UNIVERSITY OF NAIROBI

APPLICATION OF GEOSTATISTICS TO MINERAL RESOURCE MODELLING AND ESTIMATION: CASE STUDY OF GOFOLO HILL IRON ORE DEPOSIT, WESTERN LIBERIA.

BY:
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I56/40872/2021

A Dissertation Submitted in Partial Fulfilment of the Requirements for the award of the Degree of Master of Science in Geology (Economic Geology and Mineral Resources) of the University of Nairobi.

2023

Declaration

I declare that this dissertation is my original work and has not been submitted elsewhere for research. Where other people's work or my own work has been used, this has properly been acknowledged and referenced in accordance with the University of Nairobi's requirements.

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APPLICATION OF GEOSTATISTICS TO MINERAL RESOURCE MODELLING AND ESTIMATION: CASE STUDY OF GOFOLO HILL IRON ORE DEPOSIT, WESTERN LIBERIA.

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Dedication

This research dissertation is dedicated to my late grandfather and namesake, Jumbo Klah Wilson. It is also dedicated to my family and friends for their continuous encouragement, which energised me to complete the full requirements for a postgraduate degree at the University of Nairobi.

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Finally, I want to express my sincere gratitude to my loving and helpful family and friends for their prayers, encouragement, and love shown over the years.

Abstract

The Gofolo Hill deposit, situated over a regional northwest trending shear zone (Todi Shear Zone) on the margin of the Archean West African craton, occurs in one of Liberia's historic iron ore mining districts notable for several high-grade deposits. The study area is in Western Liberia, Grand Cape Mount County and bounded by latitude 6°52′46″ N to 6°53´11″ N and longitude 11°14′19″ W to 11°13′25″ W. Though the Gofolo Hill occurs with Koehnko Hill and Zaway Hill along the strike length of two historic but abandoned iron ore mines: Bomi Hills Mine and Bong Mine, the deposit is yet to undergo a full evaluation of mineral resources which will inform feasibility study and subsequently draw on conclusion about exploitation. The study aims to model the orebody of Gofolo Hill and evaluate the mineral resources by applying the geostatistical ordinary kriging method. Ordinary kriging and comparative basic estimation methods (inverse distance weighting and nearest neighbour polygon) are used to evaluate the Gofolo Hill iron ore deposit and test the precision and accuracy of the results. Results for all estimation methods were obtained by applying a 30% Fe cut-off grade and a global density of 3.00kg/m3. The ordinary kriging method estimates the project to contain 17.169Mt of ores at an average grade of 35.90% Fe. Comparable methods like IDW2, IDW3 and NNP reported 35.22%, 35.53% and 38.53% grade Fe respectively and 16.274Mt, 16.975Mt, and 14.757Mt, respectively. The comparative study through grade-volume-tonnage results, visualisation of grade block maps, statistics, and correlation coefficient shows that the IDW methods (power2 then power3) produced more comparable results to the OK method than the NNP method. Cross–validation by the slope of regression values calculated from original sample values and kriged estimates showed a strong correlation meaning good estimates, and provides a slope or mean of 0.792. Further validation was carried out on all methods by (1) comparing the 3D model volume result (estimated volume) to the block model result (calculated volume); (2) by comparing global mean grade difference; and (3) by comparing calculated standard error. These validation methods prove the precision and accuracy of estimates. The study recommends that infill drilling be done on the project to improve the estimates confidence from inferred resources to indicated or measured resources. It also suggests that other deposits within strike length and proximity, such as Gofolo north-east, Koehnko, and Zaway, which together make up the "Mofe Creek project", be fully estimated, and a full feasibility study be conducted on the project for exploitation of the mineral resource.

Table of Contents

List of Figures

List of Tables

List of Abbreviation/Acronyms and Symbols

%	Percent
2D	Two-dimensional
3D	Three-dimensional
BIF	Banded Iron Formation
BLUE	Best Linear Unbiased Estimation
BRG	Bearing
C	Celsius
CV	Coefficient of Variation
D1	Deformation 1
D2	Deformation 2
D3	Deformation 3
DD	Diamond drill
EDA	Exploratory data analysis
Eg	example
Fig	figures
Ga	giga annum or billions of years
GMDD	Gofolo Main diamond drill hole
GMRC	Gofolo Main Reverse circulation
IDW	Inverse Distance Weighting
IDW2	Inverse distance weighting power 2
IDW3	Inverse distance weighting power 3
Kg	Kilogram
Km	Kilometres
M	meter
Ma	mega annum or millions of years
Max	Maximum
Min	Minimum

Mm	millimetres
Mt	megatonnes
Mtpa	Million tonnes per annum
N	North
NNP	Nearest Neighbour Polygon
OK	Ordinary Kriging
RBF	Radial Base Function
RC	Reverse Circulation drilling
Rev	Regionalized variable
RV	Random Variable
STD	Standard Deviation
TSZ	Todi Shear Zone
UTM	Universal Transverse Mercator
WAC	West African Craton
WGS	World Geodetic System

CHAPTER ONE: INTRODUCTION

1.1 BACKGROUND

Liberia, a little but poorly-explored West African nation, remains a significant historical producer of iron ore – Africa's leading iron ore producer in the 1960s and 1970s (British Geological Survey, 2016). Despite the recent exploration work done over a long period to assess Liberia's iron ore potential, many sections of the nation remain little understood and have not been extensively investigated using modern methods (British Geological Survey, 2016). Even the iron ore resources that have been mapped, explored, or studied in recent years are yet to be fully produced. A single iron ore mine operates in Yekepa, Northern Liberia, within the Archean basement rocks of the West African craton, compared to about four mines operating in the 1960s and 1970s. The study area of this research project, the Gofolo Hill, occurs similarly within the Precambrian West African Craton. A need to quantitatively evaluate the mineral resource of the Gofolo Hill project by utilizing a geostatistical method has driven this research project.

"Mineral resource and reserve estimation is a critical step in mine development and the progression from mineral exploration to commodity production" (Jowitt et al., 2021). Mineral estimation, made possible through integrating and interpreting quality geological data and economic considerations, determines the viability of a mineral deposit. The deposit estimation must be done accurately to avoid false financial expectations since mineral resource estimations are the basis for starting a mining operation (Abuntori et al., 2021). Conventional and classical methods of estimation (also referred to as traditional methods) are used for resource evaluation and estimation. However, these methods do not consider spatial relationships among sampled values and cannot specify the accuracy of the estimations, thus leading to subjective mineral assessment (Pandey, 2014). The two significant issues with the traditional methods, error estimation and spatial relationship, solved by geostatistics, have given the geostatistical method a unique role in numerous industries.

When interpolating for unknown points, the geostatistical estimation method considers the variation in space and time (trend or general direction of a change). The semivariogram makes these considerations and generates unbiased estimates. The geostatistical interpolation methods for resource estimation and modelling techniques are grounded on a body of theoretical concepts called the 'Theory of Regionalized variables'. This theory is primarily developed and accredited to Matheron (1963, 1965, 1971) based on the practical work carried out by Krige (1951) for determining the ore grades from drill cores in a South African gold mine.

The mining sector has used geostatistics to estimate mineral resources and reserves for the last 50 years because it views spatial continuity and error estimation as the primary criteria for achieving unbiased estimates. Comparative studies by (Ali Akbar, 2012; Calder et al., 2019; De-Vitry, 2003; Gong et al., 2014; Mallick et al., 2019; Rossi et al., 2014; Shahbeik et al., 2014) on conventional methods or classical methods and geostatistical methods clearly show that geostatistical methods provide better results.

1.2 STATEMENT OF THE PROBLEM

Liberia, with a unique history of being Africa’s top iron ore producer in the 1960s, remains unexplored, systematically using modern techniques to discover new prospects and quantify previously explored deposits. The mapped and explored deposits are yet to be fully evaluated for operational purposes. Currently, a single iron ore mine is being operated in the northern part of the country compared to four mines operational in the 1960s. The Gofolo Hill is ideally located in a mining district that contains multiple exploited deposits that were operational in the 1960s and 1970s. The hill is directly within a strike length of two of the previously mined deposits and situated within the West African Craton, which Precambrian rocks are underlain. The Precambrian basement rocks are a notable source of iron ore mineralization worldwide. This proves a need to evaluate the Gofolo Hill iron ore deposit and provide qualitative and quantitative estimates, thus yielding results to inform a feasibility study.

1.3 OBJECTIVES

1.3.1 Main Objectives

The main objective of this research project is to produce a logical orebody model and utilize the ordinary kriging geostatistical method in evaluating the deposit mineral resource.

1.3.2 Specific Objectives

1) To present a 3D geological model of the spatial distribution of the ore deposit parameters and how they extend laterally using a geostatistical approach.
2) To qualitatively and quantitatively estimate the mineral resource of the Gofolo Hill deposit.
3) To determine a comparison between the geostatistical ordinary kriging method, inverse distance weighting method and nearest neighbour polygon method
4) To validate the geostatistical ordinary kriging method, inverse distance weighting method and the nearest neighbour polygon method using the Datamine Studio RM software

1.4 RESEARCH QUESTIONS

1) How can underground mineral orebodies be modelled by the 3D implicit modelling method from geospatial and geochemical data?
2) What are the qualitative and quantitative factors, and to what extent do these factors influence the evaluation of a mineral deposit?
3) How do the geostatistical ordinary kriging, inverse distance weighting, and nearest neighbour polygon methods compare in estimating an ore deposit?
4) How can the geostatistical ordinary kriging method, inverse distance weighting method and nearest neighbour polygon method be validated for the accuracy and precision of their results?

1.5 JUSTIFICATION AND SIGNIFICANCE OF THE RESEARCH

Iron is the most widely utilized metal in the world and the foundation of industrial growth. Steel is the main iron ore product used in various industries, including construction, transportation, manufacturing, and others. Steel is entirely recyclable.

Iron ore mining plays an essential role in the economy of Liberia. The lone ongoing iron ore mining project in northern Liberia, which currently produces 4.5 Mtpa, is the highest contributor to revenue generation in all tax categories. Liberia was Africa's top Iron ore producer by 1965, with four ongoing mining projects producing a whopping combined 15 Mtpa (see **Figure 1.1**). Mining activities were halted in Liberia due to the long civil war that lasted twenty-four years before production commenced in 2012 but continued till 2023 with a single mining project. The need to research to fully evaluate other projects occurring within a similar geological setting and have them moved from exploration to exploitation, thus improving Liberia's production rate, has powered this research. The additional iron ore mines will significantly improve government revenues through taxes/royalties, improve development through corporate social responsibilities, and significantly contribute to Liberian citizens' employment, thus improving their socioeconomic status significantly.

The findings of this proposed study will be helpful to scientific researchers and investors wanting to make financial investments in the mining sector in Liberia. The model used in the proposed research can be applied to other iron ore deposits of the West African Craton.

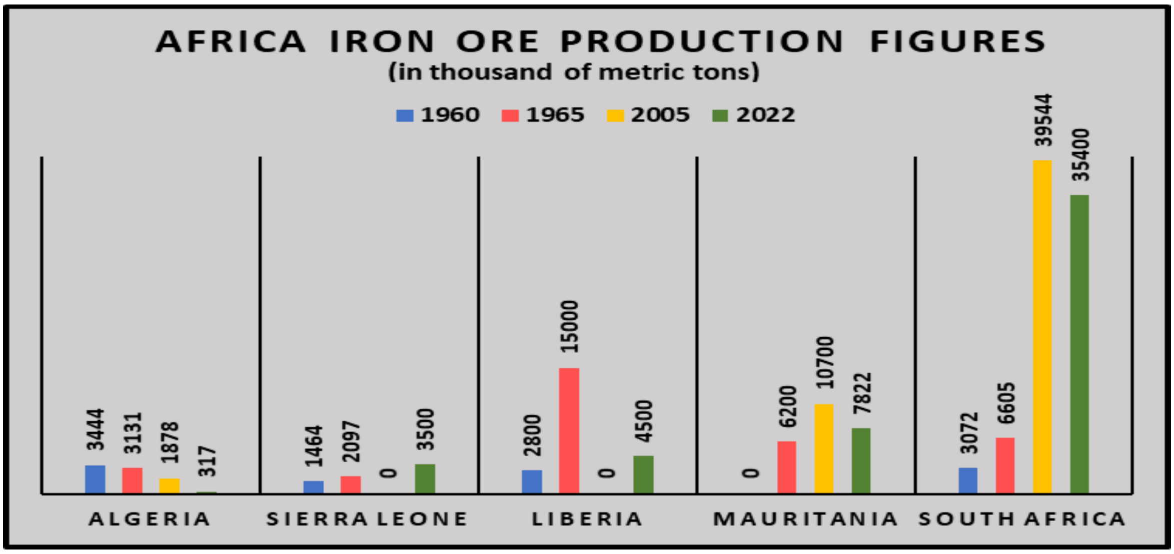


Figure 1.1: Iron ore annual figures (Benham et al., 2007; Swindell, 1967; Wisevotes, 2023)

1.6 SCOPE AND LIMITATION OF THE RESEARCH

This research study made use of four sets of exploratory data: collar data, survey data, lithology or geology data, and assay or geochemical data to achieve the objectives of the research, which is to evaluate to Gofolo Hill deposit. A geostatistical ordinary kriging method is applied to model the Gofolo Hill deposit, thereby revealing the deposit's lateral extent and depth and thoroughly evaluating the Iron ore resources the Gofolo Hill contains. Two more straightforward methods of resource estimation, the inverse distance weighting method and the nearest neighbour polygon method, were introduced to further compare with geostatistical ordinary kriging estimates and again prove the accuracy and precision of the geostatistical kriging method as well as the competency of the research. The study does not provide a conclusion regarding the viability of the Gofolo Hill Iron ore deposit or the Mofe Creek project because other essential considerations such as the competence of surrounding rock, price of the ore at the time of mining, demand for the ore, method and cost of extraction (operational costs) are required to reach an economic conclusion on mining projects.

1.7 GEOGRAPHICAL SETTING OF THE STUDY AREA

1.7.1 Location

The study area, Gofolo Hill (**Figure 1.2**), is located in Western Liberia, Grand Cape Mount County and bounded by latitude 6°52′46″ N to 6°53′11″ N and longitude 11°14′19″ W to 11°13′25″ W. It is part of three deposits (Gofolo, Zaway, and Koehnko) being studied by Tawana Resources Company under the Mofe Creek Iron Ore Project. The three deposits are along a strike from the existing Bomi Hills and Bong Range projects. The Gofolo Hill is approximately 80km northwest of Monrovia and 20km to the closest coastal location and covers approximately 850,000 sq. m. The project is reached from Monrovia, Liberia's capital city, by a sealed road and is 20 km from a prominent heavy-haul railroad for iron ore.

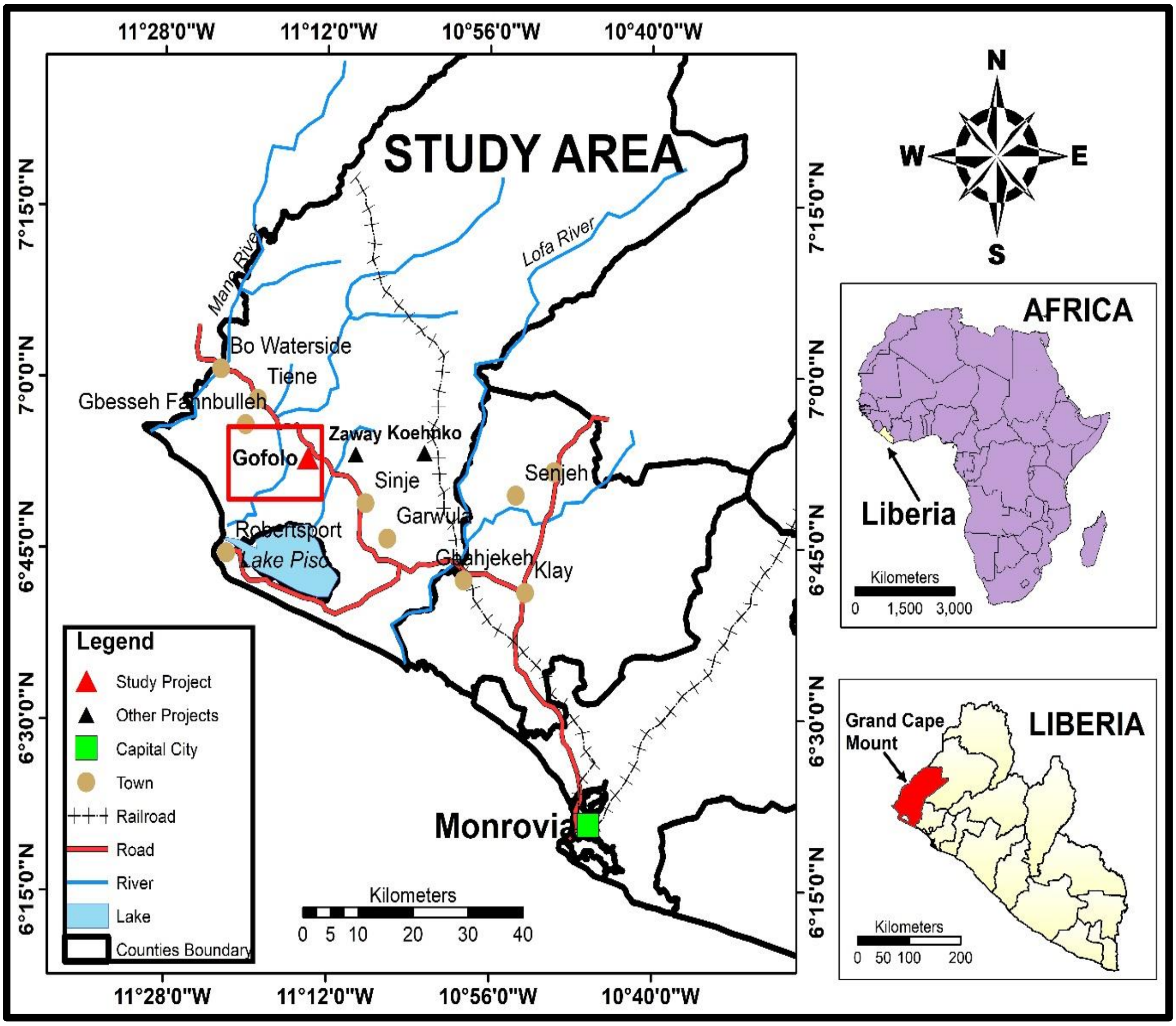


Figure 1.2: The description of the study area

1.7.2 Climate

The study area has a tropical equatorial climate with two generally recognised seasons: rainy and dry. The wet or rainy season starts in May, and the peak is reached with very intense rainfalls in June-July. Rains then gradually diminish and end in November. The dry season runs from November to late April. The temperature of the study area averages 27.29°C with an annual high temperature of 28.79°C and an annual low temperature of 25.44°C (Weather and Climate, 2023). The humidity averages 81.23%, the coldest months are August and September, and the driest month is January.

1.7.3 Vegetation

Much of the vegetation of the study area consists of secondary forest, including some evergreen forest species, bamboo, and several conifers (Tawana Resources, 2014). Several climbing species, fern species, and the Raphia Palma-pinus were found to exist in the locality of Gofolo Hill. The entire area, which is primarily covered by secondary forest, has been disturbed by shifting cultivation activities (**Figure 1.3**) for farming and agricultural purposes.

1.7.4 Land and Land Resources

Secondary forest, cultivated fields, and cleared areas make up the land cover close to the deposits. Subsistence farming, hunting, charcoal production, fishing, and artisanal mining are sources of livelihood for most communities. Most agriculture (especially farming) is done by shifting or cultivation within the study area and its surroundings (Tawana Resources, 2014). The 'slash and burn' technique is often practised as part of this shifting cultivation process. Crops grown include cassava, maize, millet, rice, and banana (**Figure 1.4**). Local residents utilize the nearby rivers for basic household activities during the dry season. Several primate species (e.g. baboons, colobus monkeys), small ungulates, and other small mammals are found in the study area. Snakes and the Agama-agama lizard species are abundant as well.

1.7.5 Physiography and Drainage

Gently undulating hills and low plains characterize the landscape surrounding the research area with partly forested hillsides (**Figure 1.5**), extensive shifting cultivation, and some small-scale plantations (e.g. palm oil) (Tawana Resources, 2014). Elevations range between approximately 12 and 86 meters above sea level. The Mafa River generally flows North East to South West direction, and its tributaries drain the Gofolo deposit and flow into the sea within the vicinity of the Lake Piso mouth.

Figure 1.3: Secondary forest cleared for farming using the shifting cultivation method.

Figure 1.4: Land use activities in the study area, (A) cassava (B) maize and banana

Figure 1.5: Aerial view of the Gofolo Hill

1.7.6 Geological Setting of the Study Area

1.7.6.1 Regional Geology

Liberia is covered mainly by the West African craton of the Precambrian age. The craton covers two age provinces of the country: the Liberian age province (2.8 – 3.3 Ga) of Archean-aged rocks in the western and central part of the country which is characterized by a granite-greenstone association and the Eburnean age province (1.8 – 2.2 Ga) of Proterozoic-aged rocks, made of volcano-sedimenatary sequence, in the eastern part (BGS, 2016; Gunn et al., 2018). The northeast-trending Cestos share zone marks the boundary between the Liberian and Eburnean provinces. A third province is the Pan African age province (500 Ma) along the coastal tip of Liberia, and its boundary is the northwest-trending Todi shear zone. **(Figure 1.6**) shows the geology of Liberia with the three age provinces. The WAC made of granite, schist and gneiss has experienced numerous tectonothermal events from the late Achaean through to the early Palaeozoic, resulting in multiple stages of intense deformation (compression, extension, strike-slip movement, high-temperature alteration, and wide-spread partial melting) (Hadden, 2006; Kromah, 1974). This complex history is partially attributable to the mineralogical variation in the iron formations (itabirites). Itabirite is indicative of a BIF that has undergone regional metamorphism and recrystallization.

