha})]^2 \quad (1)$$

where u is the vector of coordinates; $z(u)$ is the variable under consideration as a function of spatial location; h is the vector between the two; $N(h)$ is the number of pairs found at distance h apart; and $Z(u + h)$ is the value of a second variable at location h units from u.

Once the variogram is modelled, grade interpolation and estimation are done using kriging, (Kapageridis, 1999; Sinclair and Deraisme, 1974). Ordinary kriging (OK), a best linear unbiased estimator (Matheron, 1971), is a geostatistical method of local estimation by interpolation. It is based on a linear weighted average (Cressie, 1993), as presented in Equations (2) and (3).

(Estimate – real value)^2 + [Lagrange x (sum of weights – 1)] = minimum (2)

Where: Estimate = sum (weights x sample values) (3)

Lagrange = factor applied to ensure weight is equal to 1

(Sum of weights -1) = 0 (4)

The equation is differentiated to calculate the weights, resulting in the ordinary kriging system of equations. The kriging system used to derive the weights can be summarised in three matrices, C, W and D (Equation 5), where matrix C summarises the variogram values between all the samples used for the estimation. Matrix W represents the matrix of the weights the system attempts to estimate. Matrix D represents the matrix of variogram values for the distances (and directions) between the samples and points to be estimated. The C and D matrices are derived from the variogram model and used to estimate the weight (W). Declustering has also been taken care of by this matrix in the system.

$$\underset{C}{\begin{bmatrix} \gamma(1,1) & \gamma(1,2) & . & . & . & . & \gamma(1,7) & 1 \\ \gamma(2,1) & \gamma(2,2) & . & . & . & . & \gamma(2,7) & 1 \\ . & . & & & & & . & 1 \\ . & . & & & & & . & 1 \\ . & . & & & & & . & 1 \\ . & . & & & & & . & 1 \\ \gamma(7,1) & \gamma(7,2) & . & . & . & . & \gamma(7,7) & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 \end{bmatrix}} \cdot \underset{W}{\begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \\ \lambda_4 \\ \lambda_5 \\ \lambda_6 \\ \lambda_7 \\ \mu \end{bmatrix}} = \underset{D}{\begin{bmatrix} \bar{\gamma}(\bullet,1) \\ \bar{\gamma}(\bullet,2) \\ \bar{\gamma}(\bullet,3) \\ \bar{\gamma}(\bullet,4) \\ \bar{\gamma}(\bullet,5) \\ \bar{\gamma}(\bullet,6) \\ \bar{\gamma}(\bullet,7) \\ 1 \end{bmatrix}} \quad (5)$$

The weights derived are then applied to the sample values to estimate the grade of the estimation point. The last column and last row of matrix C contain ones (except the very last entry, which is a zero), the last entry of matrix D is a one, and the last entry of matrix W is a **μ** (Lagrange multiplier). These ensure that the weights add up to one (Cressie, 1993).

2.4 Inverse distance weighting (IDW)

IDW is a technique that applies a weighting factor that is based on an exponential distance function of each sample within a defined search neighborhood, at about the central point of the area to be estimated (Al-Hassan, 2011). Assuming a constant support for a two-dimensional isotropic case, the block grade is given by equation (6).

$$Z = \sum_{i=1}^{n} \frac{Z_{i\frac{1}{d_1{}^n}}}{Z_{i\frac{1}{d_1{}^n}}} \quad (6)$$

Where Z is the estimated variable of the block grade; Zi is the value of the sample at location i; di is the separation distance from point i to the point of reference, and n is the power index.

3. Results and Discussion

3.1 Geological model of the deposit

Three-dimensional geological models of the deposit showing overburden and gravel layers were created (Figures 2a and b). The average thickness of overburden and gravel layers were 2.75 m and 2.33 m, respectively.