1.7.6.2 Local Geology

The Gofolo Hill is about 10km from the abandoned Bomi Hills mine, 80km from the historic Bong Mine, and 45km from the Mano River mine. The hill is situated just over the regional northwest-trending shear zone (Todi Shear Zone – TSZ) on the (interpreted) edge or boundary of the West African Craton (WAC) (Tawana Resources, 2014). The TSZ denotes the division between the Liberian age province in the east and the (reworked) western Pan-African age province along the Liberian coast(Gunn et al., 2018). The study area occurs within Archean composite gneiss units consisting of biotite-rich granitic gneiss, hornblende-bearing granodiorite to diorite gneiss, syenite, amphibolites, mafic schists, quartzites, and itabirites. Cross-cutting, northwest/south-east trending dolerite dykes associated with the opening of the Atlantic occur throughout the study area. Iron mineralization is hosted within itabirite units of Archaean or Palaeo-proterozoic age with mafic intrusives and interbedded quartzites, unconformably overlying granitic gneiss basement of the West African Archaean Craton (WAC). Most mineralization hosted within the oxide and silicate facies units is folded, faulted, and locally partially re-crystallized. The most significant structural trend, northwest/southeast, is associated with the country scale Todi Shear (see **Figure 1.6**). Tawana Resources (2014) scoping report outlines the three major deformation events likely to impact the study area. D1-D2 were likely transgressive and D3 was much later:

1. D1: Infolding and recrystallization of BIF to itabirite (Liberian Orogeny?)
2. D2: Compression and Re-folding of itabirite (Eburnian Orogeny?)
3. D3: Further re-crystallization and coarsening of itabirites to current form (Todi Shear; Pan-African Orogeny and opening of Atlantic)

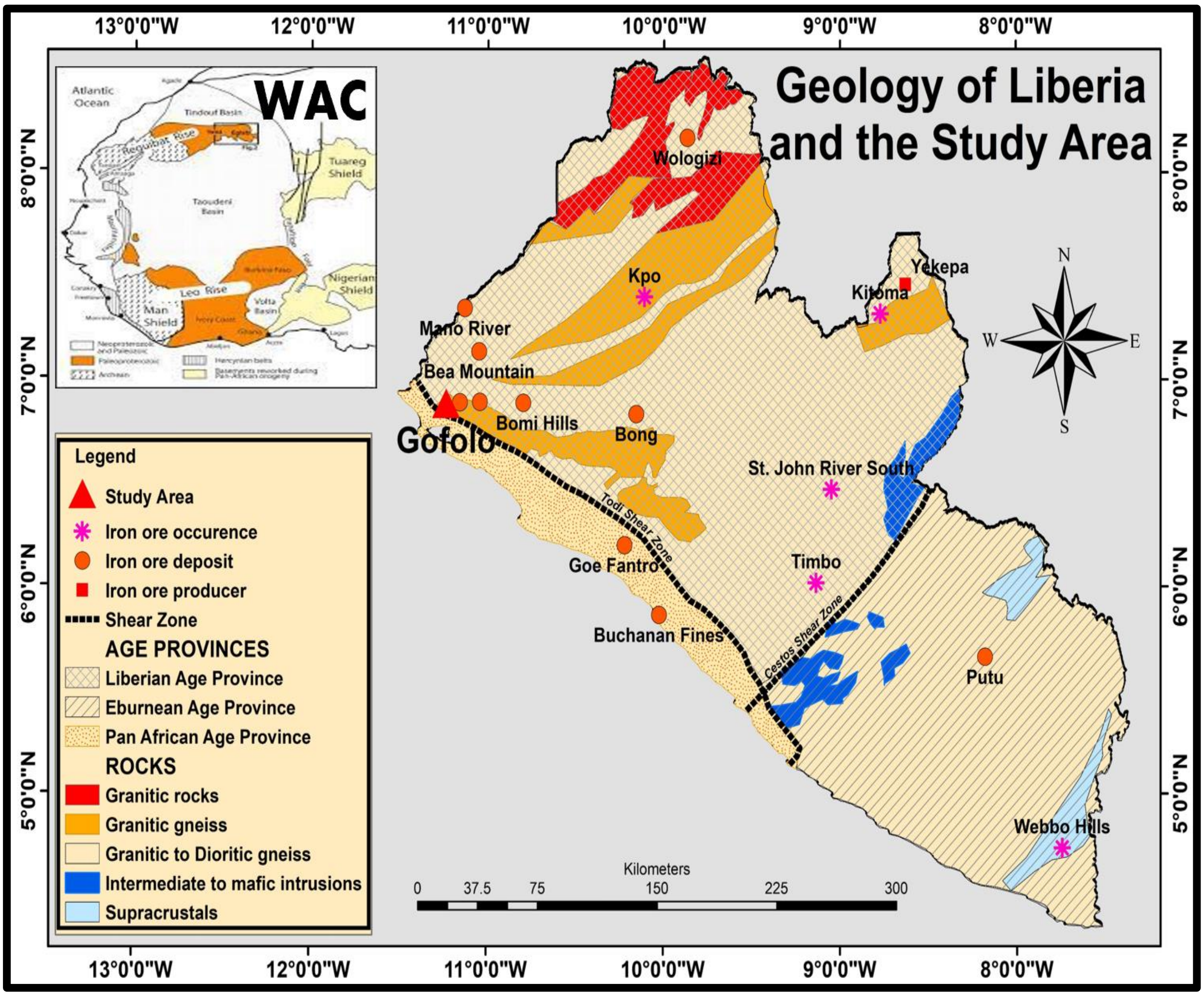


Figure 1.6: Geological Map of Liberia showing major iron ore deposits

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

This chapter provides an overview of relevant works of literature related to the research project. The review is carried out in line with the proposed objectives. It begins with a review of 3D geological modelling methods, both explicit and implicit modelling methods, and draws a comparison. A review of the Geostatistical ordinary kriging, inverse distance weighting, and nearest neighbour polygon methods is presented.

2.2 Theory of Geostatistical Modelling and Estimation

The geostatistical modelling and estimation foundation is based on a theoretical concept known as the theory of Regionalized Variables. This theory was developed by Matheron (1963, 1965, 1971) based on the practical work carried out by Krige (1951, 1952) for determining the ore grades from drill cores in a South African gold mine. A Regionalized variable has a geographical location (coordinate axes), spatial position, and correlation. In ore reserve estimation, most regionalised variables display two distinct aspects: a trend showing irregular fluctuation and a structural reflection or aspect of the geographical features.

The theory of regionalized variables has two goals:

i. to adequately represent the geographical characteristics of regionalized phenomena and
ii. to deal with the difficulties of estimating regionalized variables using sample data.

To attain these goals, Matheron (1963) presented a probabilistic interpretation of regionalized variables that led to the emergence of Geostatistics as an ore reserve estimation technique in the early 1960s.

The geostatistical methods work well with metallic and non-metallic minerals, precious and base metals, BIFs, fossil fuels, etc. It uses how the sample values relate to one another to quantify the deposit's natural characteristics and mineralization trend. Based on these quantifications, geostatistics uses a semi-variogram as a primary tool for spatial dependency to produce estimation with the slightest variance and the estimation of results error, none of which are considered by the conventional or classical estimation methods.

2.3 Solid Orebody Model

An orebody model is crucial for the design and operation of a mine; thus, it must be appropriately presented considering the minerals' local geology, structural characteristics, and geochemical concentration. Ronald (2017) defines a geological orebody model as "a computer-based three-dimension (sometimes 2D) wireframe model that is the culmination of interpreted geoscientific data for a particular area of interest or deposit". The geoscientific data on and below the earth's surface includes drill holes, geophysical, structural, or lithological data. The ore body model is then created from geoscientific data by interpolating between sample points (Pandey, 2014). To model an orebody accurately, it is required to locate geological regions or domains of similarity within which the modelling should be done. The domain can be created from the deposit's grade zones or lithology (geology). The two main geological models are the explicit model and the implicit model. To ensure precision and accuracy of a deposit orebody, these two models (explicit and implicit) consider several factors referred to as "Rules of Thumb" and outlined by Ronald (2017) as:

i. Explain how the model will be utilized or the clear objective of the model
ii. Understand the deposit/area geology (local and regional geology)
iii. Incorporate all trusted data sources
iv. Fundamental statistical understanding of the data
v. Prioritize regional considerations before modelling the deposit size.
vi. Start with a geologic structural framework
vii. Keep it as simple as it needs to be
viii. Do not forget the waste
ix. Reconcile your shape in 3D

Explicit Solid Model

The traditional or conventional approach of explicitly defining three-dimensional (3D) ore-waste and geological boundaries relies heavily on a laborious manual digitizing process (Kentwell, 2019). An explicit geological ore model uses a mining software package to create a hand-digitized wireframe model. This is viewed more as a model constructed by a human (geologist or resource geologist) rather than a model done by a computer algorithm (implicit model). Explicit or traditional wireframing is a lengthy and time-consuming manual digitization process based on the boreholes' geological record. The model is a lengthy, repetitive and tedious method involving dividing the orebody into sections, digitizing the outline, and connecting the intersections by strings (**Figure 2.1**). The strings are then converted into a triangulated wireframed model (**Figure 2.3 a**). The wireframes that are formed from the linked strings are to be checked and appropriately validated to ensure that there are no openings. Open wireframes are a grave issue as evaluating the volume is impossible with almost all geological modelling software. The workflow of the explicit or traditional model can be generalized as digitizing polylines, creating 3D wireframes, and verifying or validating them.

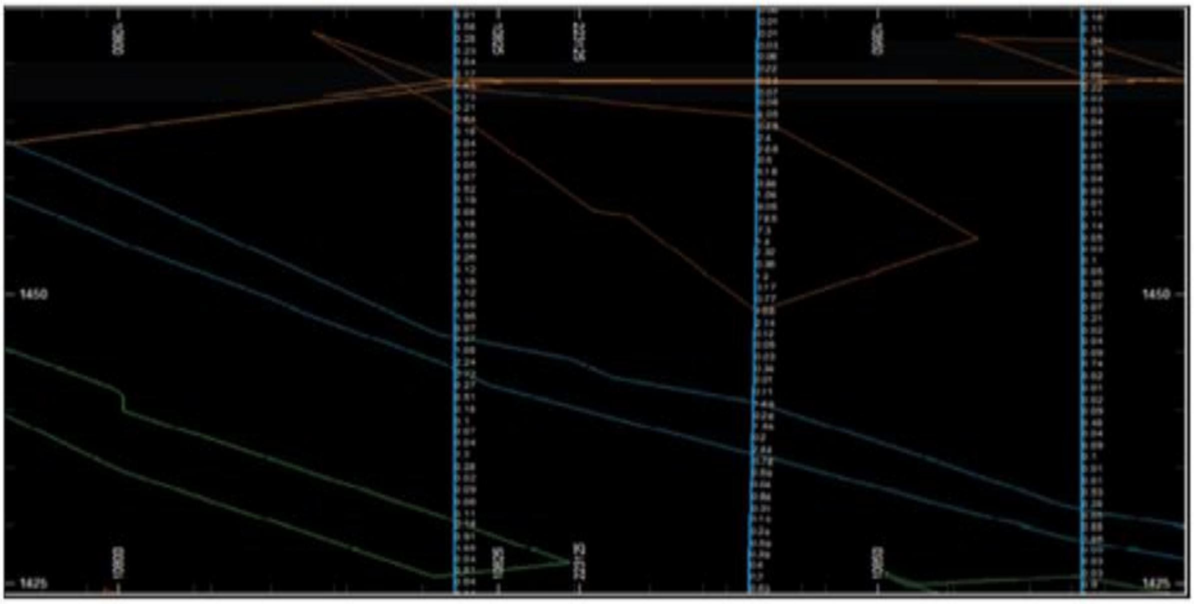


Figure 2.1: Explicit modelling showing hand-digitized drill holes strings (Birch, 2014)

Implicit Solid Model

The implicit geological modelling method is a technique that uses a radial basis function (RBF) to create and update geological models effectively from drill-hole data (Birch, 2014). The RBF interpolation was developed similarly but independent of the (Matheron, 1963) theory of regionalized variables. This interpolation requires each or every value to be utilized in calculating the weights. The implicit modelling approach is created to produce geological models directly from data without extensive manual digitization. Implicit models (**Figure 2.2 and Figure 2.3b)** are automatic computer-based models that can present precise and accurate ore body models in reduced time, an advantage over the explicit modelling method. The reduced time is due to the workflow of implicit models not including the manual time-consuming sectional digitization process **(Figure 2.4**). All time is given to the resource personnel to set parameters that will be modelled and validated.

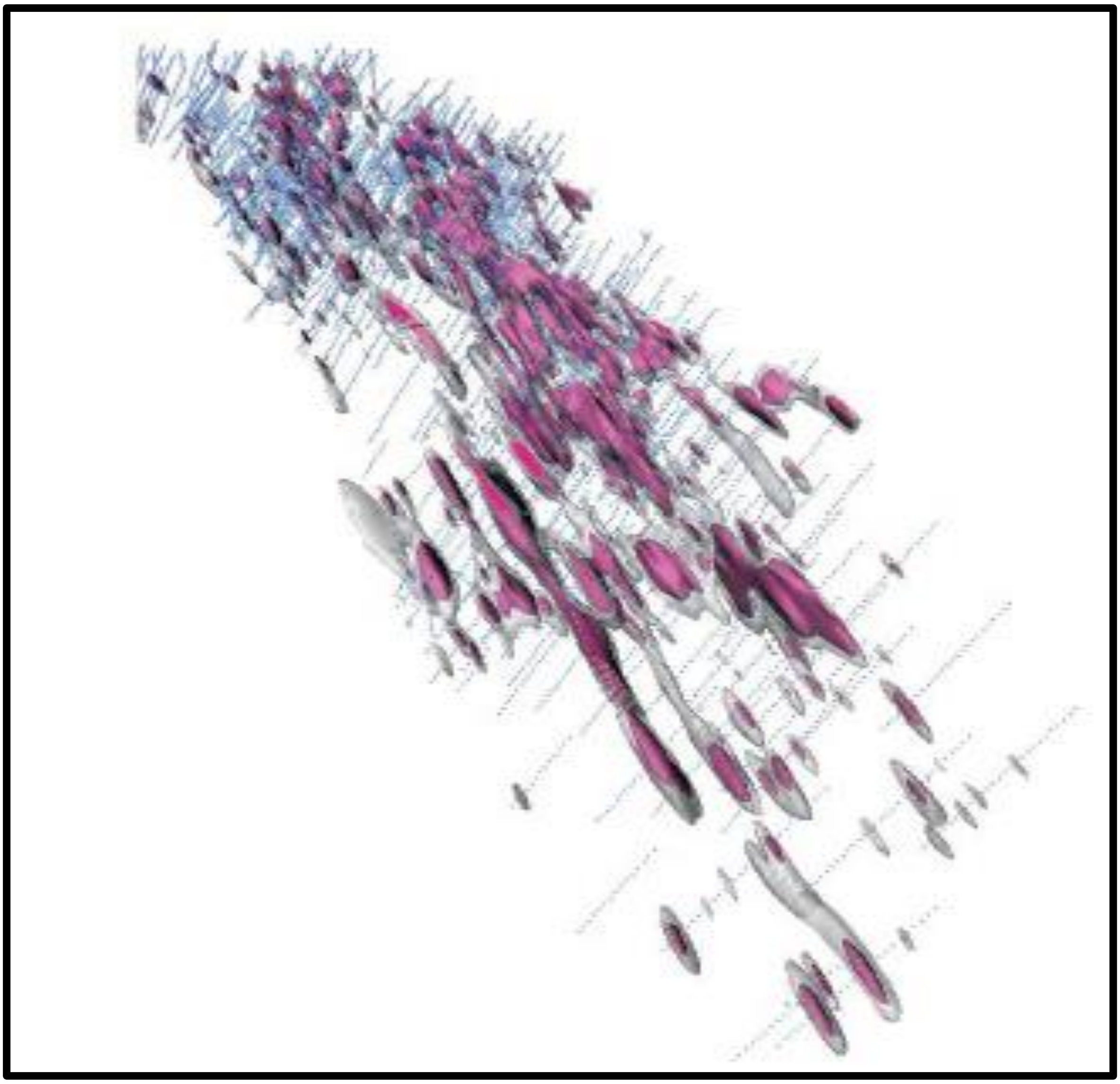


Figure 2.2 A model generated by the Implicit modelling method (Cowan et al., 2003)

2.3.1 Progression of Geological Orebody Modelling

(Kentwell, 2019) provided an overview of the rough timeline showing how the geological model has developed from the traditional hand-drawn explicit process to the modern implicit (computer-automated) process.

- 100 – 30 years ago: a paper with hand-drawn polygonal sections.
- 30 – 20 years ago: hand-drawn but digitized 2D strings to 3D wireframing from a plan and sectional interpretation
- 20 years ago to now: Radial Base Function (RBF) adapted to the mining industry with advanced improvements

2.3.2 Comparison of the Orebody Models

The explicit or traditional modelling method is the first developed method for orebody modelling. With technological advancement (computer), an implicit modelling method has been developed. The two methods (explicit and implicit) are still being used at a similar comparative level, with geologists (or resource geologists) preferring one modelling approach over the other for reasons primarily due to personal convenience. Kentwell (2019) paper tends to compare both methods and concludes that they both require a degree of manual inpu; as such, only the speed of implicit modelling gives it an advantage over the explicit method. Generally, the implicit model is seen to be better than the explicit as the advantages, with other literature highlighting the reduced computing time (speed), reduced workflow steps, and the possibility of the solid model being replicated as notable advantages. A comparison is presented below for an explicit and implicit model by a generated solid model (**Figure 2.3**), a workflow for producing the models (**Figure 2.4**), and attributes (characteristics) of the two techniques (**Table 2.1**).

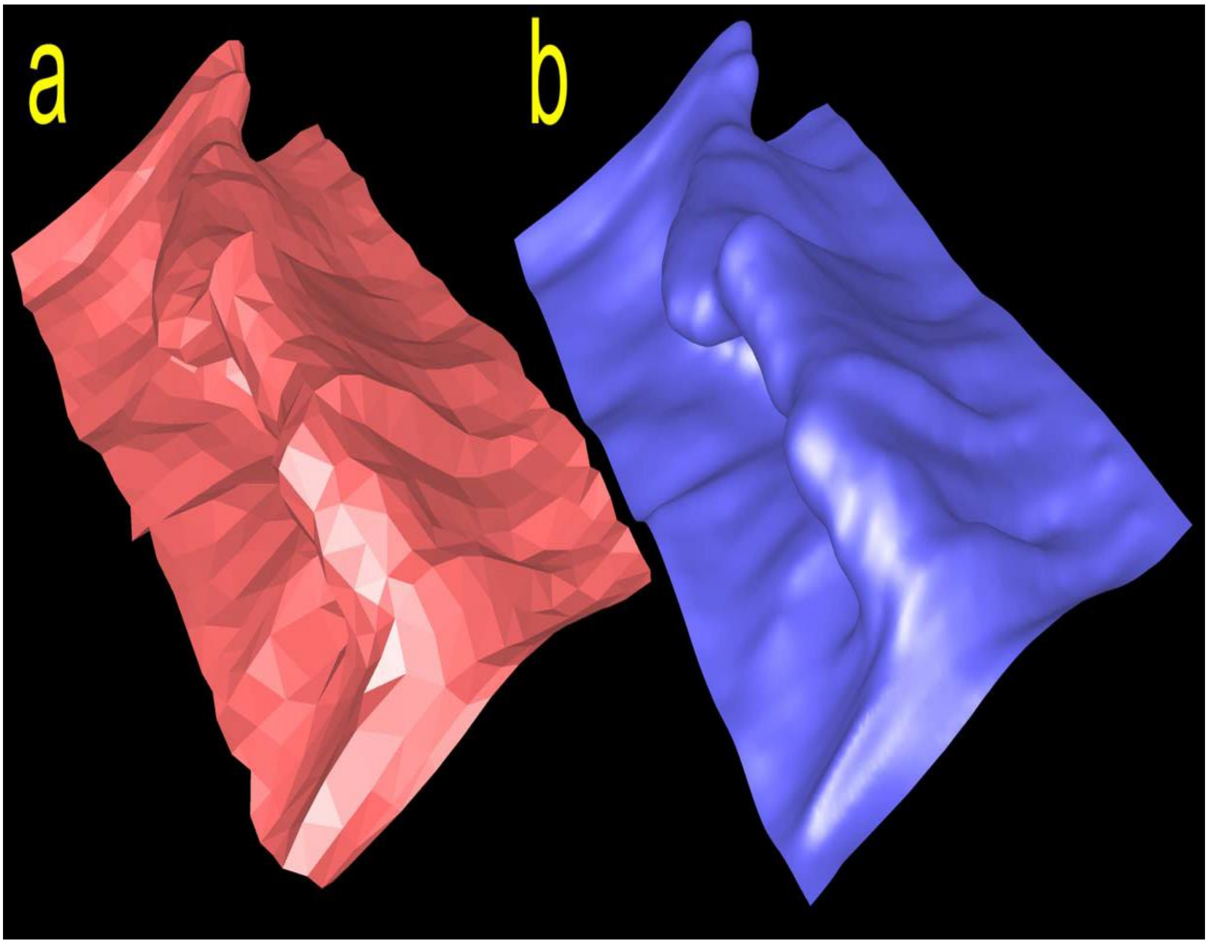


Figure 2.3: Model of an overturned fold a) Explicit, and b) Implicit (Cowan et al., 2002)

A workflow comparing the Explicit and Implicit model

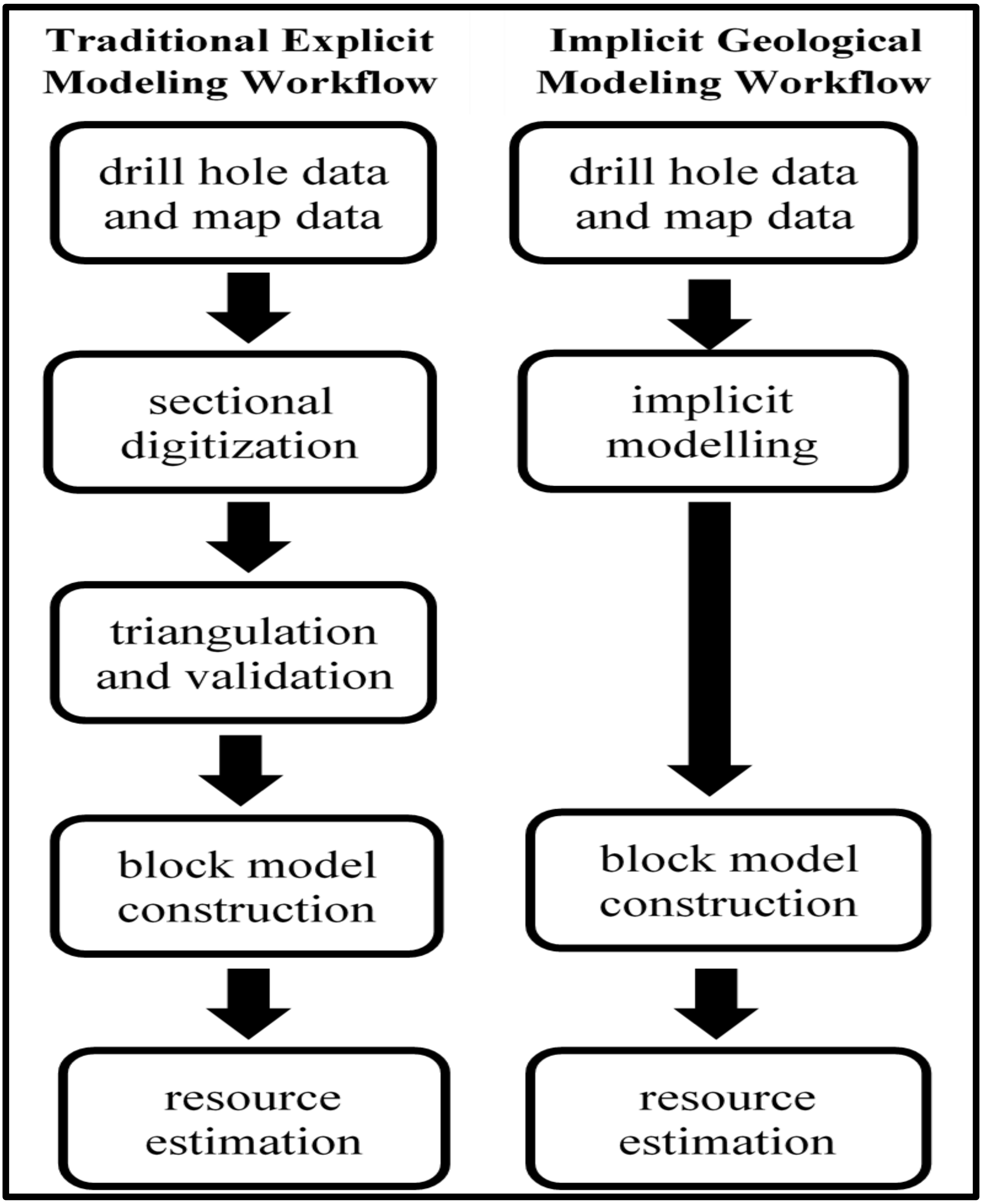


Figure 2.4: Workflow of Explicit and Implicit model (Cowan et al., 2011)

Comparing the attributes of Explicit and Implicit geological model

Table 2.1: Comparing the attributes of Explicit and Implicit geological modelling methods

ASPECT	EXPLICIT	IMPLICIT
Drill hole contact honouring	Done manually	Done automatically
The minor curve that fits between points	Nothing, just straight lines. Digitization of curves is manual.	Yes
Speed of modelling	Slow	Very fast
Accurate 3-D modelling (e.g., drill hole sectional fences are not needed)	No (only sectional digitization is possible)	Yes (sectional interpretation is not the only option)
Replicating of models	No (Replicating manual digitalization is impossible.)	Yes……assuming the same parameters.
Can the same data be used to produce numerous models?	Yes, but it is not practical since it takes so much time.	Yes
Block model update	Tedious and timely (takes about a month to make annual update)	Yes (daily and weekly or as decided by the geological team)
Ore grade differentiation	Not categorized (hand digitization is based on the project's cut-off, ore-waste)	Ore grade can be categorized into high, medium, low, and waste.
Incorporation of data	Preferably reliable drill data since modelling takes days to complete	Can model any data type since implicit modelling is faster and quicker

2.4 Geostatistical Approach in Mineral Resource Estimation

Geostatistics works best with spatially correlated samples within an orebody by combining statistics (minimum, maximum, mean, mode, median, standard deviation, variance, coefficient of variation, skewness, and kurtosis), theory of probability (probability density function) and geology. This means spatial distribution of ore grade values must first be classified for accurate results by modelling a variogram before grade interpolation using various kriging methods can be done based on the grade continuity depicted by the sample positions and variograms (Dominy et al., 2004; Dutta et al., 2010).

2.4.1 Semi-variogram: an experimental model

Semi-variance is the function that quantifies the degree of spatial variability in a set of sample values (grade values). It relates to how samples are dispersed across a regional space. Geostatistical interpolation employs the semivariogram to generate the best linear unbiased estimate (BLUE) at each location. To build a semi-variogram, we compare one value from our sample to all the others at constantly increasing time intervals or "lags." (Bohling, 2005). The semi-variogram function, denoted by $\gamma(h)$, is computed mathematically by **Equation 2.1** below (Bohling, 2005):

$$\gamma(h) = \frac{1}{2N}\sum_{i=1}^{n}[Z(X_i) - Z(X_i + h)]^2 \tag{2.1}$$

$Z(X_i)$ is the value of the regionalized variable at a point X_i in space, $Z(X_i + h)$ the grade at another location (lag distance), and N is the pairing number.

In geostatistical modelling and estimation, an experimental variogram, which displays the value differences of the raw data at various distances, is first constructed and then fitted to a theoretical variogram. The theoretical variogram is the best-fit mathematical model that is used to infer spatial relationships. Abuntori et al., (2021) concluded that the semivariogram makes the geostatistical method an upgrade to the inverse distance weighting method. The experimental semi-variogram (**Figure 2.5**) provides the following details about the mineral deposit characteristics as outlined by Pandey (2014):

An indicator of continuity of mineralization: Mineralization continuity is shown by the steady growth of the semi-variance $\gamma(h)$ for constantly increasing lag distance (h). The curve's expansion shows how regionalized the samples are, and its smooth growth shows how continuous the mineralization is.

Range or zone of influence: The range refers to the point on the semi-variogram curve at which the curve levels off. It is the distance up to which the regionalized component has its effect. Sample points that fall beyond the range separation are uncorrelated.

Sill: The sill is the corresponding value of the semi-variogram function γ(h) for which the semi-variogram levels off.

Nugget to Sill Ratio: It indicates consistency in the regularity of a deposit. An increase in this ratio marks a decrease in the regularity of the deposit that may result from erratic grade distribution. A considerably high value of this ratio requires greater attention.

A measure of the trend: A visual glance at the semi-variogram may reflect a trend in the dataset. A conspicuous hump between certain lag distances and a dip in the semi-variogram curve characterizes the trend. This requires the removal of the trend and then performing semi-variography of the residuals that reflect deviations from the trend.

A measure of Anisotropy: When the semi-variograms calculated for all pairs of points in various principal directions exhibit different types of behaviours, such as ranges differences, they reflect anisotropy.

Models fitting (experimental - theoretical)

For every experimental variogram created, there should be a best fit of a theoretical model.

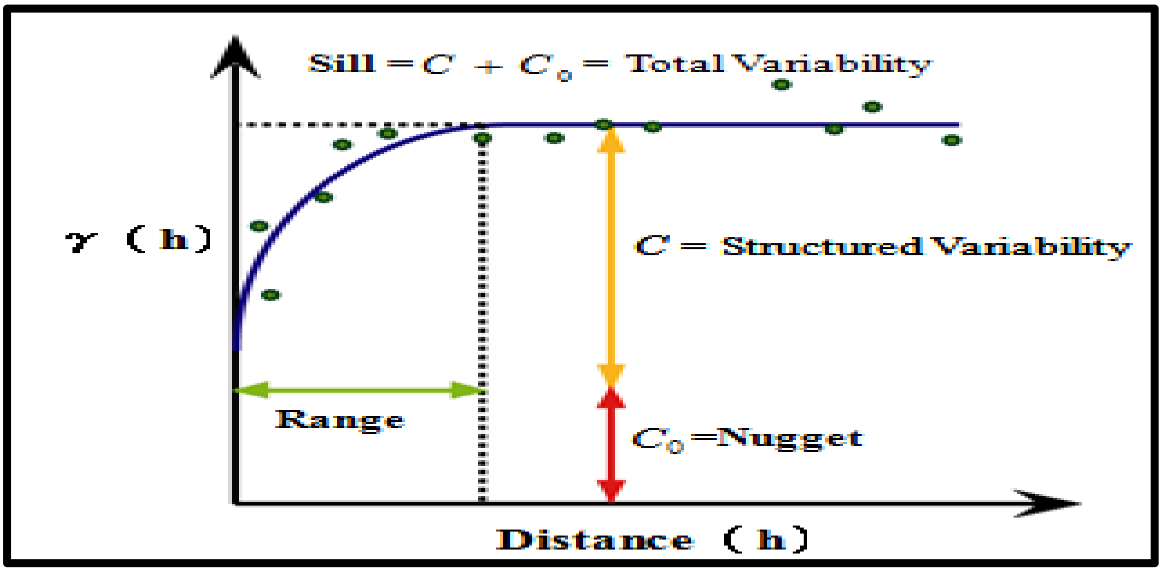


Figure 2.5: Semi-variogram experimental model (Supergeo, 2017)

2.4.2 Theoretical models for semivariogram fitting

Linear Model

The simplest semi-variogram model (**Figure 2.6**) is the linear model. The linear model lacks a range, and the semi-variance γ(h) increases continuously as the lag distance (h) increases. It has a modest continuity and is sometimes reflected in iron ore deposits. **Equation 2.2** shows an equation in the linear form that describes the linear model:

$$\gamma(h) = Ah + B \tag{2.2}$$

A is the rate of change or slope, and B (intercept) is a constant.

Spherical Model

The spherical model is suitable for modelling mineral deposits with sample values that become independent or uncorrelated once the range of the model is attained. Beyond the range of the variogram is a constant sill (**Figure 2.5, Figure 2.6**). The formula for the Spherical (Matheron) model is given in **Equation 2.3** below:

$$\begin{array}{ll} \gamma(h) = \left\{ C_o \left[\dfrac{3h}{2a} - \dfrac{1}{2}\left(\dfrac{h}{a}\right)^3 \right] \right\} & for\, h \le a \\ C_o & for\, h > a \end{array} \tag{2.3}$$

Exponential Model

The exponential variogram model is sometimes used to model precious metals such as gold, but rarely. It has a steeper slope toward the origin than the other model types (**Figure 2.6**). The formula in **Equation 2.4** gives the exponential model:

$$\gamma(h) = C_o \left[1 - \exp\left(-\frac{h}{a} \right) \right] \tag{2.4}$$

Gaussian Model

The Gaussian model distinctively shows a parabolic curve near the origin (**Figure 2.6**). The curve's horizontal segment at the origin indicates very low variability for close or short lag distances. The formula in **Equation 2.5** gives the Gaussian model:

$$\gamma(h) = Co \left[1 - \exp\left(-\frac{h^2}{a^2} \right) \right] \tag{2.5}$$

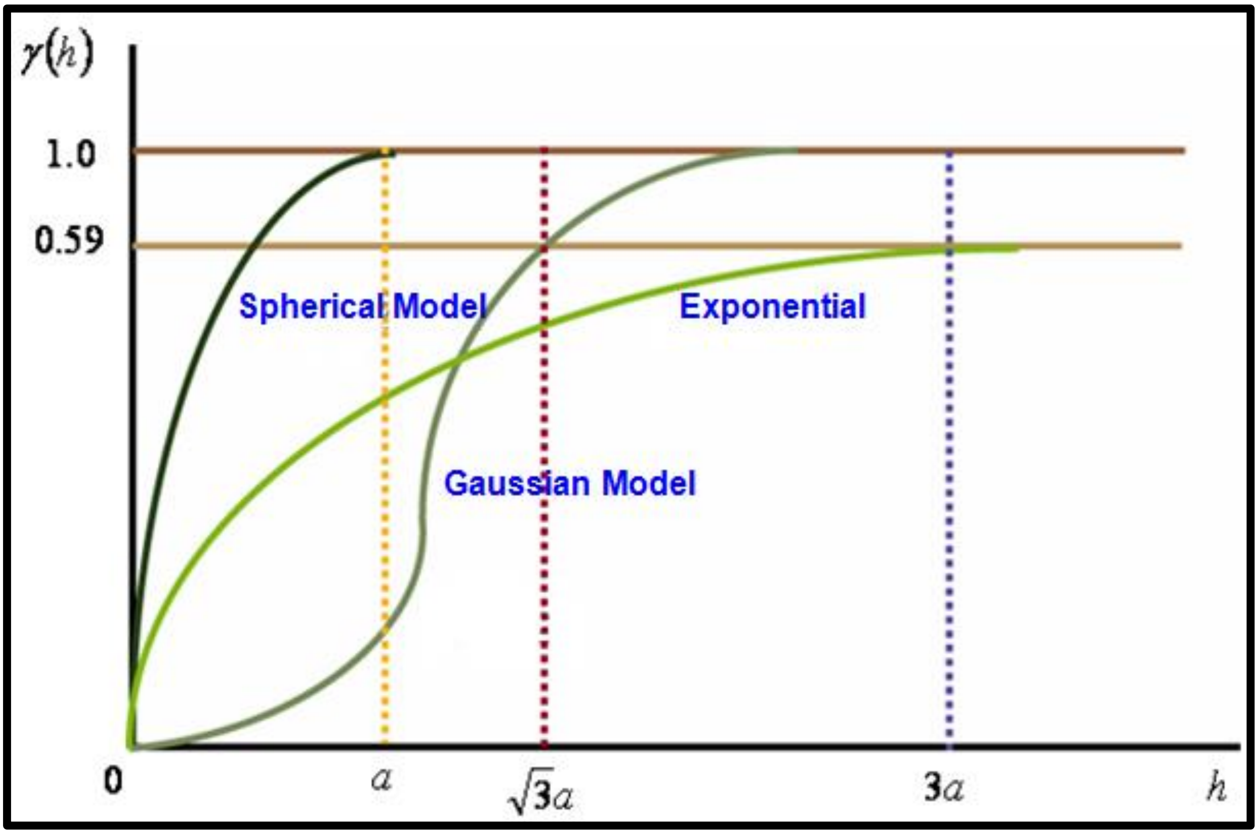


Figure 2.6: Semi-variogram theoretical models (Supergeo, 2017)

2.4.3 Kriging interpolation in resource estimation

The kriging interpolation method is used in estimating unsampled points or locations by the used of sampled or known values. The semi-variogram is a tool, used for geostatistical kriging estimation, that provides essential information about the trend that exists in values over a certain area. The simplest known geostatistical methods are the ordinary kriging method (or simply referred to in most literature as kriging) and the simple kriging method.

2.4.3.1 Ordinary Kriging

The simplest geostatistical method for estimating values of a regionalized variable using the data collected from a semi-variogram is the ordinary kriging. The ordinary kriging method is often just labelled shortly by the single word kriging. It is a geostatistical tool identified by the acronym BLUE: "best linear unbiased estimator" (Mallick et al., 2019). "Best" since the variance error is minimized; "linear" because the estimates are weighted linearly, and "unbiased" because it tries to make the error equal to zero. An external parameter known as the Lagrange multiplier is utilized in the ordinary kriging method to achieve a minimum kriging variance. Kriging interpolation can be carried out on a point or a block of ground. (**Figure 2.7**) shows the interpolation of an unknown point and unknown block from known neighbouring sample points.

Point Kriging

Point kriging, which applies the theory of regionalized variables, is a technique for interpolating or estimating a point from a series of nearby sample points. In point kriging, the sum of the weight coefficients equals one, and the error produced is kept to a minimum.

A point kriging estimate takes the form of **Equation 2.6**:

$$Z^*(u) = \sum_{i=1}^{n} \lambda_i Z(u_i) \tag{2.6}$$

Z* is the actual value estimate at "Z", λ_i is the sample weight coefficient, and Z represents the individual values at sample points.

The form of the linear estimator is shown in **Equation 2.7**:

$$E\left[Z^*(u)\right] = \sum_{i=1}^{n} \lambda_i E\left[Z(u_i)\right] = m \tag{2.7}$$

To demonstrate the unbiased situation, the weights must fulfil **Equation 2.8**:

$$\sum_{i=1}^{n} \lambda_i = 1 \tag{2.8}$$

The estimated variance is given by **Equation 2.9**:

$$\begin{aligned} \sigma^2(u) &= Var\left[Z(u) - Z^*(u)\right] \\ &= E\left[\left(Z(u) - \sum_{i=1}^{n} \lambda_i Z(u_i)\right)^2\right] \\ &= \sum_{j=1}^{n}\sum_{i=1}^{n} \lambda_j \lambda_i C(u_i - u_j) - 2\sum_{i=1}^{n} \lambda_i C(u_i - u) \end{aligned} \tag{2.9}$$

$C(u_i - u)$ is the semivariance of Z between the sampling point u_i and the target point u and $C(u_i - u_j)$ is the semivariance between the ith and jth sampling points.

The objective is to have the calculated variance minimized under unbiased conditions. A linear equation system may also be used to address this optimization issue and achieve unbiasedness.

Introducing the Lagrange multiplier μ as shown in **Equation 2.10** will produce the weights that minimize $\sigma^2(u)$.

$$\begin{gathered} \sum_{j=1}^{n} \lambda_j \gamma(u_i - u_j) + \mu = \gamma(u_i - u_j) \qquad i = 1, \ldots.., n \\ \sum_{j=1}^{n} \lambda_j = 1 \end{gathered} \tag{2.10}$$

The kriging variance $\sigma_K^2(u)$ is finally given in **Equation 2.11** as:

$$\sigma_K^2(u) = \sum_{i=1}^{n} \lambda_i \gamma\left(u_i - u\right) + \mu \tag{2.11}$$

Block kriging

The Block kriging method is similar to the point kriging method. It is a technique for estimating a block of space or area using nearby sample values utilizing the regionalized variables theory. The volume of the block is estimated using the formula in **Equation 2.12**:

$$Z(V) = \frac{1}{|V|} \int_{v} Z(u)du \tag{2.12}$$

The form of the linear estimator, similar to the point kriging, is given in **Equation 2.13**:

$$Z^*(V) = \sum_{i=1}^{n} \lambda_i Z(u_i) \tag{2.13}$$

To demonstrate the unbiased situation, the weights must fulfil **Equation 2.14**:

$$\sum_{i=1}^{n} \lambda_i = 1 \tag{2.14}$$

The estimated variance of block kriging is given as shown in **Equation 2.15**:

$$\sigma^2(V) = Var\left[Z(V) - Z^*(V)\right] = -\bar{\gamma}(V,V) - \sum_{j=1}^{n}\sum_{i=1}^{n} \lambda_j \lambda_i \gamma(u_i - u_j) + 2\sum_{i=1}^{n} \lambda_i \bar{\gamma}(u_i, V) \tag{2.15}$$

The average variogram value is given in **Equation 2.16** and **Equation 2.17**:

$$\bar{\gamma}(u_i, V) = \frac{1}{|V|}\int_{v} \gamma(u_i - u)\, du \tag{2.16}$$

$$\bar{\gamma}(V,V) = \frac{1}{|V|}\int_{v}\int_{v} \gamma(u - v)\, du\, dv \tag{2.17}$$

The minimization of the estimated variance $\sigma^2(V)$ under the unbiasedness condition leads to the linear equation system shown in **Equation 2.18**:

$$\begin{aligned} &\sum_{j=1}^{n} \lambda_j \gamma(u_i - u_j) + \mu = \bar{\gamma}(u_i, V) \quad i = 1, \ldots\ldots, n \\ &\sum_{j=1}^{n} \lambda_j = 1 \end{aligned} \tag{2.18}$$

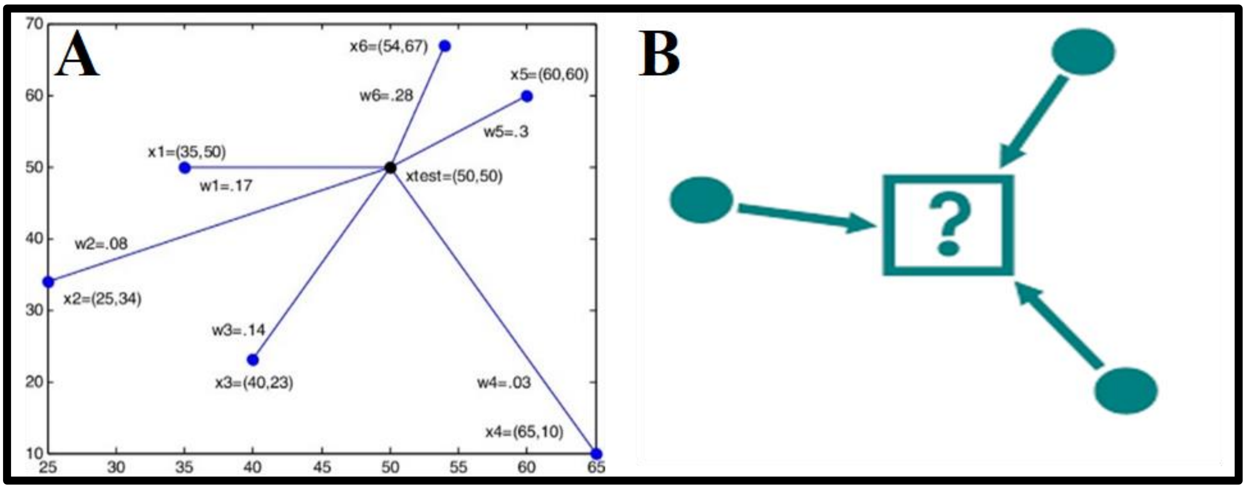


Figure 2.7: a) point kriging (Jia et al., 2009) and b) block kriging (Deutsch et al., 2015)