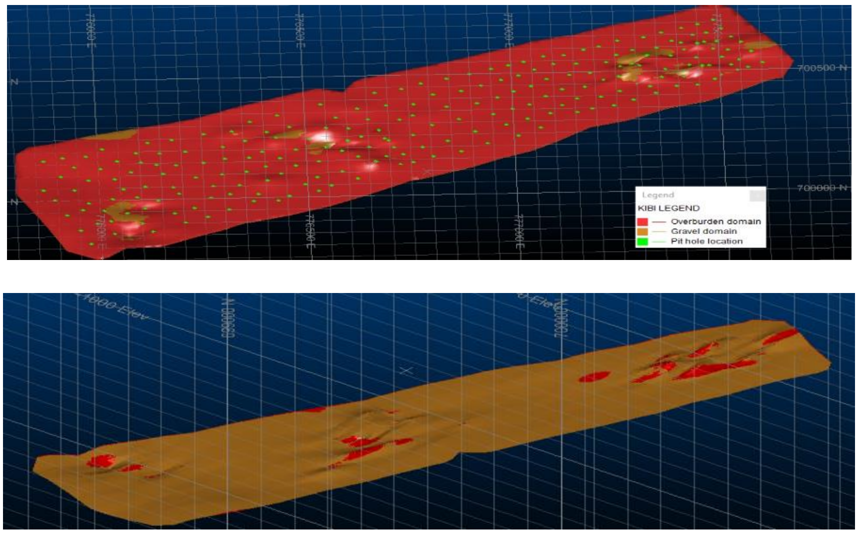


Figure 2: a) Model of overburden layer of alluvial deposit (plan view), b) model of auriferous gravel layer of alluvial deposit (bottom view)

Even though the study area has undulating topography, the overburden covers most areas of the deposit, except a few locations where the gravel layer appears within the overburden. A vertical cross-section of the model was created to show the two layers of the deposit.

3.2 Statistical and Geostatistical Analysis

Results of the statistical analysis carried out on the data were presented using histograms, log probability curves and mean and variance plots. The minimum and maximum assay values were 0.001 g/m^3 and 4.6 g/m^3, respectively. However, any set of data with a coefficient of variation of not less than 1 must be cut to eliminate extreme values, otherwise known as outliers, which tend to skew the data distribution (Dominy and Annels, 1997). There were no outliers in the data and the coefficient of variation (CV) of 1.0 is within an acceptable value. Hence, no top-cutting was done on the dataset. Data was positively skewed (1.201). The inflexion points were used to estimate the approximate lower cut-off and top-cut for the dataset. The top-cut value is almost close to the maximum assay value of 4.6, but the spatial distribution of high grades in the dataset does not appear random. The lower cut-off is estimated at around 1.5, constituting about 70% of the data. According to Krige (1978), natural distributions of gold values in many deposits appear lognormal. Therefore, a lower cut-off was not applied to this deposit.

The strike, dip and plunge of the deposit were used to determine rotation angles for the data for subsequent construction of variograms with Snowden Supervisor software. The strike of mineralisation was defined on the horizontal continuity fan and a maximum direction of continuity of 70^0. The dip of mineralisation was defined on the across-strike continuity fan at a maximum direction of 340^0. The plunge of mineralisation was defined on the dip plane fan and a maximum direction of continuity of 65^0. Using these continuity directions, a rotation angle of 0^0, 0^0, 65^0 in X, Y and Z axis were produced using the ZXZ rotation type and Datamine Compatibility Option.

Spatial continuity analysis using variograms was carried out on the 1 m composite sampling data for the auriferous gravel. These variograms correspond to the three principal directions of along strike, across strike and downhole of the alluvial deposit. The resulting model for the along-strike variogram appears to be erratic. Its lag distance was subsequently adjusted and kept close to the pit spacing of around 50 m with a 10% tolerance. Sample pairs were checked in the variography process, with sufficient numbers present, and plotted on the graphs for easy visualisation. The variograms were modelled using the spherical modelling structure, which produced a nugget of 0.34. A 1 m lag in the downhole direction of the variogram allowed the short-scale structures and nuggets to be determined. A variogram for the down dip was produced using a 30 m lag and 10% tolerance applied to the lag spacing (Figure 3).