2.4.3.2 Simple Kriging

For ordinary kriging predictions, there is an assumption that the unknown mean is a value that is the same over the domain under study. In some events, a mean may be known or possibly assumed. A simple kriging method can be used for predictions by assuming second-order stationarity where there are known (not necessarily constant) mean. The simple kriging estimates are linear sums of the data but include the mean µ. Simple Kriging's equation is presented in **Equation 2.19** as a linear estimator with the following form:

$$Z^*(u) = m(u) + \sum_{i=1}^{n} \lambda_i \left(Z(u_i) - m(u_i) \right) \tag{2.19}$$

The unbiasedness condition means **Equation 2.20** should meet the condition:

$$E\left[Z^*(u) - Z(u)\right] = m(u) + \sum_{i=1}^{n} \lambda_i E\left[Z(u_i) - m(u_i)\right] - m(u) = 0 \tag{2.20}$$

The variance estimator is expressed in **Equation 2.21** as:

$$\begin{aligned} Var\left[Z^*(u) - Z(u)\right] &= E\left[Z^*(u)^2 + Z(u)^2 - 2Z^*(u)Z(u) \right] = \\ &\sum_{i=1}^{n}\sum_{j=1}^{n} \lambda_i \lambda_j C(u_i - u_j) - 2\sum_{i=1}^{n} \lambda_i C(u_i - u) \end{aligned} \tag{2.21}$$

This results in the simple kriging equation system is given in **Equation 2.22**:

$$\sum_{j=1}^{n} \lambda_j C(u_i - u_j) = C(u_i - u) \tag{2.22}$$

2.5 Basic methods in mineral resource estimation

2.5.1 Inverse Distance Weighting (IDW)

The inverse distance weighting (IDW) estimation is a method that applies a weighting factor that is based on an inverse distance function of each sample with a set of known sample values about the central point of an unknown ore block". The objective of this linear interpolated method is to assign assay value (that is, grade) or the depositional parameters (that is, thickness) to a block within a specified volume based on a linear combination of the surrounding sample locations (Pandey, 2014). A generally accepted assumption is that a sample value (grade value) would decrease as one moves away from a point and increase as one moves toward that point (First Law of Geography). The IDW method interpolated value is a function of distance, but instead of directly applying distance to interpolate or estimate, the method uses the inverses of the distance hence the name Inverse distance weighting method. Mineral deposits having a suitable geometry with low to high-grade variability can be evaluated using the IDW method. (**Figure 2.8**) shows how an unknown point at the middle is being interpolated by neighbouring samples at distances using the IDW method. The formula in **Equation 2.23** gives the IDW method:

$$Z^* = \frac{\sum_{i=1}^{n} \frac{Z_i}{d_i^n}}{\sum_{i=1}^{n} \frac{1}{d_i^n}} \tag{2.23}$$

Where Z* is the grade at the point being interpolated, Z_i is the grade of the sampled point, d_i is the distance to the sampled point, and n is the selected exponent (can be 1, 2, or 3).

If 2 is the selected exponent for calculating, which is the most common exponent used by computers to calculate grade at a point or block sampled, the method is termed the Inverse Distance Squared (IDS) Method. If the power of inverse distance is 3, the method is called Inverse Distance Cube (IDC).

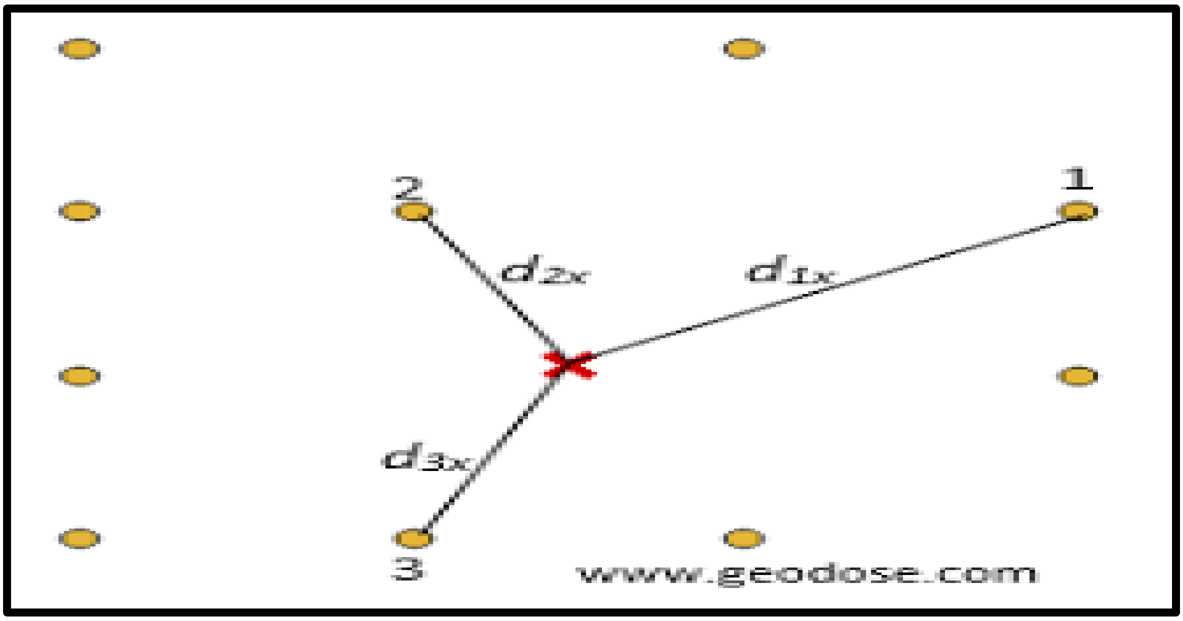


Figure 2.8: Inverse distance weighting method (Geodose, 2019)

2.5.2 Nearest Neighbour Polygon (NNP)

The nearest neighbour polygon (NNP) method is one of the most straightforward interpolation techniques for calculating unsampled values. This method predicts the attributes of unsampled points by assigning values based on nearby polygons. Only one point or the nearest sampled point value is assigned to the point that is being estimated. The NNP method is mainly used when other robust interpolation methods are not applicable in predicting or estimating the outcome of data. It can also be used as a follow-up method to show that the robust interpolation method of estimations is within an accepted range, thus proofing their precision and accuracy. (Bargawa et al., 2020; Mallick et al., 2019) in separate research, compared the nearest neighbour polygon method with the inverse distance weighting method and the ordinary kriging method.

CHAPTER THREE: METHODOLOGY

3.1 Introduction

This chapter presents the methodology (materials and methods) used to achieve the objectives of this research. The general design is to rework exploratory data (collar, survey, assay and lithology) to produce an orebody model and resource estimates (qualitative and quantitative mineral estimates) (see **Figure 3.1**). As outlined in **Figure 3.2,** the workflow included geological database creation, exploratory data analysis (EDA), domain analysis, semi-variography, solid 3D ore modelling, mineral resource estimation (geostatistical ordinary kriging, IDW, and NNP), and results comparison. The reverse circulation drilling data on the Gofolo Hill in Grand Cape Mount County, Western Liberia, was used.

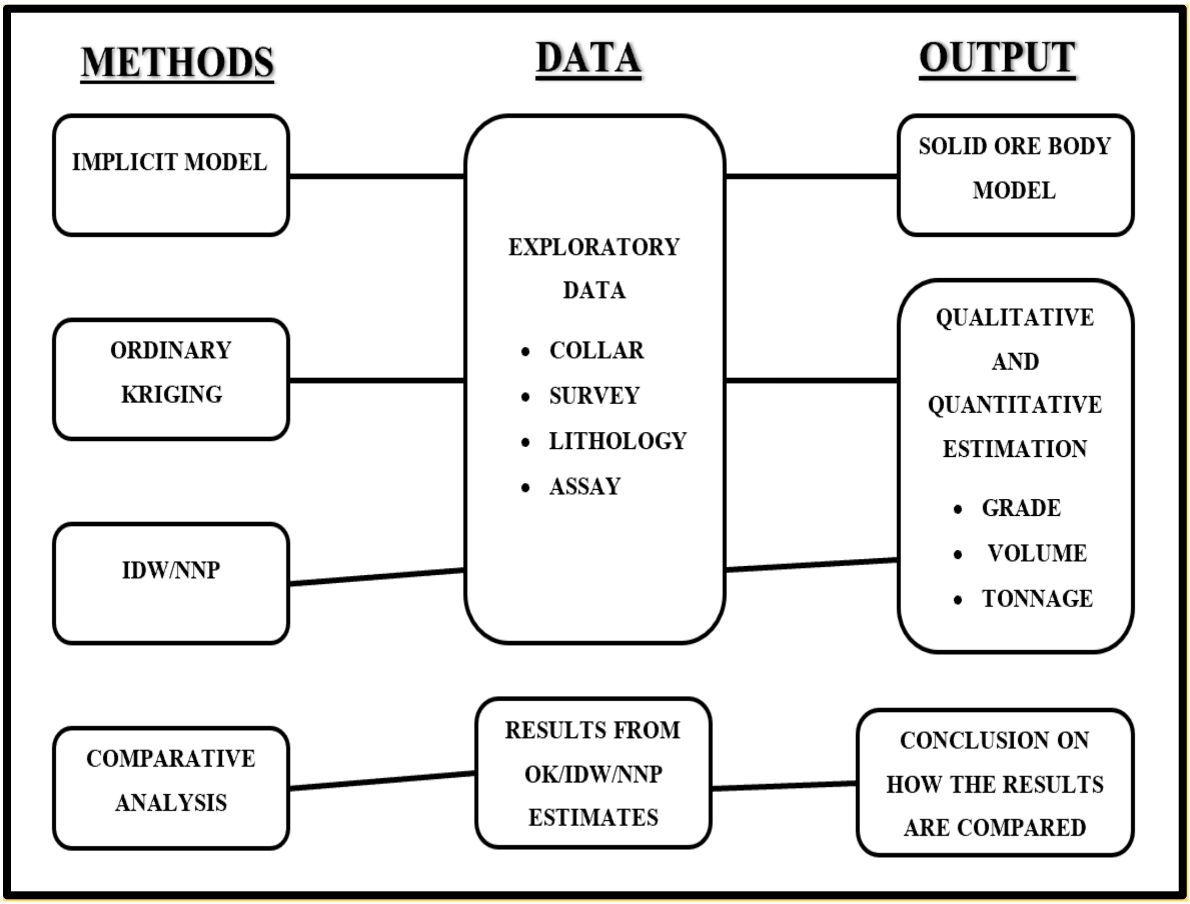


Figure 3.1: Research design showing the data used, the method used and the output

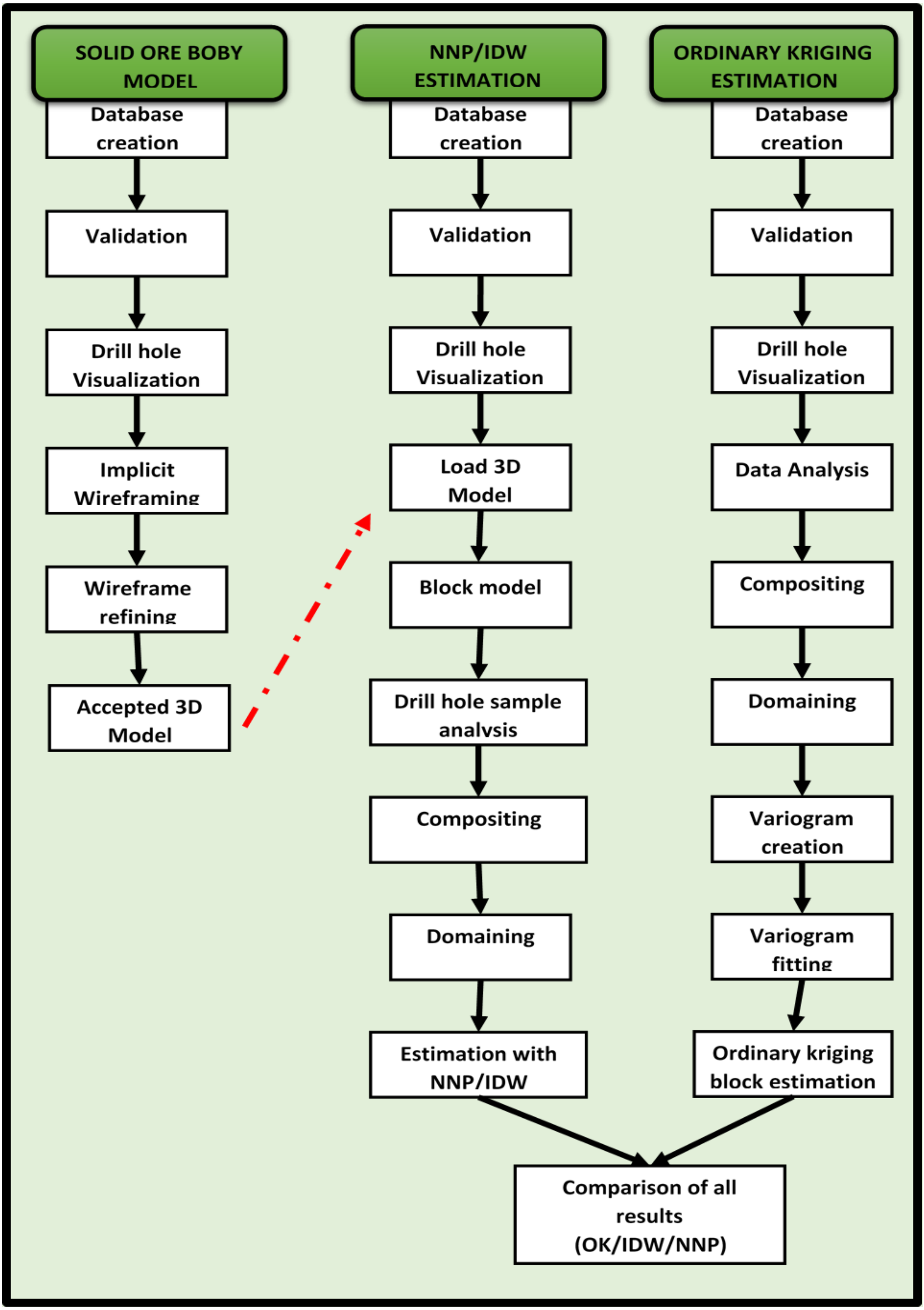


Figure 3.2: Workflow of the research showing steps followed to achieve the objectives

3.2 Data types, data acquisition and Pre-processing

Thirty-nine (39) reverse circulation (RC) exploratory data for the Gofolo Hill deposit were used for resource modelling and estimation. Two diamond drill holes (DD) data were used to validate the precision and accuracy of the RC data. The minimum and maximum drill hole depth is 42m and 156m, respectively. The average drill hole depth is calculated to be 87.9m. The minimum and maximum elevation at which the project is drilled is 61.4m and 218.3m, respectively. The average elevation of the drill hole project is 124.4m. The geographical extent of the project is shown in (**Table 3.1**). Thirty-six (36) holes were drilled at 50-degree dip, while three holes were drilled at 90 degrees dip (vertical holes). All the drill holes followed the projected geographical coordinate system: UTM WGS_29N.

The Datamine Studio RM 1.13 software was used for data analysis to complete the solid 3D geological model and resource estimation. ESRI ArcGIS 10.8.2 software was used to produce maps for the study area. The four exploratory data tables (collar, survey, assay and geology) were pre-processed to organise, clean, and validate each table. A geological database was created from the four tables, validated, composited at 2m and then visualized. The collar table contains data on the location of the drill holes. The survey table includes data on the orientation at which the holes were drilled. The assay table contains the elemental analysis or the iron grade, and the geology table includes data on the rock types. The data pre-processing step revealed that all assay values were accurate, but about 700 (or 30%) of the lithological or geology data was absent. This did not affect the integrity of the research since the model and estimation were strictly based on the grade shells (assay values) and not the geological or lithology domain. A 30% Fe cut-off grade was applied to the project since iron ore worldwide is considered 30% or above.

Table 3.1: Geographical extent of the project

	Easting (m)	**Northing (m)**	**Elevation (m)**	**Depth (m)**
Minimum	252606.66	761008.43	61.44	42.00
Maximum	254269.85	761770.05	218.28	156.00
Average	253309.85	761385.50	124.38	87.94
Range	1663.19	761.61	156.84	114.00

3.3 Exploratory data analysis: principles

Descriptive statistical analysis was carried out on the drill hole data to evaluate the distribution of the values since geostatistics is most effective with normally distributed data. Normally distributed data shows a normal bell curve with variance and mean that has little variation. A lognormal data transformation could have been used will be done if the data does not reflect a normally distributed histogram curve. The assay's visual normal curve and the statistical assay values (CV, skewness, kurtosis) proved that the data was normally distributed and was modelled and estimated as a single domain.

Distribution curve analysis

The assay values showed a normal distribution curve. The normal distribution, or the Gaussian distribution, is a probability distribution that shows a proportional symmetry about its mean, with most values grouped around the peak and having values that tape off equally in all directions (**Figure 3.3**). This distribution shows that data close to the mean occur more frequently than data far away from the mean. The normal distribution is fitted by the value of skewness and kurtosis or by graphically approximating a straight line. The numerical value of skewness should be zero or close to zero, and that of kurtosis should be three or close to three.

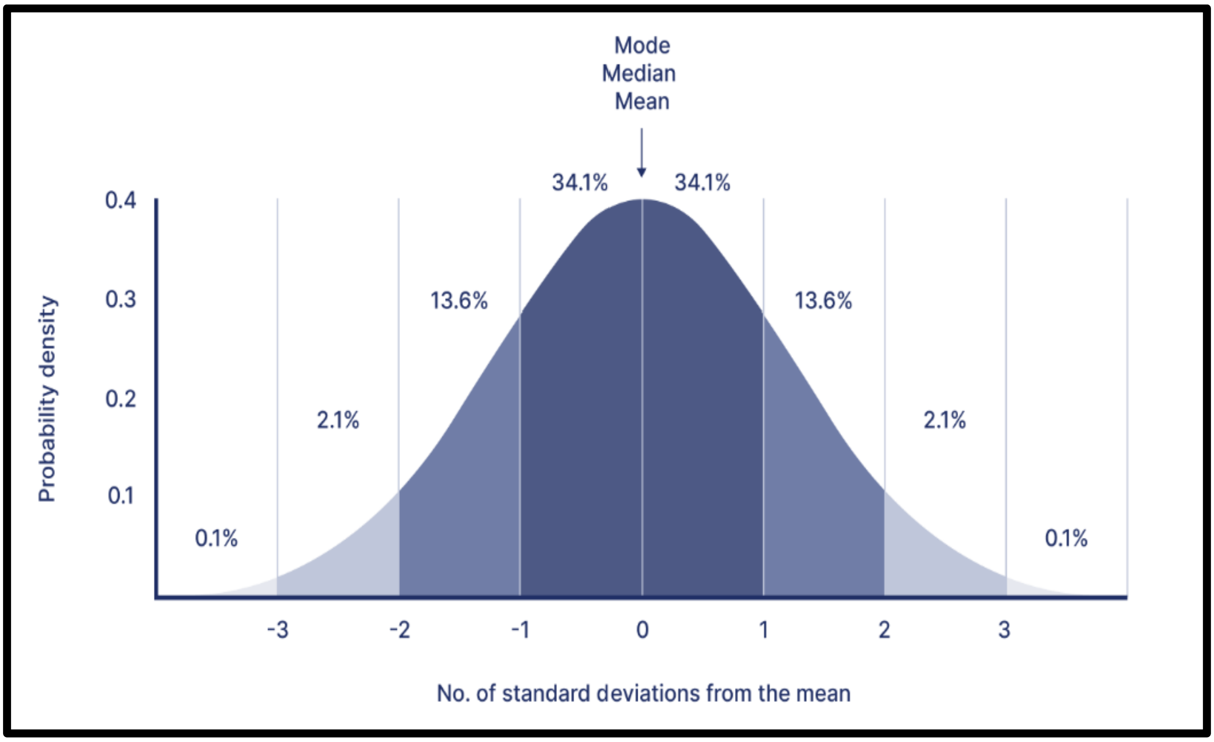


Figure 3.3: Standard normal distribution curve (Bhandari, 2023)

Skewness

Skewness **(Figure 3.4)** measures how symmetrical a distribution is or how well the distribution lacks symmetry. It displays how much a random variable (RV) deviates from the mean. A distribution is normal or symmetrical if the left and right ends of the curve are alike. The skewness value for a symmetrical distribution is 0. This case has a mean, median, and mode equal or nearly equal. Skewness showing a value greater than 0 is termed right-skewed, while Skewness showing a value less than 0 is termed left-skewed. (**Table 3.2**) presents a description of skewness and the different types.

A distribution is considered highly skewed if the skewness is less than -1 or greater than 1; moderately skewed if the skewness falls between -1 to -0.5 or 0.5 to 1; and approximately symmetric if the skewness falls between -0.5 and 0.5. The formula of Skewness is given in **Equation 2.24**:

$$Skewness = \frac{\sum (x-\overline{x})^3}{(n-1)S^3} \tag{2.24}$$

S represents the standard deviation and $\overline{x}$ is the mean.

Table 3.2: A description of the different types of skewness

Types of Skewness	Value	Description
Negatively skewed	Less than 0	Longer left tail than right (mean<median<mode)
Normal distribution (No skewed)	0	Symmetrical curve (mean=median=mode)
Positively skewed	Greater than 0	Longer right tail than left (mode<median<mean)

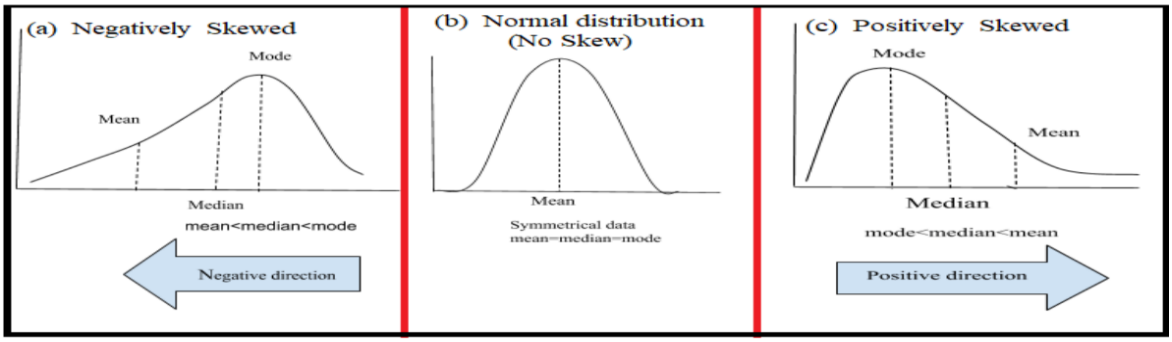


Figure 3.4: Curves showing skewness distribution (Alnassar, 2020)

Kurtosis

Kurtosis (**Figure 3.5**) is a statistical measure that indicates how heavy-tailed or light-tailed a distribution is or whether the distribution is taller or shorter than a normal distribution. This can be simplified as how flat our graph's distribution is or whether it is displaying a peak. It also shows the degree to which values are concentrated around the mean. For an ideal normal distribution, the kurtosis value is three or close to 3, greater than three is considered positive, and less than three is considered negative. Since kurtosis is spoken of with consideration of excess kurtosis (-3), the normal distribution is considered for kurtosis near 0, positive for kurtosis > 0, and negative for kurtosis < 0.

The formula for calculating Kurtosis is given in **Equation 2.25**:

$$Kurtosis = \frac{\sum\left(x-\bar{x}\right)^4}{\left(n-1\right)S^4} \qquad (2.25)$$

S represents the standard deviation and $\bar{x}$ the mean.

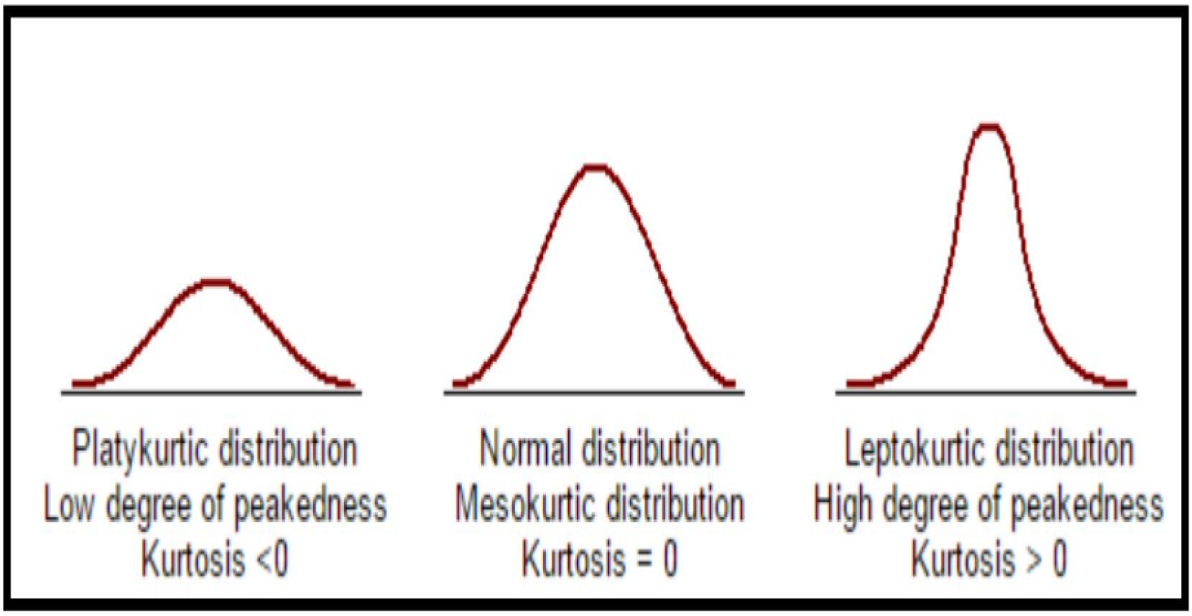


Figure 3.5: Kurtosis distributions (Alnassar, 2020)

Coefficient of Variation classification

The coefficient of variation, commonly called the relative standard deviation, displays the relative variability observed in data. It shows the dispersion of the data about the mean. When a CV is evaluated, the value is represented in a percentage. A lower percentage indicates a lower CV, and a higher percentage indicates a higher CV. The lower the CV value, the better since it shows that the spread of data values is low relative to the mean.

Equation 2.26 gives the formula for CV:

$$CV = \frac{\sigma}{\mu} \tag{2.26}$$

Where σ is the standard deviation, and μ is the mean.

3.3.1 Lognormal distribution analysis

Not all data values show a regular bell-shaped curve or are distributed normally. When a distribution curve is skewed, and the kurtosis value is significantly greater than or less than 3, a lognormal distribution will represent the distribution. Such a curve is either convex up or convex down. In this case, a data transformation will be used to obtain symmetrical distribution before block kriging is used for geostatistical estimation. The assay data were analyzed to be normally distributed; therefore, there was no need for data transformation.

3.4 Domaining in Resource Estimation

Exploratory data analysis through CV, skewness, kurtosis and visualization of histogram curve was used to conclude on the project being evaluated with a single geological domain. EDA aims to understand the characteristics of the data under study and to recognise similar geological domains based on geological features (alteration, mineralogy and lithology) and spatial continuity of grades (Duke et al., 2001; Emery et al., 2005). Glacken et al., (2001) define "a geological domain as an area or volume within which the mineralisation characteristics are more similar than outside the domain". Although geological features or aspects should be considered in determining the interpolation domain, regular and common practice is using assay grade (Duke et al., 2001). This shows it is a best practice to domain with knowledge of the geology and structure complemented by the mineralization. A full statistical analysis should be enough to delineate domains for estimation and produce unbiased results by relating only data of the same mineralization style. Sterk et al. (2019) emphasized the need to have domain estimates only based on values within a domain and not considering external values. If the vital point of resource estimation is not well considered, it would negatively affect the integrity of the estimates and lead to biased or false estimates. Two types of domain boundaries are considered in domaining: the hard and soft.

Sterk et al. (2019) outline rules of good practice that should be followed for resource estimates and resource models involving domaining:

i. Principle input of the domain should be geological information
ii. Recognize the distinction between geological and estimating domains.
iii. Think of the domain-building process as an iterative one.
iv. Analyse the statistics for stationarity
v. Grade-based domains should be handled properly.
vi. Analyse the boundaries.
vii. When feasible, employ implicit approaches, but do so with caution.
viii. Clearly describe all that has been done.

3.4.1 Soft boundary domaining

A soft boundary may exist if the domain has a boundary with grade values that evolves continuously across the next domain (**Figure 3.6a**). This indicates a smooth transition across domains regarding the locally average grade. The data on both sides of the boundary are well correlated and can be utilized to increase the assessment of mineral resources close to domain borders. A professional geological interpretation often deduces this correlation. The soft boundary domain considers analysing zones for mineralogical units as high-grade, low-grade, and medium-grade. These zones can be defined and analysed or estimated separately to show more accurate results.

3.4.2 Hard boundary domaining

"A hard boundary is defined as an abrupt or sudden variation of a quantitative variable (assay values) when moving from one domain to another" (Ekolle-Essoh et al., 2022). Structural controls on grades will prevent normal smooth transitions between geological domains, such as faulting and displacements. This results in an abrupt change in the characteristics of neighbouring domains. The grade will likely alter suddenly, especially if the deposit is heterogeneous from one domain to another. A deposit with a hard domain boundary shows assay values that do not vary continuously across boundaries (**Figure 3.6b**). It is essential to carry on boundary analysis before resource estimation to enable points to be estimated by a neighbourhood of points limited to a domain in which the point lies.

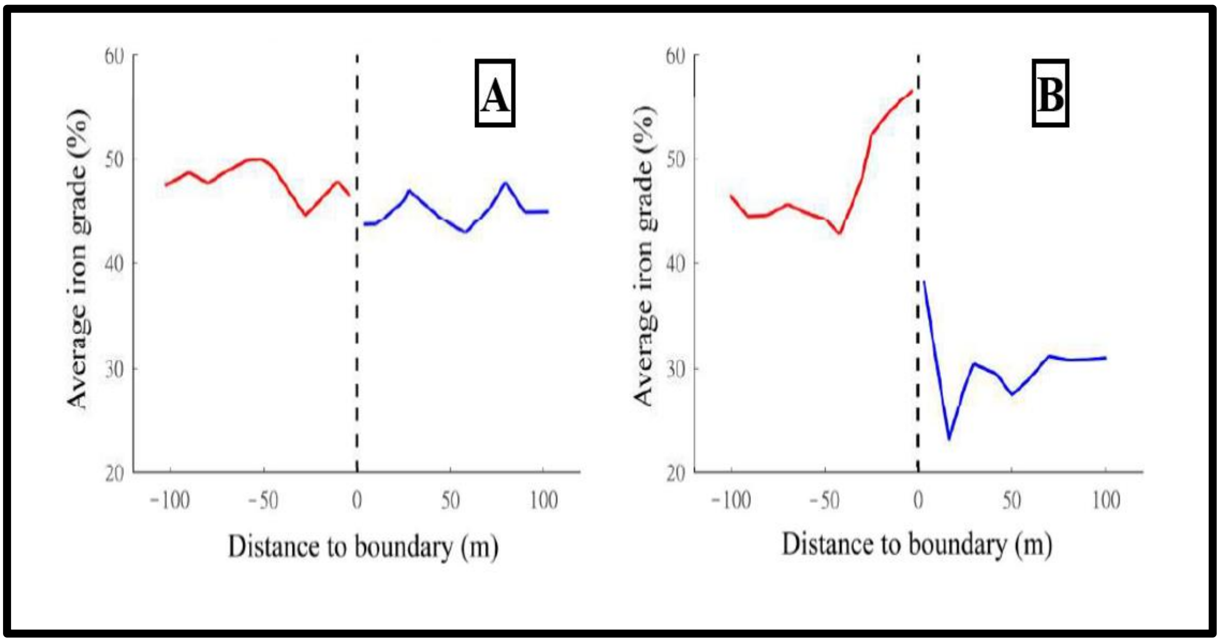


Figure 3.6: domain: a) soft boundary and b) hard boundary (Ekolle-Essoh et al., 2022)

3.5 Orebody Modelling

The orebody was modelled after applying a 30% Fe grade cut-off to the drill hole data. An accurate and precise model is necessary for reliable resource estimation and effective mine development. Its main aim is predicting and estimating the ore body's volume, tonnage and grade. The ore model follows the completion of a mineral exploration program to show in 3D the size, shape and extent of the mineral deposit occurring below the subsurface. According to Glacken et al. (2001), the deposit's model, the complex geology, and the need for accuracy are some factors that influence the type of orebody models used.

Explicit and implicit geological models are the two categories of geological models. The explicit or traditional model was first developed, and it involves manual digitization. In contrast, the implicit geological or automated model has developed over the last 50 years due to advancements in computers and technology. The explicit method entails sectioning and creating strings which are then merged to produce a pseudo-three-dimensional model.

By employing a computer algorithm to create a pseudo-3D model from the exploratory data, implicit modelling eliminates the tedious process of manual digitization. The construction of a mathematical constraint allows for the 3D visualization of different features of the data. The different features can be a geology model showing the mineralized zone against the waste, a non-mineralized zone, or multiple zones separated into high-grade, medium-grade, low-grade, and waste. It is essential to validate all models to ensure accuracy and reduce future mining risks. Implicit models can be updated and adjusted automatically as more data becomes available. As a result, the models are more effective and flexible. Another essential feature of the implicit modelling approach is its capacity to simultaneously construct and visually examine many models based on various interpolation factors.

Ore body models are later used to create block models, which are spatially georeferenced and comprise blocks of a defined size. The Block models are used for grade interpolation and are filled with geological information. The block model geometry (or size) is very crucial. Sub-blocks in blockmodels depend on the model's extent and resolution to produce a result without flaw when dealing with regions at the edges of geological contacts.

3.6 Mineral resource estimation

The estimation of the project is made using a global cut-off grade of 30% and a global density value of 3.0 kg/m^3. Iron ore must contain at least 30 percent Fe to be classified as a deposit, hence the use of the global cut-off. According to Tawana Resources (2014) Scoping study, the density of the iron formation ranges from 2.8 to 3.2 kg/m^3. An average of the minimum and maximum density values, 3.0 kg/m^3, which is also the same as the global density value for estimating inferred iron ore resources, is used for tonnage estimation.

The mean grade is calculated using **Equation 3.1**.

$$Mean\ grade = \frac{\sum(category\ grade\ x\ tonnage)}{\sum tonnage} \tag{3.1}$$

The tonnage for each category of grade range is calculated using **Equation 3.2.**

$$tonnage = volume\ x\ density \tag{3.2}$$

The total tonnage is calculated using **Equation 3.3**

$$total\ tonnage = \sum tonnage \tag{3.3}$$

3.6.1 Geostatistical estimation using ordinary kriging

After geological database creation and validation, data analysis, solid model creation, geostatistical ordinary kriging estimation were carried out for the Iron (Fe) assay values. The Exploratory data analysis was completed to ensure that the geostatistical estimation is based on normally distributed data. The primary undertaking in geostatistical estimation is the creation of a semivariogram (or variogram). The experimental semi-variogram was created following the trend pattern revealed in the anisotropy map. When the experimental variogram has been produced, it is then followed by a fitting of the theoretical variogram to show the correlation of all the grade elements. The modelled variogram was then used to produce the estimation for the kriging method.

3.6.2 Basic Estimation with IDW and NNP Methods

The inverse distance weighting (IDW) interpolation method and the nearest neighbour polygon (NNP) interpolation method were used in this project to compare their grade estimates with the estimates produced by the geostatistical ordinary kriging methods. These methods can also approximate functions' value for a specific place in space. The nearest neighbour polygon approach chooses the value of the nearest point in space without considering the value of other nearby points. This is similar to using the nearest value as a proxy to the point being interpolated. The inverse distance weighting method calculate estimates by averaging the nearby sample weights by the distance from the point that is being estimated.

3.7 Model-validation for estimation methods

It is vital to get a true and accurate model by cross-validating it. A possible way to achieve this is by testing the estimated kriging results using cross-validation. The slope of regression values was calculated for the project and then used to validate kriging estimates. The regression slope compares the actual grade values of points and the calculated grade values of blocks, and the goal is to have a mean slope that is nearly 1. A good correlation was shown for our kriged estimates by the mean slope value calculated. Conditional bias occurs if the mean slope is less than 0.5 or greater than 1.5, showing underestimation and overestimation, respectively.

Collectively, all methods were validated in three ways:

1. By comparing wireframe volume results: wireframe estimated, and wireframe calculated volume results
2. By comparing the drill hole input values mean and the block estimate values mean
3. By comparing the standard error: the standard error is computed by **Equation 3.4** below:

$$SE = \frac{\sigma}{\sqrt{n}} \tag{3.4}$$

SE is the standard error; σ is the sample standard deviation, and n is *the* number of samples.

CHAPTER FOUR: RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter uses drill-hole data to present the results and discussions of the Gofolo Hill Iron ore project in Grand Cape Mount County, Western Liberia. The results include geological modelling and resource estimation using the advanced estimation method (geostatistical ordinary kriging method) and basic estimation methods (nearest neighbour polygon and inverse distance weighting method). A comparison is made of the three methods used on the project.

4.2 Project description

The Gofolo Hill iron ore project, with a strike length of about 2km, and Zaway and Koehnko, collectively under the Mofe Creek Iron Ore project, appear to represent the strike continuation of Bomi Hill and Bong Iron ore Project, two famous iron ore projects in Liberia by the 1960s. The Gofolo Hill project was drilled using the diamond-core drill (DD) and reverse circulation (RC) methods. Two DD holes were drilled for twinning study purposes (that is, to confirm the accuracy and precision of RC drill holes) and for geotechnical studies. Thirty-nine (39) RC drill holes with a grid spacing of 200mx60m were used for mineral resource modelling and resource estimation purposes (**Figure 4.1**). (**Appendix 1)** presents the project's combined collar and survey data. (**Appendix 2**) shows the drill holes with labelled borehole IDs.

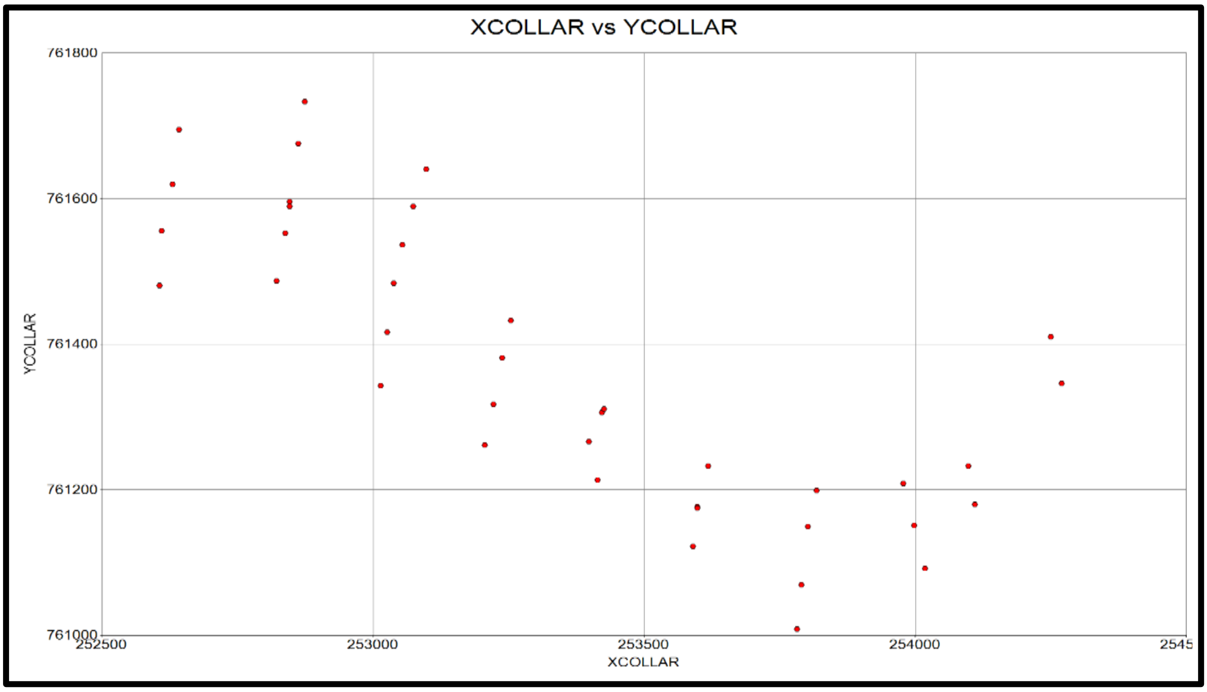


Figure 4.1: A plan view of the thirty-nine (39) RC drill holes used for resource estimation

4.3 Geological database creation and Validation

A geological database was created using the Datamine studio RM 1.13.35 software. A total of four tables were uploaded to the software to create the geological database for the project. The four tables uploaded are the collar table, survey table, assay table and geology table (**Table 4.1**). The Datamine software requires two mandatory files or tables for the database: the collar and the survey table, and optional table(s) such as assay, geology, zone, etc.

Table 4.1: Headings for drill holes tables used to create a geological database

COLLAR TABLE				
HOLE ID	**EASTING (m)**	**NORTHING (m)**	**ELEVATION (m)**	**DEPTH (m)**
GMRC010	253053.3233	761536.8102	111.2037476	72
GMRC013	252629.6505	761620.3772	92.08198942	60
SURVEY TABLE				
HOLE ID	**DEPTH AT (m)**	**DIP (°)**	**AZIMUTH (°)**	
GMRC020	0	51	340	
GMRC032	40	48	26	
ASSAY TABLE				
HOLE ID	**FROM (m)**	**TO (m)**	**Fe (%)**	
GMRC001	54	56	37.8	
GMRC004	116	118	36.87	
GEOLOGY TABLE				
HOLE ID	**FROM (m)**	**TO (m)**	**LITHOLOGY**	
GMRC018	40	41	ITA	
GMRC027	58	59	HEM	

Upon creating the database, a validation check was made to ensure the data was void of errors.

A static desurveyed drill hole file was created with the following validation checks:

- Input validation.
- Checked field names.
- Checked parameters.
- Checked collar file collar.
- Checked the survey file survey.
- Dip convention: positive dips are downwards
- checked sample file(s).
- checked from/to interval is not duplicated or overlaps of the next sample
- checked if the downhole “to value” of a sample is greater than the downhole from value.
- Checked output file drill holes.
- Merged 2 sample files.
- desurveyed.
- Validated sample files.

The results from the software showed that no problems or errors were identified. The desurveyed drill hole file contains 1525 samples.