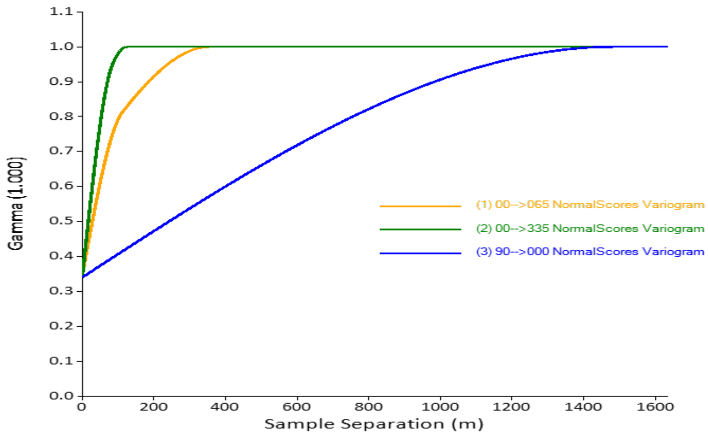


Figure 3: Combined continuity variogram

Table 2: Results of Kriging Neighbourhood Analysis (KNA)							
Block Centroid		Block Discretisation		Search Angle		Multi-Block KNA	
X	775866	X	4	Angle 1 (Z)	65	Tolerance Distance (X)	10
Y	699792	Y	4	Angle 2 (Y)	0	Tolerance Distance (Y)	10
Z	198.3	Z	1	Angle 3 (X)	0	Tolerance Distance (Z)	10
Search Range	Structure	Minimum Coordinate		Maximum Coordinate		Number of samples	
Dr1	1485	X	775856	X	777614	Minimum	3
Dr2	1485	Y	699782	Y	700744	Maximum	25
Dr3	1485	Z	188	Z	290		

3.4 Modelling of the resource block

Interpolation of gold grades for the auriferous gravel into a 3D resource block model and its estimation were carried out in Datamine Studio RM software using the Ordinary Kriging technique. This set of specifically sized blocks represents the shape of the alluvial orebody. The parameters of this block were used to estimate the resource.

However, an optimum cutoff grade of 0.4 g/m^3 based on experience was assumed to represent the optimum cutoff grade for the deposit. Hence, the resource was estimated at a cut-off grade of 0.4 g/m^3 and a total of 20.07 million tonnes or 12.453 million cubic metres of auriferous gravel at an average grade of 0.51 g/m^3 was obtained. This resource is expected to produce about 204238 ounces of gold after mining and processing.

IDW to the power 0, 1, 2, 3, 4 and 5 estimates for the same deposit were generated and compared to the OK estimate. The purpose is to compare the two estimation methods in terms of ounces of gold each method will generate and check how far or close these estimates differ from each other. It could be observed that between the cutoff grades of 0.0 - 0.25 g/m3 both the OK and IDW curves show similar expected ounces of gold (Figure .4). Beyond 0.25 g/m^3 cutoff grade, all the IDW curves to the power 0 – 5 generate different ounces of gold for a specific cutoff grade. At this stage, the resource estimator is not certain as to which power of IDW to use for comparison against OK. Ravenscroft (1992) stated that one criterion used to compare different resource estimation methods is an analysis of the correlation between the estimates. This was done, and the results of the correlation analysis are presented in Table 3.

Table 3: Spearman's Correlation Matrix of Ok and IDW Estimates							
	IDW^0	IDW^1	IDW^2	IDW^3	IDW^4	IDW^5	OK
IDW^0	1.000						
IDW^1	0.988	1.000					
IDW^2	0.99	0.986	1.000				
IDW^3	0.974	0.965	0.985	1.000			
IDW^4	0.957	0.953	0.974	0.994	1.000		
IDW^5	0.94	0.933	0.96	0.976	0.982	1.000	
OK	0.988	0.983	0.99	0.981	0.968	0.94	1.000

The OK-IDW^2 curves (Figure 4) seem to correlate well since their correlation coefficient of 0.99 is higher than that of OK versus IDW^0, IDW^1, IDW^3, IDW^4 and IDW^5.