4.4 Proof of comparable accuracy: RC and DD holes comparison

Two diamond drill holes were completed on the Gofolo Hill project to provide confidence in the data from the reverse circulation drilling method. Besides twinning to confirm the precision and accuracy of the geochemical or assay report, the DD holes were completed for geotechnical and metallurgical studies. The two DD holes are GMDD001 and GMDD007, which compared the RC holes GMRC006 and GMRC013, respectively (**Figure 4.2**). An analysis was done on the results of the two drilling methods to understand how they relate and draw a conclusion on the assay values from the reverse circulation (RC) drilling method. The results using summary statistics (Error! Reference source not found. and Error! Reference source not found.), scatterplot (

Figure 4.3: Scatter plot comparing the twin holes (GMDD001 and GMRC006) and Error! Reference source not found.) and Fe grade comparison (**Figure 4.4** and Error! Reference source not found.) showed an acceptable correlation between the data of the two techniques used for drilling; therefore the RC data were used for mineral resource estimation and mineral resource modelling. (**Appendix 3a** and **b**) shows the full statistical comparison of the twin holes.GMD001 and GMRC006 shows a correlation coefficient of 0.758 while GMDD007 and GMRC013 corellation results to 0.825. The two values represents acceptable good correlation.

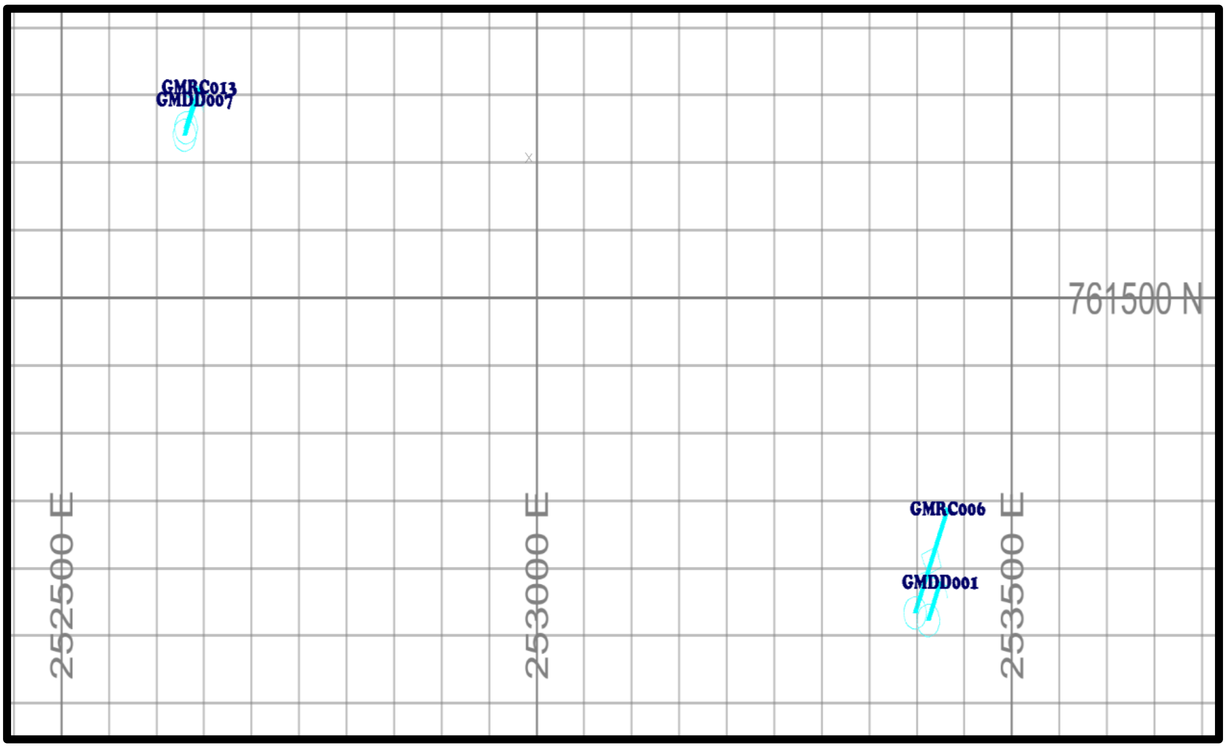


Figure 4.2: Twin holes: GMDD07/GMRC013 (upper left) and GMD01/GMRC06 (right)

Comparison of twin holes 1: GMDD001 GMRC006

Three (3) methods of comparison were used to show the relationship between the holes drilled using the RC method and that of the more accurate DD drilling method to confirm the precision and accuracy of the geochemical results. Statistical comparison, regression plot (scatter plot) and a line graph comparing the Fe grade of GMDD001and GMRC006 values all revealed that the grade values from the RC assay show acceptable comparison.

Table 4.2: Summary statistics comparison of twin holes one (1)

NAME	GMDD001 (%)	GMRC006 (%)
Total Samples	21	21
Minimum	36.418	35.660
Maximum	59.390	60.320
Range	22.972	24.660
Mean	50.145	48.920
Standard Deviation	7.307	8.333
Coefficient of Variation	0.146	0.170
50th Percentile	54.009	52.410
Correlation Coefficient	0.758	

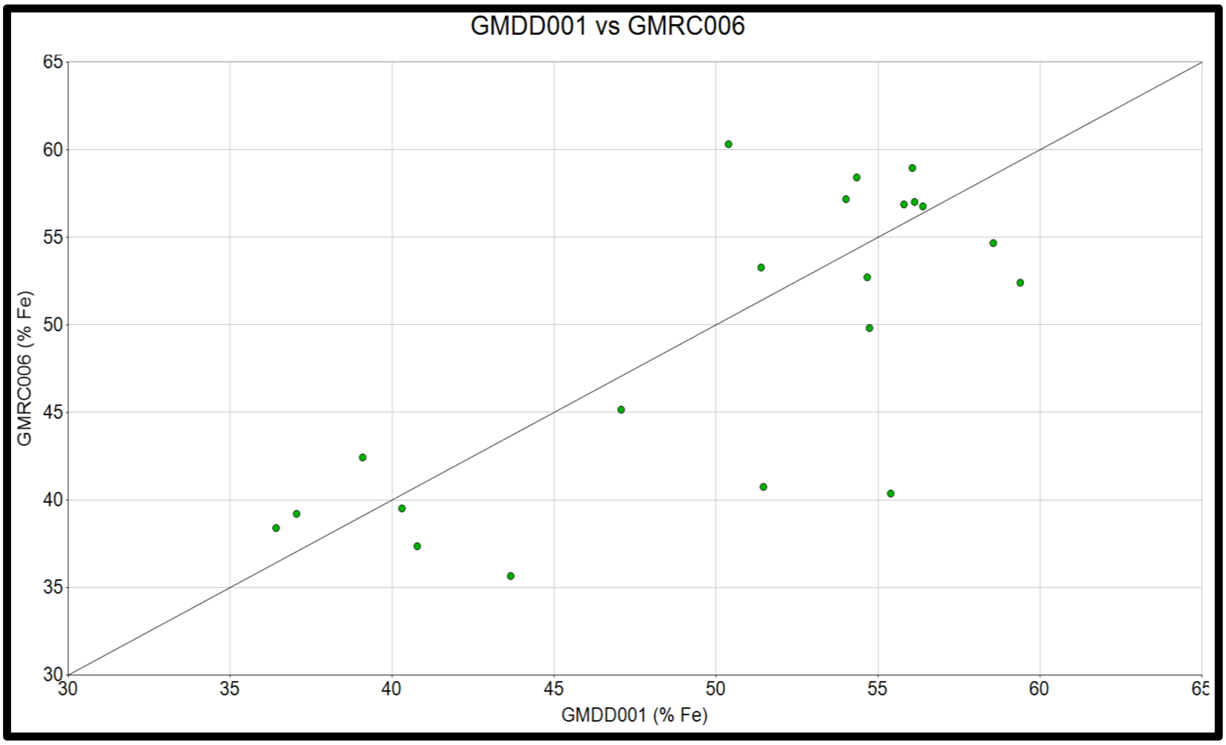


Figure 4.3: Scatter plot comparing the twin holes (GMDD001 and GMRC006)

Line graph comparing the DD hole GMDD001 and RC hole GMRC006

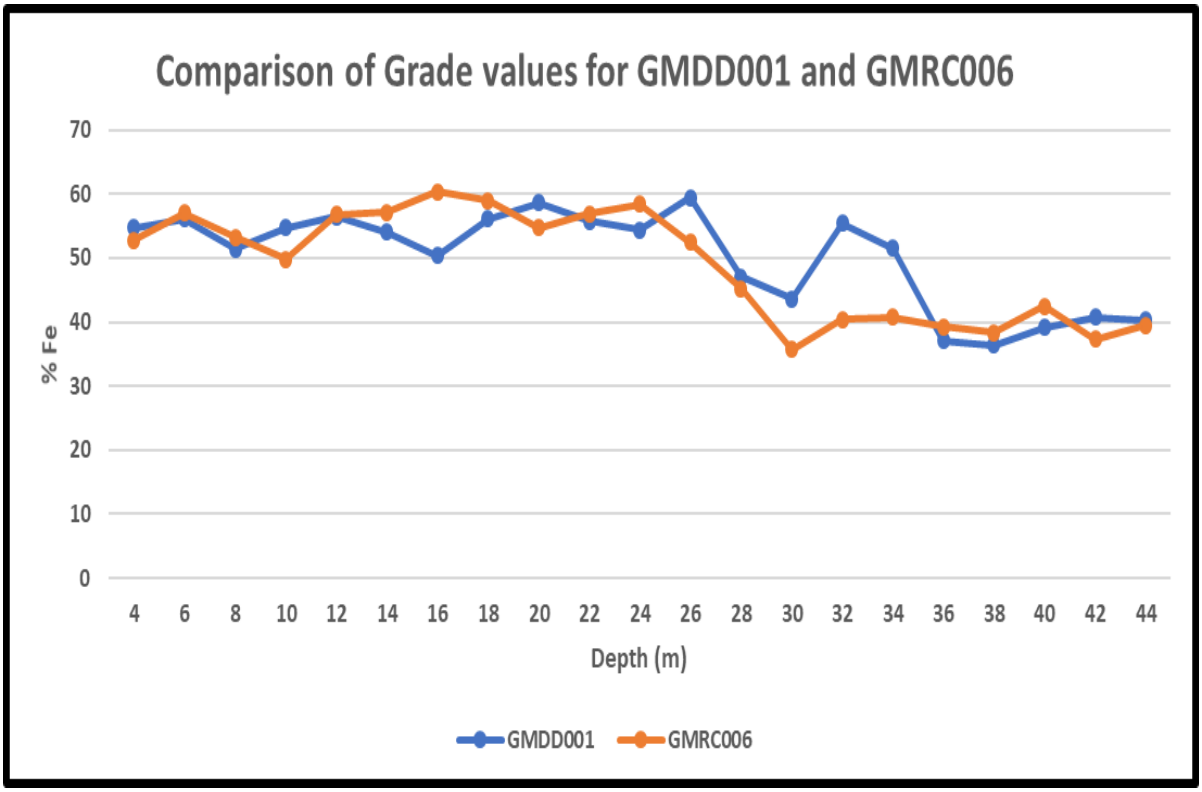


Figure 4.4: Line graph comparing the twin hole Fe grade (GMRC006 and GMDD001)

Comparison of twin holes 2: GMDD007 and GMRC0013

Twin holes two were also compared using the same three (3) methods to confirm the accuracy and precision of results. The methods of comparison were statistical comparison, regression plot (scatter plot) and a line graph comparing the Fe grade of GMDD007 and GMRC013 values. Results show a close correlation.

Table 4.3: Summary statistics comparison of twin holes two (2)

NAME	GMRC007 (%)	GMDD013 (%)
Total Samples	21	21
Minimum	17.334	18.590
Maximum	58.467	56.510
Range	41.132	37.920
Mean	39.569	39.931
Standard Deviation	11.618	9.876
Coefficient of Variation	0.294	0.247
50th Percentile	40.480	40.660
Correlation Coefficient	0.825	

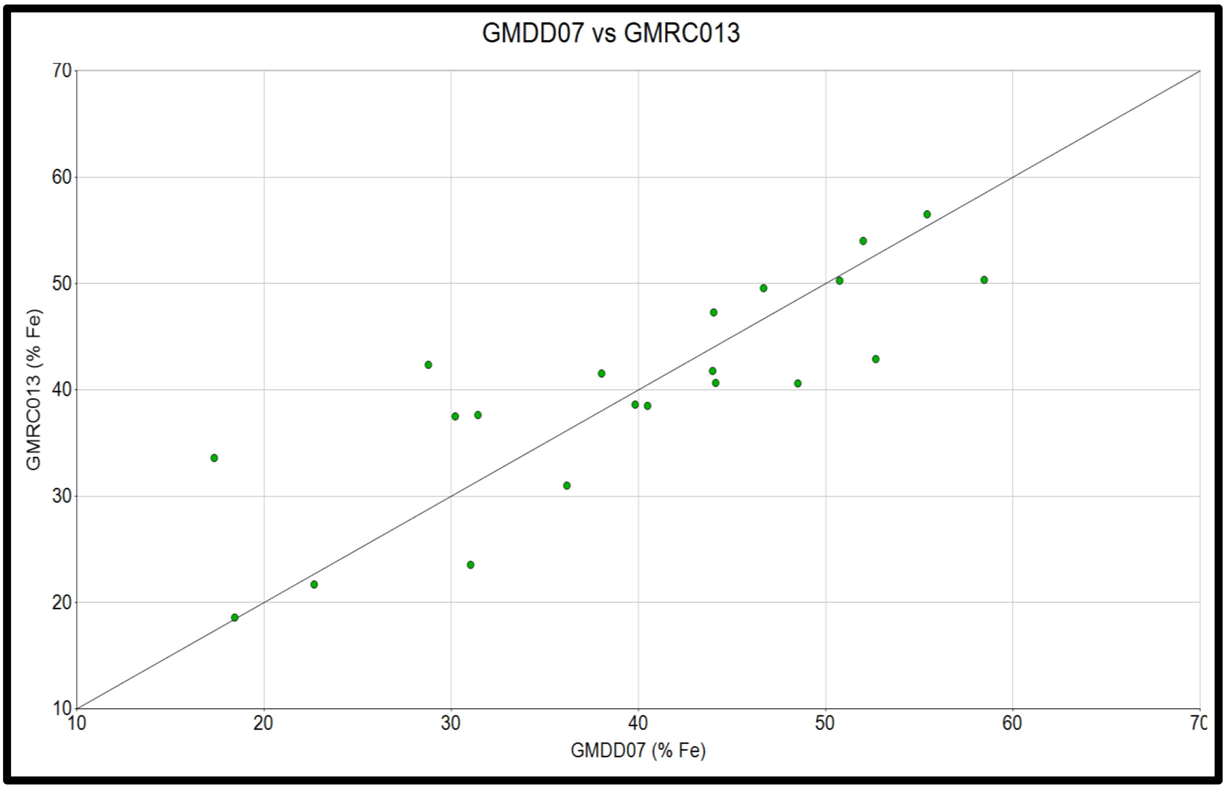


Figure 4.5: Scatterplot comparing the twin holes (GMDD007 and GMRC013)

Line graph comparing the DD hole GMDD007 and RC hole GMRC0013

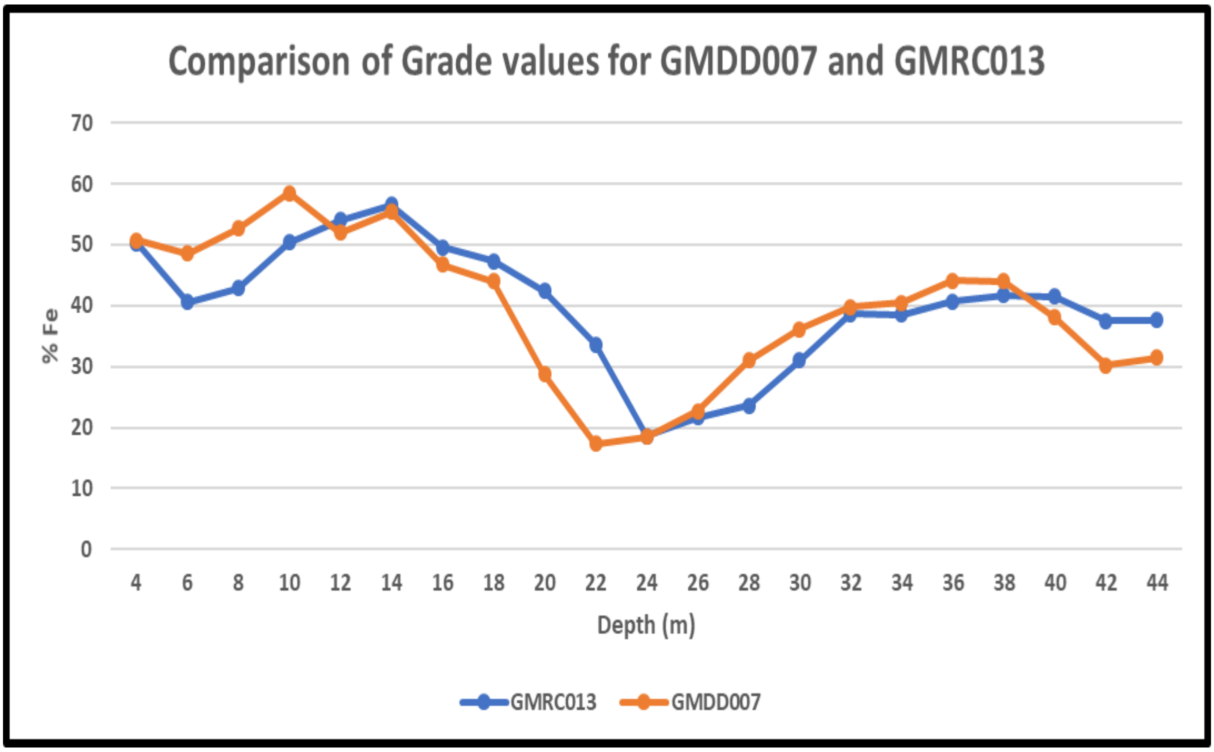


Figure 4.6: Line graph comparing the twin holes Fe grade (GMDD007 and GMRC013)

4.5 Exploratory Data Analysis

Exploratory data analysis (EDA) is the process of analysing data to observe and summarize the main characteristics. The exploratory data analysis was completed on the raw samples of assay data to detect outliers, initiate a top cut, detect sample errors or mistakes, and evaluate missing data. Univariate analysis (single element analysis) was carried out on the Fe assay values only, though other elements such as SiO_2 and Al_2O_3 are essential in evaluating the viability of an iron ore project. The summary statistics (**Table 4.4)** and histogram (**Figure 4.7)** revealed that the data is relatively normal, proving that data transformation is neglected. The kurtosis value in our summary statistics is -0.466. A kurtosis value close to zero represents data that are distributed normally. Another test of the data distribution is the value of skewness. The skewness value of 0.486 shows an approximately symmetrical curve, as seen in the histogram, meaning our data is approximately distributed normally. With a low standard deviation and a coefficient of variation value of 0.625, lower than the maximum value considered for mineral resource estimation practice (1.5), estimation was carried out with a single domain. Full statistics of the raw sample data can be seen in (**Appendix 4a)**

The decision for outlier and top cutting (or capping) was reached by keenly investigating the probability plot. A probability plot **(Figure 4.8**) that is relatively linear or shows little or no change in slope means there is no need to apply a top cut (capping) to the data. Application of top cut (capping) is essential for data with outliers or data showing extremely high grades that, if not treated, would present bias estimation of a project.