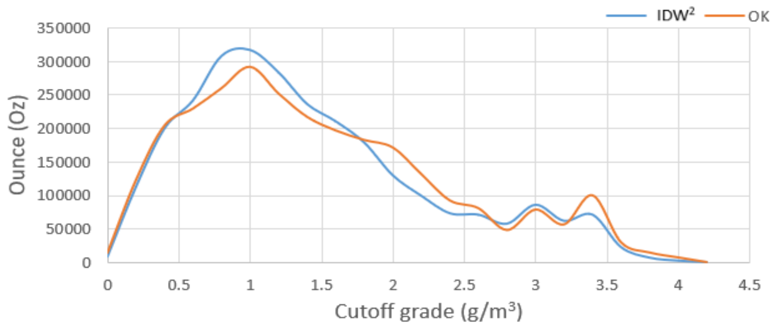


Figure 4: OK and IDW² curves

In Figure. 4, between the cutoff grades of 0.0 - 0.5 g/m³, the ounces of gold expected to be produced from both the OK and IDW² are almost the same. However, between the cut-off grade of 0.5 - 1.8 g/m³ the ounces of gold for IDW² are relatively higher than that of OK. Again, between the cutoff grades of 1.8 – 2.7 g/m³, the expected ounces of gold for IDW² are relatively lower than that of OK. These erratic changes in ounces of gold versus cutoff grades could probably be attributed to some of the drawbacks associated with the IDW such as the non-accounting for anisotropy; non-accounting for dealing with clusters; non-accounting for nugget effect; and last but not least the choice of power of estimation being arbitrary (Yamamoto, 2000; Glacken and Snowden, 2001). The block models generated using OK and IDW² for the deposit were colour contoured to show the range of gold mineralisation within the auriferous gravel (Figure 5). Blocks containing high gold grades of ore could be observed against low-grade or barren blocks. The generated resource estimate is presented in Table 4.

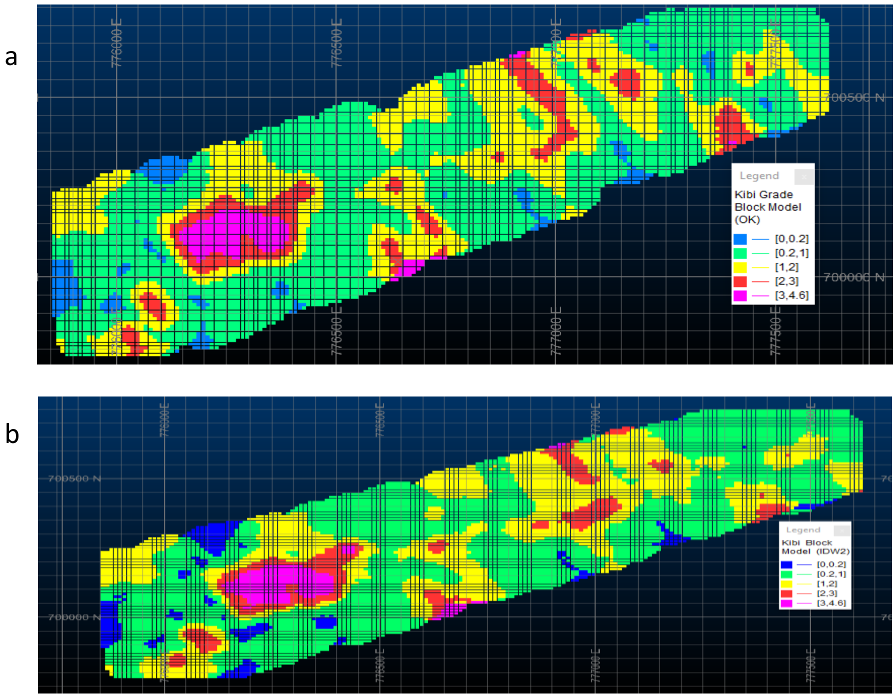


Figure 5: a) OK block model (plan view) *b) IDW² block model (plan view)*

At a cutoff grade of 0.4 g/m³, a total of 19.968 million tonnes or 12.48 million cubic metres of auriferous gravel at an average grade of 0.50 g/m³ was estimated using IDW². This resource, after mining and extraction, would produce about 200104 ounces of gold. Comparing the two estimates (Table 4), OK is expected to produce 4134 ounces of gold, representing 2.02% higher than the IDW².

Table 4: Comparison of OK and IDW² estimates

Method	Cutoff grade (g/m³)	Specific gravity	Volume	Tonnage (Volume)	Average grade (g/m³)	Ounces	Difference (%)
OK	0.4	1.6	12453000	20068800	0.51	204238	
IDW²	0.4	1.6	12480000	19968000	0.50	200104	
OK-IDW²				100800		4134	2.02

4. Conclusion

Ordinary kriging (OK) and inverse distance weighting (IDW) techniques were employed to estimate the gold content of the alluvial gold deposit in the Kibi gold district, utilizing data from hand-dug pits. The ordinary kriging technique provided estimates closer to the projected values than the IDW method. At a cut-off grade of 0.4 g/m³, we estimated 20.07 million tonnes, or 12.453 million cubic meters, of auriferous gravel with an average grade of 0.51 g/m³. This is projected to yield approximately 204238 ounces of gold after mining and extraction. This estimate reflects the material with reasonable potential for eventual economic extraction.

Consequently, ordinary kriging can be considered a viable alternative method for estimating alluvial gold deposits. We recommend conducting reconciliation studies to compare the actual ounces of gold produced from the mining and extraction of the alluvial gravel against the resource estimates. This comparison will help ascertain which of the two estimation methods, ordinary kriging or inverse distance weighting, yields result that align more closely with actual production values.

ACKNOWLEDGMENT

The authors wish to acknowledge the management and staff of Kibi Goldfields Limited for making data available for the research.

REFERENCES

Abouchami W, Boher M, Michard A, and Albarède F., 1990. A major 2.1 Ga event of Mantle magmatism in West Africa: An early stage of crustal accretion. Journal of Geophysical Research, 95, Pp. 17605–17629.

Abzalov, M., 2016. Resource Estimation Methods, Applied Mining Geology, Modern Approaches in Solid Earth Sciences 12, Springer International Publishing Switzerland, DOI 10.1007/978-3-319-39264-6_16.

Agyeman, K., 2020. Integrated Approach to Effective Exploration and Exploitation of Alluvial Gold Deposits: A Case Study of the Kwabeng Mine in Ghana, West Africa. PhD Dissertation, KNUST, Ghana.

Al-Hassan, S., 2011. Statistical Models, University of Mines and Technology, Unpublished MSc Lecture Notes, Tarkwa, pp. 127.

Awudu, G.I., 1994. A study of the mineral investment climate of Ghana: A project report submitted in partial fulfilment for Postgraduate (Professional) Diploma Degree in Mining Engineering. http://hdl.handle.net/123456789/3445 (Accessed on 18 July, 2020)

Bohling, G., 2005, "Introduction to Geostatistics and Variogram Analysis", Kansas Geological Survey, Vol. 1, pp.1-20.

Bookstein, R., 2013. Exploration and Evaluation Method to Gold in Alluvial deposits.

Clark, I., 1980. The Semi-Variogram in Geostatistics. Elsevier Scientific Publishing Company, Amsterdam, 364p.

Clark, I., 2010. Statistics of geostatistics? Sampling error or nugget effect? South, J. Afr. Inst. Min. Metall 83: Pp. 187-198. https://www.saimm.co.za/Journal/v110n06p307.pd https://doi.org/10.4236/ojg.2017.711115

Cressie, N. A. C., 1993. Statistics for Spatial Data. Wiley Series in Probability and Mathematical Statistics: Applied Probability and Statistics. New York: John Wiley and Sons, Inc.

David, M., 1977. Geostatistical Ore Reserve Estimation. Elsevier Scientific Publishing Company, Amsterdam, 364p.

Dominy S.C., Annels, A.E., 1997. Geology in the Resource and Reserve Estimation of, Narrow Vein Deposits, Exploration and Mining Geology, Mining Technology IMM Transactions section A,Vol. 6, No. 4, pp. 317-333,.

Dzigbodi-Adjimah, K., and Gawu, S.K.Y., 1994. Guides to alluvial gold deposit exploration in Ghana. Journal of Science and Technology. 14(3).

Foli, G., Agyemang, K., Brako, B A., Gawu, S.K.Y., Nude, P.M., 2020. Characterisation of Alluvial gold exploration data to improve gold recovery in Ghana. Arabian Journal of Geosciences. 11p. https://doi.org/10.1007/s12517-020-06073-4

Glacken, I. M. and Snowden, D.V., 2001, Mineral Resource Estimation, In: Mineral Resource and Ore Reserve Estimation-The AUSIMM Guide to Good Practice, pp 189-198, The Australasian Institute of Mining and Metallurgy, Melbourne.

Griffis, R. J., 1998. Explanatory Notes - Geological Interpretation of Geophysical Data from Southwestern Ghana. Minerals Commission, Accra, 51p.

Griffis, R. J., Agyeman, K. and Rae, J. A., 1989. History of the Goldenrae Alluvial Gold Project. Unpublished paper.