Table 4.4: Summary statistics for the raw drill hole data

NAME	VALUE (%)
Total Samples	1525
Minimum	0.940
Maximum	60.320
Range	59.380
Mean	20.460
Variance	162.999
Standard Deviation	12.767
Coefficient of Variation	0.624
Skewness	0.486
Kurtosis	-0.466
50th Percentile (Median)	19.210

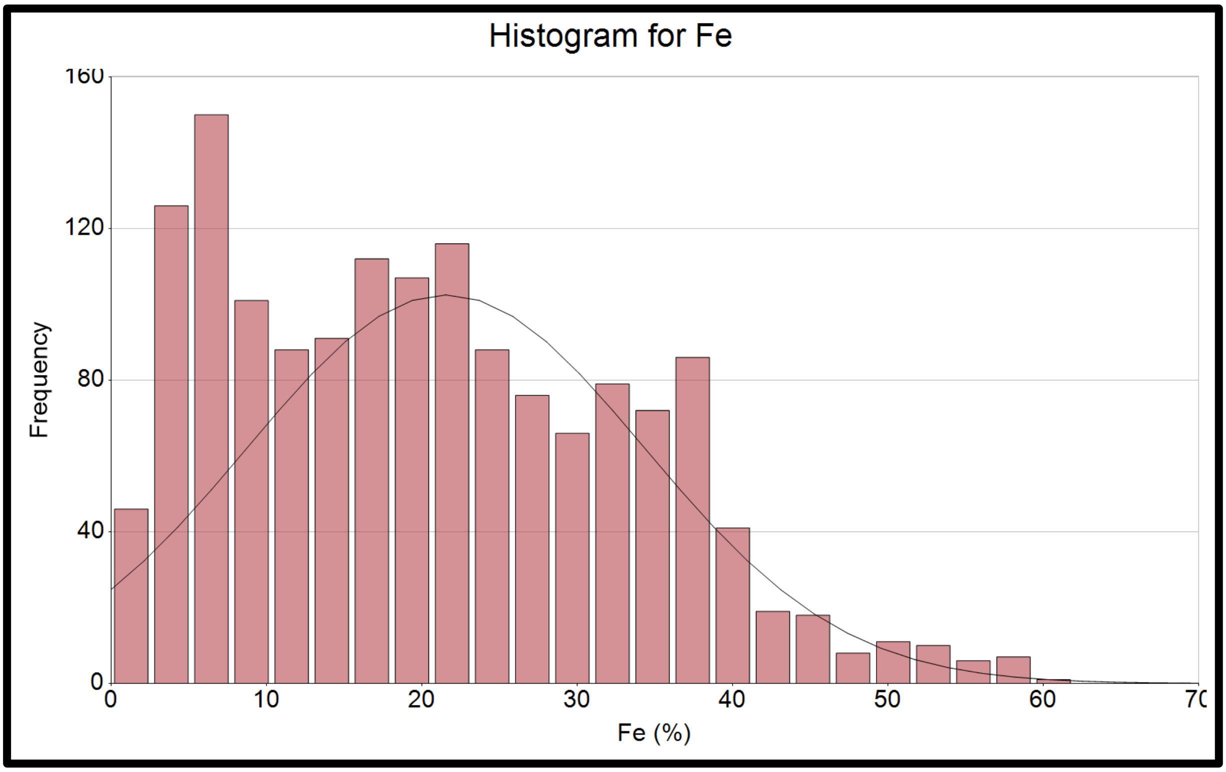


Figure 4.7: Histogram of Fe grade values of raw sample data composited at 2m

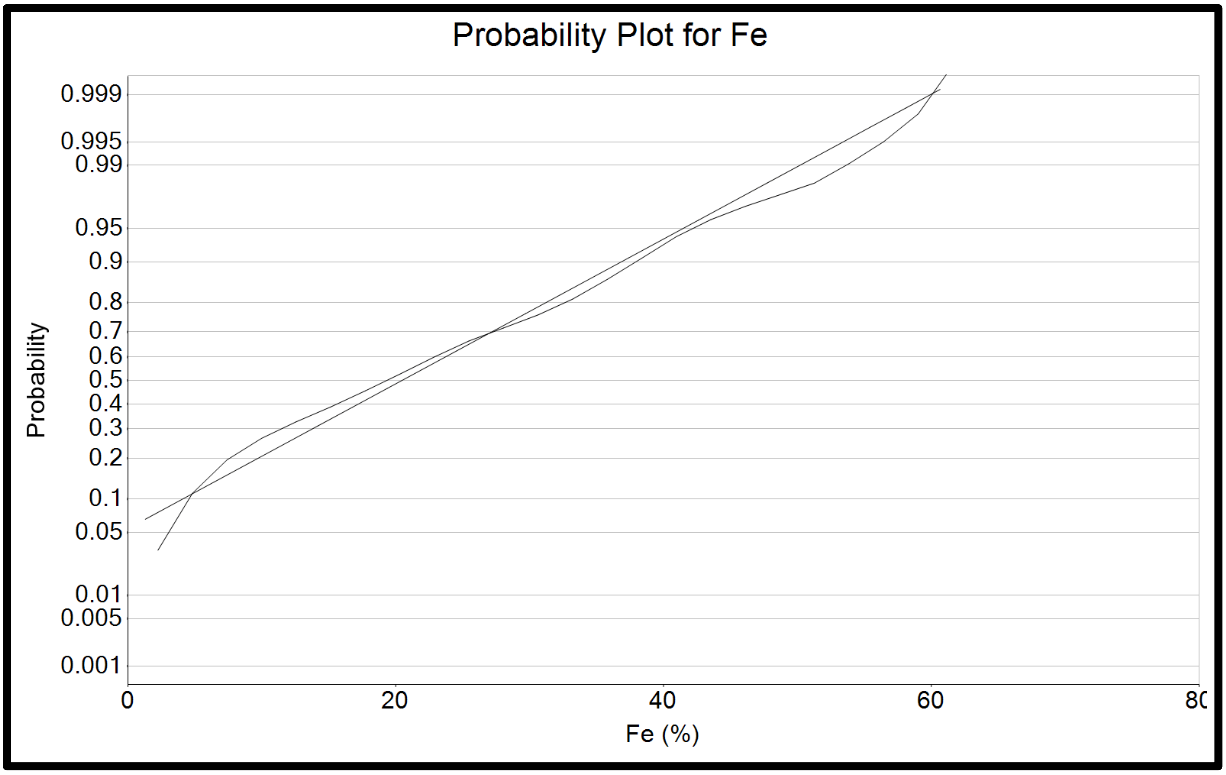


Figure 4.8: Probability plot of raw sample data

Compositing drill hole length

In resource estimation, it is vital to composite data to have equal volume or support and thus reduce the data variance. RC drilling is done with equal length. The data for this project were drilled at a 1m sampling interval and logged geologically at 1m but then assayed at 2m. The geological database was created using the four tables (collar, survey, assay and geology) at then composited at 2m sample length to show downhole sample homogeneity. (**Figure 4.9**) shows a histogram for the 2m length composited data.

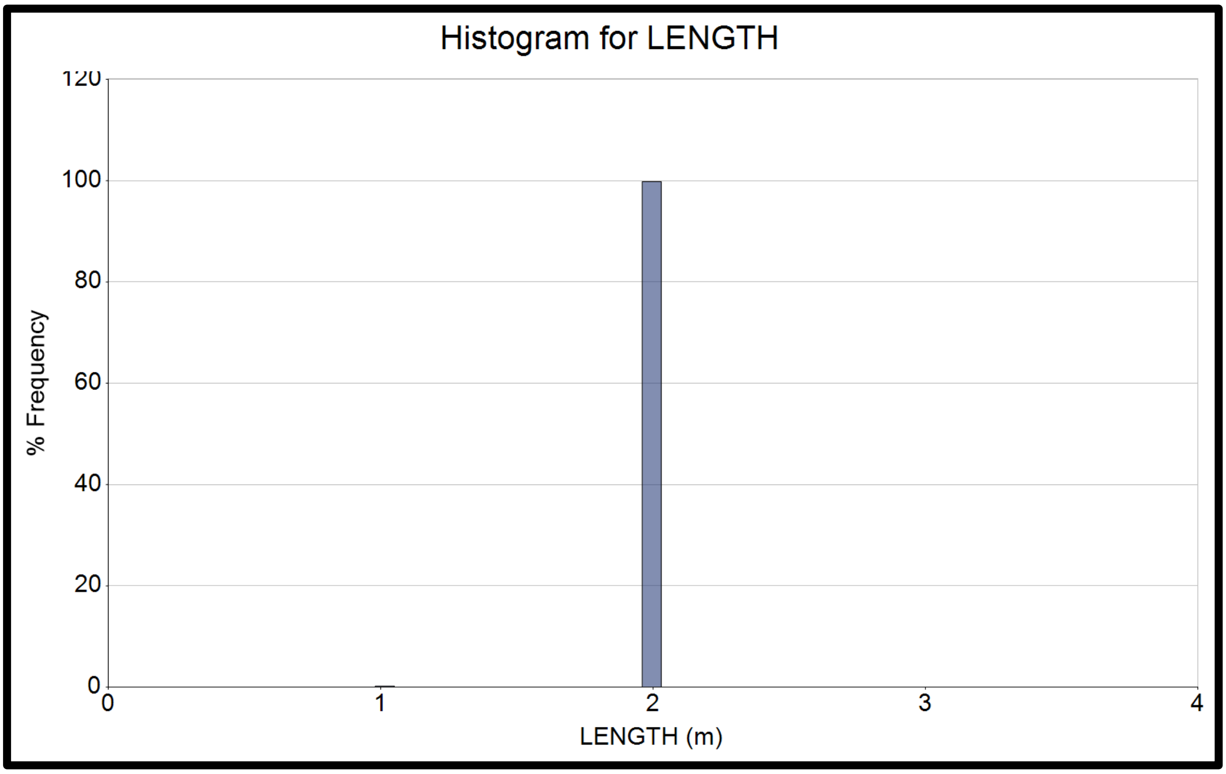


Figure 4.9: Histogram of composited length data showing 100% downhole length of 2m

Domain evaluation

A domain is an area, zone or region with more similar mineralisation or similar statistical attributes. A single domain was considered for the project because of three primary reasons: (1) the visualization of the histogram shows a normal distribution, and summary statistics values such as skewness, kurtosis and, importantly, coefficient of variation (value <1.5) are within the accepted range for mineral resource estimation without a domain, (2) geology or lithology table missing about 40% of the lithological data and (3) the probability plot showing a straight line since a deviation from the straight line for a probability curve shows that multiple populations need to be separated in numerous domains.

Data Visualization and grade cut off

A grade cut-off of 30% Fe was applied to the project since iron ore deposits worldwide are considered 30% or above. It is important to note that besides cut-off grade, other important factors are to be considered before a mineral resource project can be deemed viable or economical. (**Figure 4.10**) shows a cross-section (east–west view) of the drilling project, with red representing ore and blue representing the waste after applying the 30% grade cut-off.

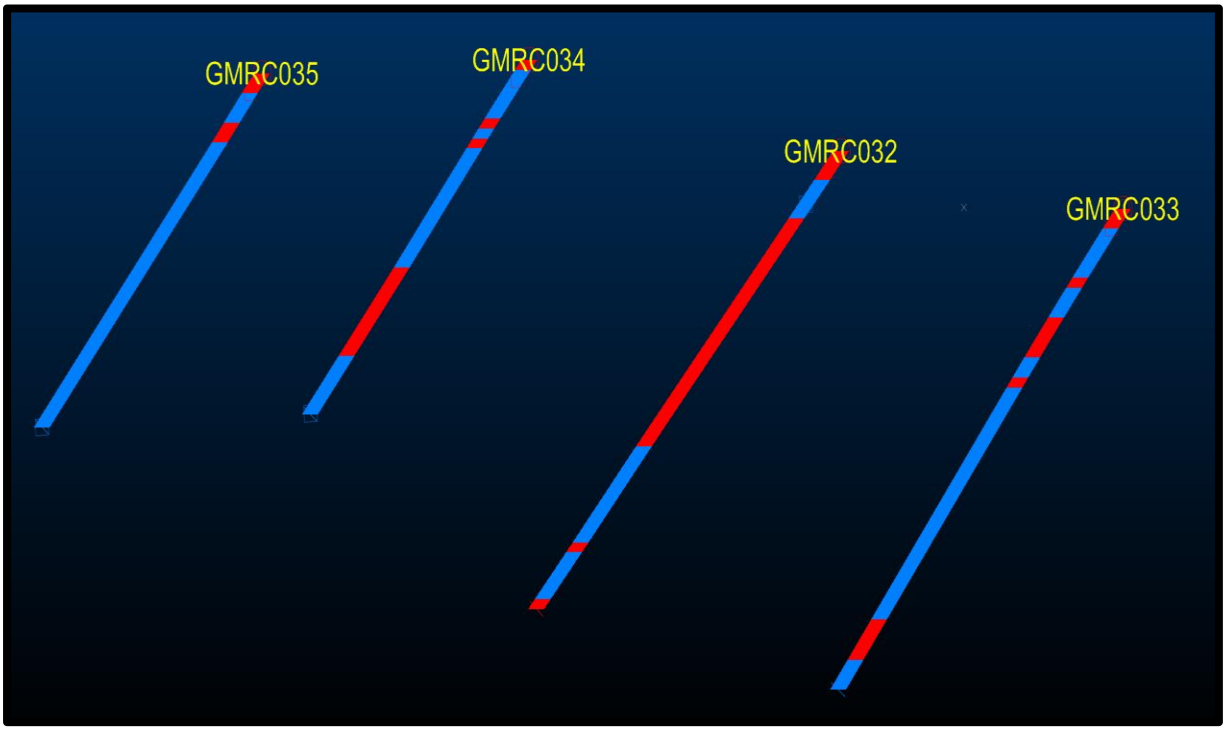


Figure 4.10: Cross-sectional view (east-west) of holes showing ore in red and waste in blue

4.6 Resource Modelling

Objective one (1) of this research was completed by the creation of a 3D solid model using a 30% Fe grade cut-off to reveal the extent and shape of the orebody below the surface. To achieve this, an ore-waste composite table was first created to separate zones of ore from zones of waste. These zones were added to the drill hole database with 1 representing ore and 0 conveying waste. The ore was then modelled keenly after the cut-off grade (grade shell model). The model shows two layers: an upper main orebody and a lower orebody. (**Figure 4.11**) shows the 3D solid model or wireframe in plan view, and (**Figure 4.12**)shows the model looking due north. The wireframe or 3D model volume, tonnage and surface area report, and geographical extent are presented in (**Table 4.5** and **Table 4.6)** respectively.

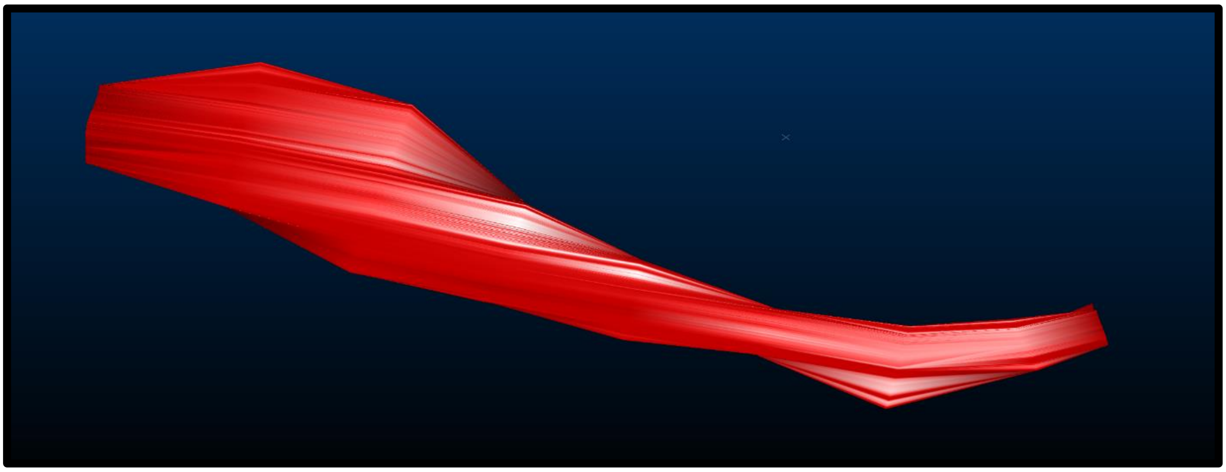


Figure 4.11: A plan view of the 3D Geological model

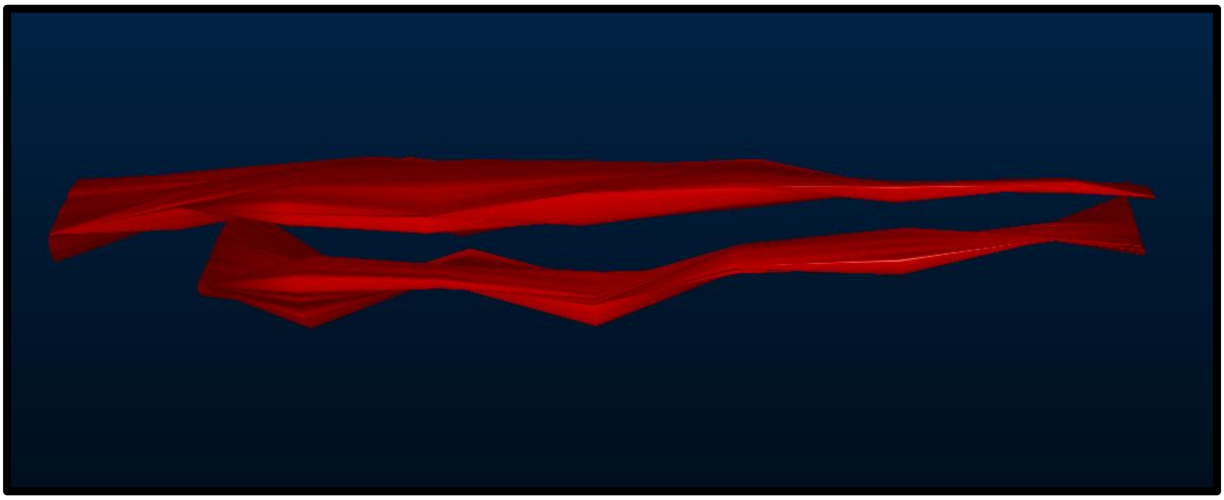


Figure 4.12: 3D model (due north) showing the main top orebody and a lower ore body

Validation of the wireframe (3D model)

The wireframe (3D model) was validated (clean and fixed) to verify the integrity of the surface, automatically fix errors where possible, make the surface normal for reliable volume calculation and visualization and finally remove duplicate points and edges. The verification test carried out were:

- Remove duplicate vertices, empty faces and duplicate faces
- Check for open edges, shared edges, crossovers and feature edges

The results revealed that the model had a single surface, and no errors were found for all the faces and edges. Cleaning of the wireframe was done to satisfy best practices, as there was no surface cleaned since all earlier verification tests were negative.

Table 4.5: Properties of the wireframe showing volume, tonnage and area calculation

NAME	VALUE
Number of triangles	13,704
Enclosed volume (m^3)	6,248,455.49
Enclosed tonnage (tonnes)	18,745,366.46
Projected lower area (m^2)	424,941.19
Projected upper area (m^2)	424,941.19
Total surface area (m^2)	951,138.19

Table 4.6: Properties of the wireframe showing the full geographical extent and dip

NAME	MINIMUM	MAXIMUM
X-COORDINATE (m)	252618.34	254113.16
Y-COORDINATE (m)	761044.64	761748.54
ELEVATION (m)	-29.52	112.82
SURFACE DIP (°)	0.05	90.00

4.7 Block Modelling for resource estimation

A block model is a basic need for mineral resource estimation. It is also the basis for completing the objective two and three of the research which is to quantitatively and qualitatively estimate the mineral resource of Gofolo Hill and determine estimation methods comparison. An empty block model (**Figure 4.13**) was created considering the extent of the deposit's wireframe, drill hole length and spacing. The wireframe extent is considered so that the created block model can be large enough (larger than the wireframe) to capture the full wireframe and sample points used for grade interpolation. A block size of 50m x 20m x 5m was selected in consideration of the drill hole spacing of 200m x 60m. The rule of thumb or best practice for a block size is that the block model size should be ¼ to ½ the drill hole spacing of the project. The parameters of the empty block model created are reported in (**Table 4.7**).

Table 4.7: Properties of the empty block model showing cell size and geographical extent

	Cell size	**Model size**		**Cell count**
	Size (m)	**Minimum (m)**	**Maximum (m)**	**No of cells**
X	50	252506.5	254156.50	33
Y	20	760908.10	761888.10	49
Z	5	-135.42	179.58	63
				101,871

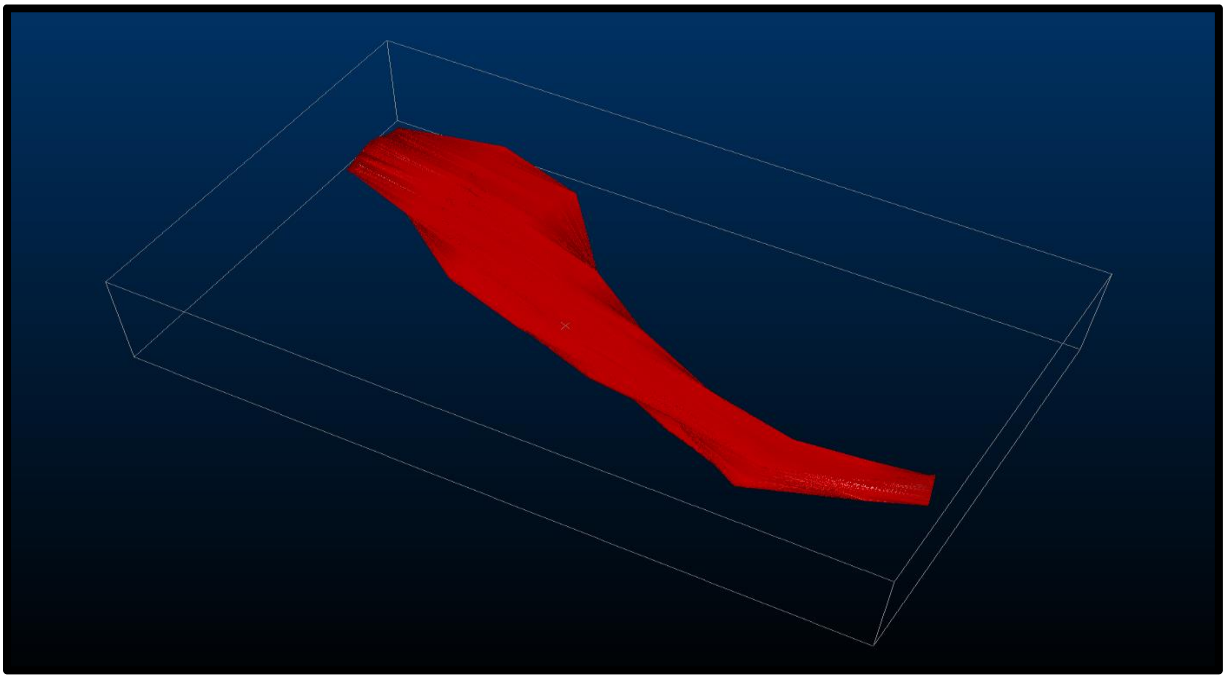


Figure 4.13: A perspective of the empty block model created around the 3D solid orebody

The empty block model earlier created was then filled to show our designated 50mx20mx5m blocks. The blocks cover the wireframe (3D model). The stacked blocks are shown below in a plan view (**Figure 4.14**) and a view looking due north (**Figure 4.15**). The filled block model is then used for grade interpolation and subsequent volume-tonnage-grade reports.