Griffis, R. J., Rae, J. A. and Agyemang, K., 1991. A Case History of the Goldenrae Alluvial Gold Project: in K. Barning (ed.), Symposium on Gold Exploration in Tropical Rain Forest Belts of Southern Ghana, Minerals Commission, Accra, Pp.135-150.

Griffis, R.J., Barning, K., Agezo, F.L., and Akosah, F.K., 2002. Gold Deposits of Ghana; Minerals Commission of Ghana, Pp. 432.

Griffith, S.V., 1960. Alluvial prospecting and mining. Second revised edn, Pergamon Press, NewYork. Pp. 253.

Kapageridis, I. K., 1999, Application of Artificial Neural Network Systems To Grade Estimation, Published Doctoral Dissertation, University of Nottingham, England, UK, 267 pp.

Krige, D.G., 1978. Lognormal-de Wijsian Geostatistics for Ore Valuation. S. Afr. Inst. Min. Metall. Monograph No.1.

Luebe,A., HirdesW.,Mauer R., and Kesse G O., 1990. The early Proterozoic

Birimian Supergroup of Ghana and some aspects of associated gold mineralization Precambrian Res, 46. Pp. 139- 165.

Matheron, G., 1971. The theory of regionalized variables and its applications. Les cahiers du Centre de Morphologie Mathematique, Fontainebleau, No. 5, Pp. 211.

Mboudou GMM, Fozao KF, Njoh OA, Agyingi CM., 2017 Characterization of alluvial gold-bearing sediments of Betare Oya District-East Cameroon, implication for gold exploration and recovery. Open Journal of Geology 7: Pp. 1724–1738. https://doi.org/10.4236/ojg.2017.711115

Nkrumah. R., Agyemang, K., Foli, G., Gawu, S. K. Y., Nude, P. M., 2019. Evaluation of Placer Deposit Within Ghana a Case Study of the Kwabeng Placer Gold Deposits North Western Flank of Atewa Range, Eastern Region, Ghana. International Journal of Engineering Research and Technology (IJERT), ISSN: 2278-0181, Vol. 8 Issue 11, 12p. http://www.ijert.org

Novak, Z. K., Vidacek, R., Ilijas, T. and Pavic, P., 2017: Application of the deterministical and stochastical geostatistical methods in petrophysical modelling, case study upper Pannonian reservoir in Sava depression.– Geologia Croatica, 70/2, Pp. 105–114. doi: 10.4154/gc.2017.10

Oman, P. S., 1997. A preliminary Report. Details of the Open Pit Mine model. Regional copper- nickel study. Minnesota Environmental Quality Board. https://www,goggle.com/search? Assessed 12 January, 2013.

Rael, J., Agyeman, K., Griffis, R.J., 2009, Technical Report on the Kibi Goldfields Mine, Kwaben gold Project. Chevyrock Engineering LLC. Naples. p34-43. https://www.xtragold.com/resources/report/2_3_1KibiGoldProject_TechnicalReport- NI_43_101.pdf Assessed 30th July, 2021.

Ravenscroft, P.J., 1992. Recoverable reserve estimation by conditional simulation. Geological Society, London, Special Publications, 63, Pp. 289-298.

Rossi, M.E. and Deutsch, C. V., 2013. Mineral resource estimation. Springer Science and Business Media.

Sinclair, A. J. and Deraisme, J., 1974, A Geostatistical Study of the Eagle Copper Vein, Northern British Columbia, CIM Bulletin, Vol. 746, pp. 131–142.

Smith, S. M., Amanor, J. and Byrne, D., 2012. Independent Technical Report. Apapam Concession, Kibi Project, Eastern Region, Ghana. Pp. 97. https://www.xtragold.com/_ KibiGoldProject-TechnicalReport_NI-43-101.pdf

Vann. J., Jackson, S. and Bertoli, O., 2003. Quantitative Kriging Neighbourhood Analysis for the Mining Geologist. A description of the method with worked case examples. In: 5th International mining geology conference. Bedigo: AUSIMM. (Vol. 8, pp.215-223).

Yamamoto, J.K., 2000. An alternative measure of the reliability of ordinary kriging estimate. J. Mathematical Geology 32(4), Pp. 489-509.