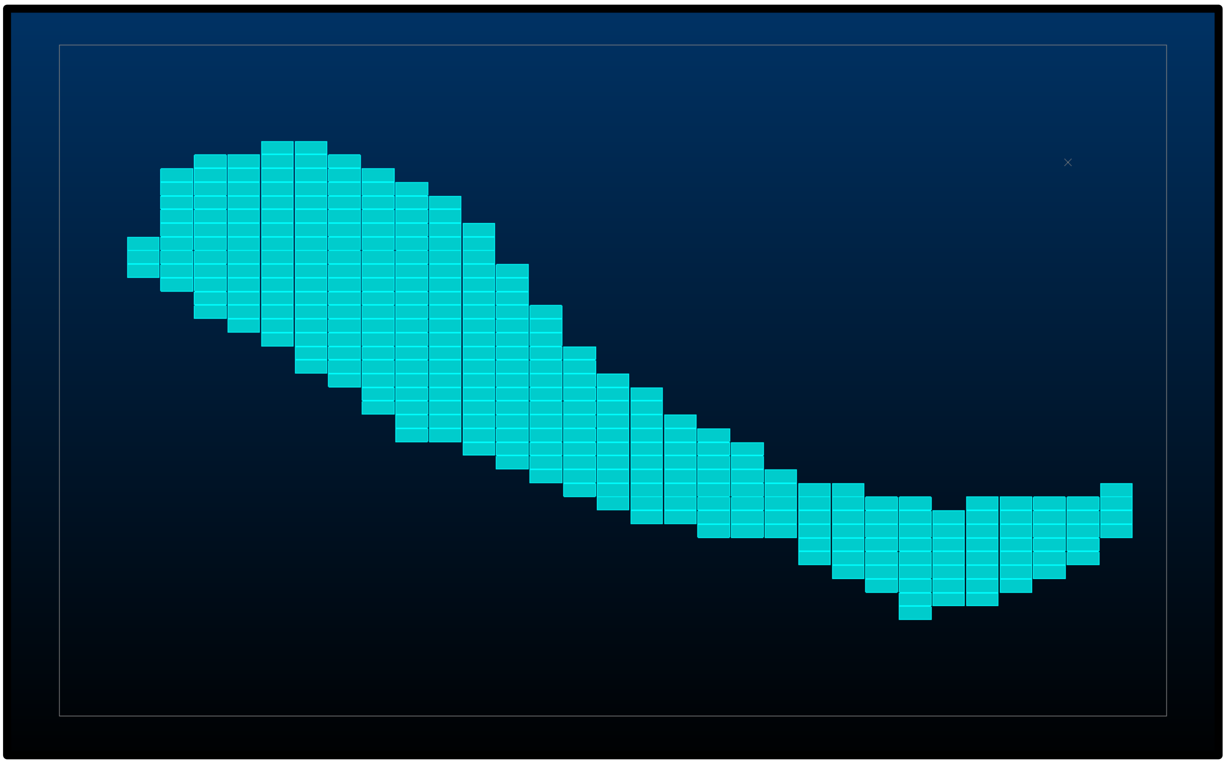


Figure 4.14: A plan view of the filled block model

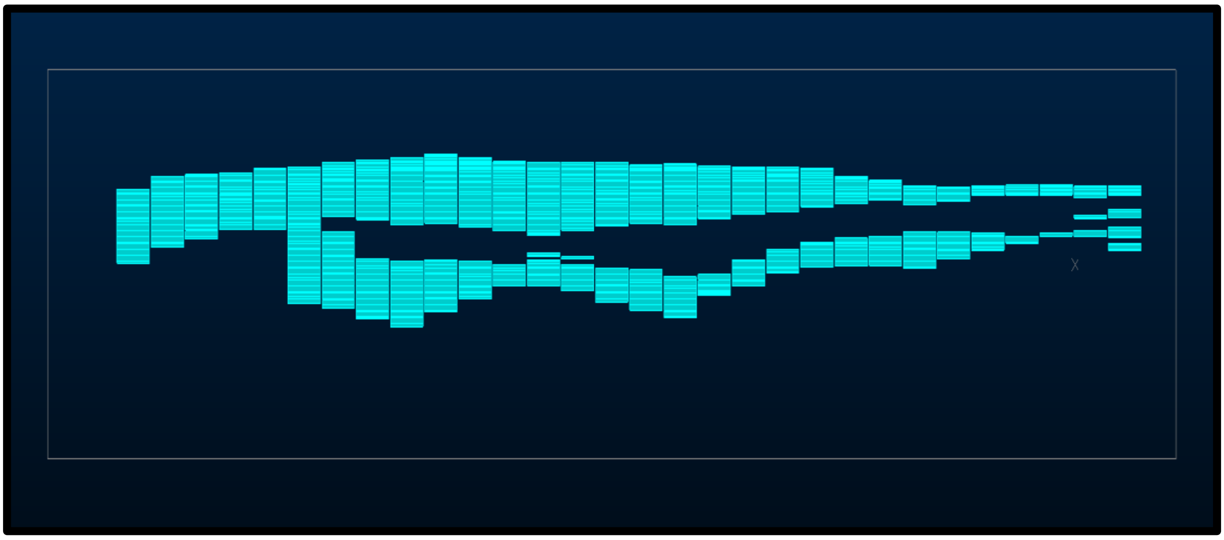


Figure 4.15: Block model shown looking due north

Mineralized holes clipping

To avoid condition bias such as over-estimation or under-estimation, the drill hole (or composited 2m drill hole) was clipped to the wireframe to have only points within the wireframe used to interpolate the grade blocks. (**Table 4.8**) shows the summary statistics of the mineralized samples clipped from the raw drill hole data for interpolation purposes. The data shows a histogram with a normal distribution (**Figure 4.16**). Full statistics of the clipped mineral holes data is presented in (**Appendix 4b**).

Table 4.8: Summary statistics for clipped mineralized hole data

NAME	VALUE(%)
Total Samples	359
Minimum	3.360
Maximum	60.320
Range	56.960
Mean	34.414
Variance	87.466
Standard Deviation	9.352
Coefficient of Variation	0.272
Skewness	-0.029
Kurtosis	0.912
50th Percentile (Median)	34.360

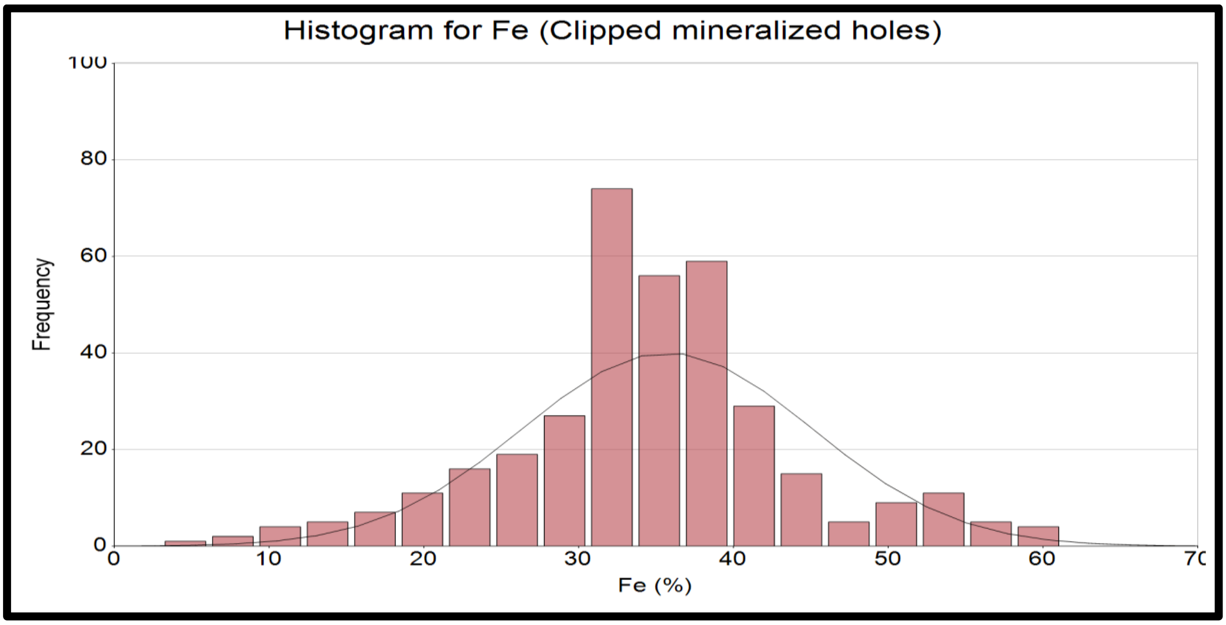


Figure 4.16: Histogram of the clipped mineralized holes

4.8 Resource Estimation of Gofolo Hill

Objective two (2) of this research was completed using the geostatistical ordinary kriging method and basic estimation method (IDW and NNP) to evaluate the mineral resource of the study area, Gofolo Hill. Results from the estimation will then be used for a comparative study. Justification for the use of global cut-off grade and global density value, as well as grade and tonnage calculation used for estimation, is presented in **section 3.6.**

4.8.1 Geostatistical estimation of the deposit

For geostatistical interpolation, it is essential to note that the estimation is based on a semi-variogram. A semivariogram is used to measure the spatial variability or correlation among data. The variogram map was created and then fitted to show the anisotropy or trend of the data. From the trend revealed by the data, an experimental variogram was created and then fitted to a theoretical spherical variogram. The variogram models (**Table 4.9**) were used to interpolate grade values for unsampled or unknown points. (**Table 4.10**) shows a single structure variogram model parameters.

Table 4.9: Variograms used for geostatistical ordinary kriging estimation

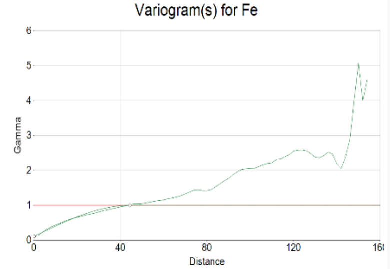
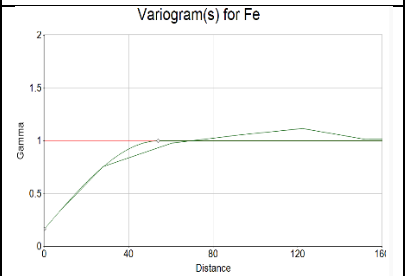
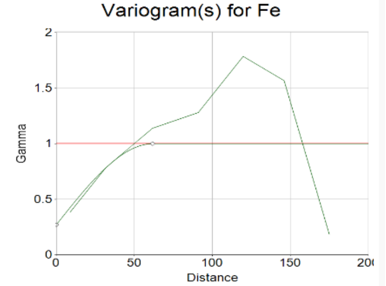
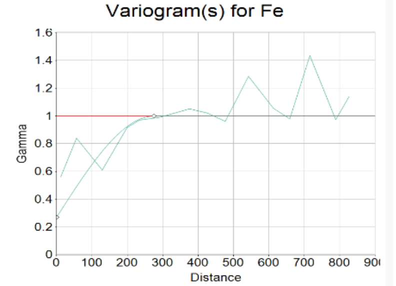
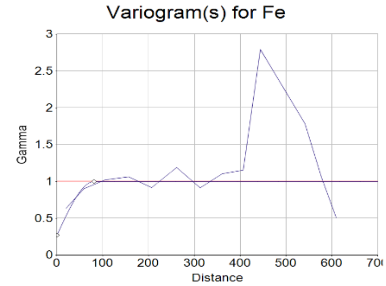
DOWNHOLE	**OMNIDIRECTIONAL**	
		
DIRECTIONAL VARIOGRAMS		
		

Table 4.10: Parameters for variogram model

Angle (°)					**Range (m)**		
First (Z)	**Second (Y)**	**Third (X)**	**Nugget**	**Sill**	**(X)**	**(Y)**	**(Z)**
100	0	0	44.2	119.0	80.8	274.7	61.7

The block model was interpolated using the ordinary kriging geostatistical method. Ordinary kriging is a geostatistical method labelled as BLUE – best linear unbiased estimator. This method estimates a block or a point using nearby sample points utilizing regionalized variables. (**Figure 4.17** and **Figure 4.18**) show the interpolated block model in a plan view and a view due north, respectively.

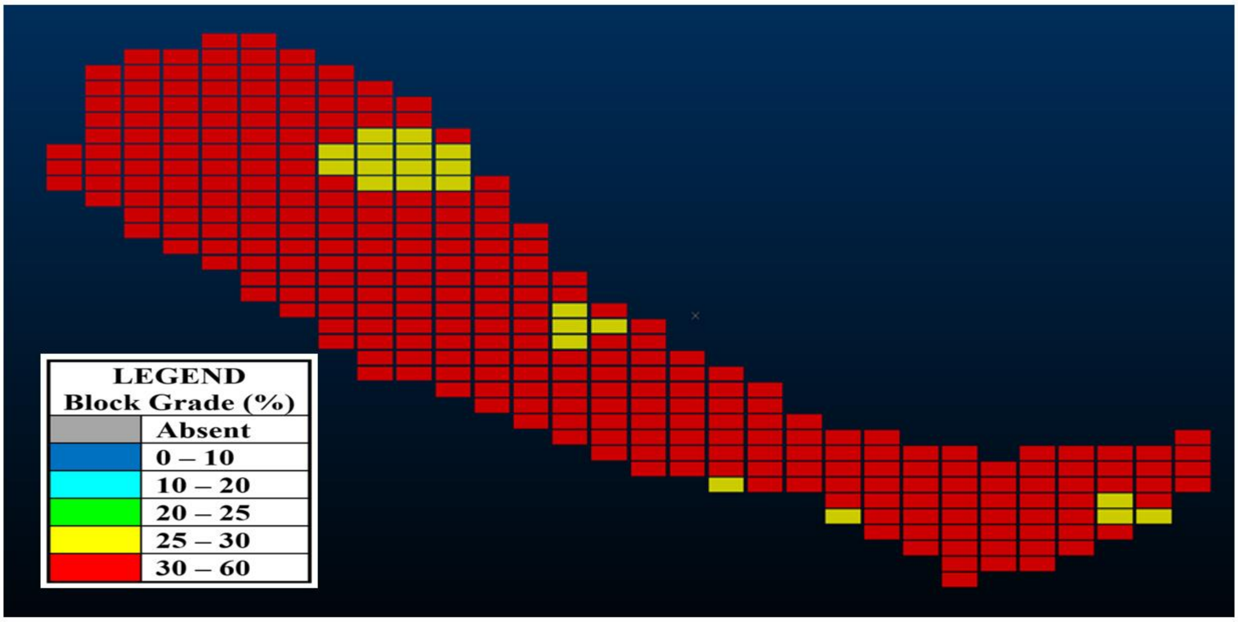


Figure 4.17: A plan view of block model interpolated by the OK method

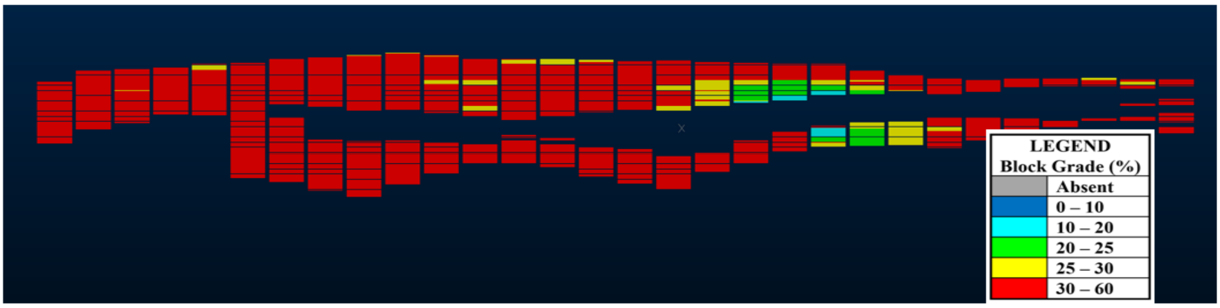


Figure 4.18: A due north view of the block model interpolated by the OK method

The parameters produced by the semi-variogram and the ones shown in (**Table 4.11**) were used for the ordinary kriging geostatistical estimation:

Table 4.11: Parameters used for OK estimation

Parameter	**Value**
Length of search ellipse in the x-direction (m)	250
Length of search ellipse in the y-direction (m)	250
Length of search ellipse in the z-direction (m)	40
Minimum samples used for estimation	3
Maximum samples used for estimation	20

4.8.1.1 OK Resource estimation report

The mineral resource was estimated using a global density of 3.00kg/m3. The results for the block model volume, tonnage and grade are as follows:

Table 4.12: Resource estimation of the full wireframe by the OK method.

Volume (m^3)	**Tonnage (tonnes)**	**Mean grade (%)**
6,230,098.95	18,690,296.85	35.17

Applying the 30%Fe grade cut-off, the mineral resource of the project was estimated using the OK method in grade categories as follows:

Table 4.13: Estimation after applying 30% grade cut-off (OK method)

Category	**Volume (m^3)**	**Tonnage (tonnes)**	**Density (kg/m^3)**	**Grade (%)**
30 – 35	2,911,922.27	8,735,766.80	3	33.03
35 – 40	2,043,831.98	6,131,495.95	3	37.14
40 – 45	559,933.54	1,679,800.63	3	42.06
45 – 50	177,457.30	532,371.90	3	46.78
50 – 55	30,000	90,000	3	50.60
Total	**5,723,145.24**	**17,169,435.71**	**3**	**35.90**

4.8.2 Nearest Neighbour Polygon (NNP) interpolation

The block model was interpolated using the nearest neighbour polygon (NNP) method. The nearest neighbour polygon method is the simplest method of interpolation. The value of the nearest known point is selected for the unknown point being interpolated. (**Figure 4.19** and **Figure 4.20**) show the interpolated blocks in a plan view and a view looking due north, respectively.

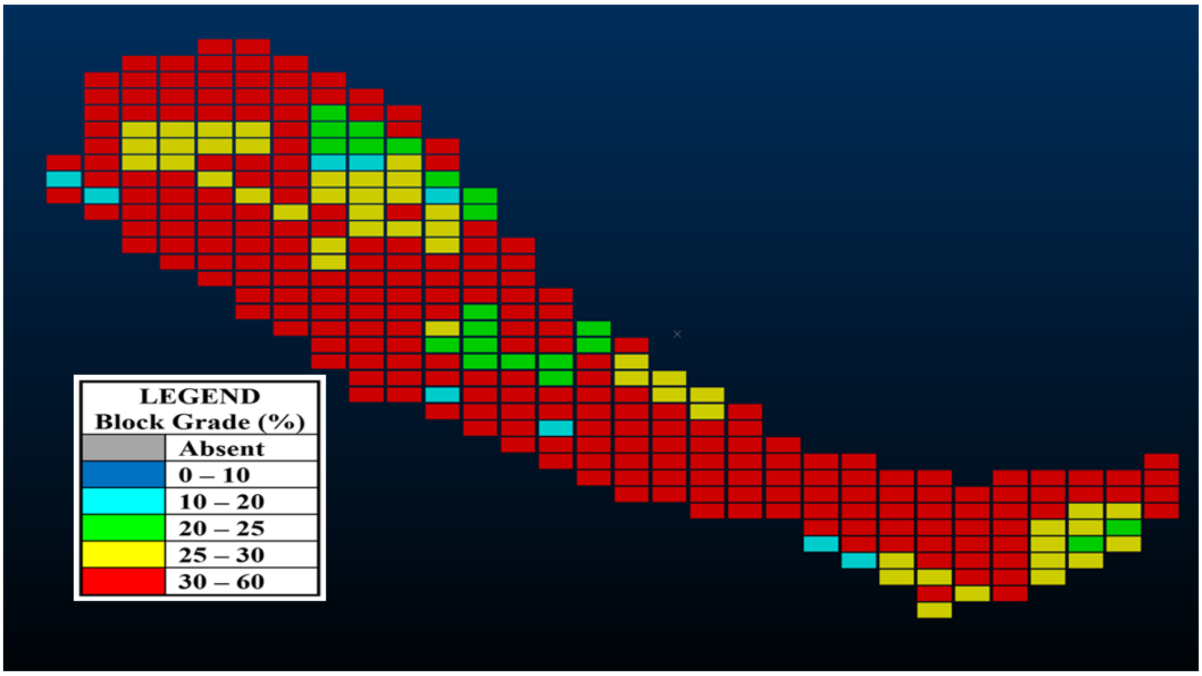


Figure 4.19: Plan view of block model interpolated by the NNP method

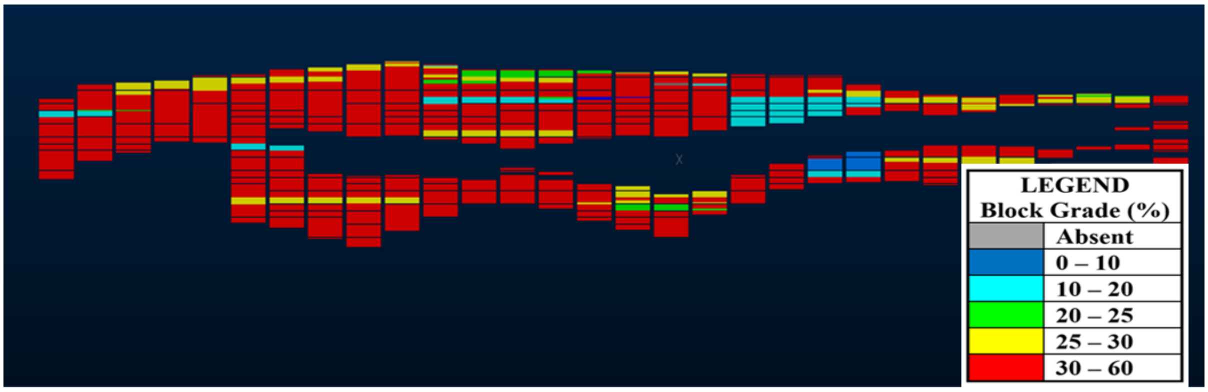


Figure 4.20: A due north view of the block model interpolated by the NNP method

The parameters used for NNP estimation are shown in **Table 4.14.**

Table 4.14: Parameters used for NNP estimation

Parameter	Value
Length of search ellipse in the x-direction (m)	250
Length of search ellipse in the y-direction (m)	250
Length of search ellipse in the z-direction (m)	40
Minimum samples used for estimation	1
Maximum samples used for estimation	1

4.8.2.1 NNP Resource Estimation Report

The mineral resource was estimated using a global density of 3.00 kg/m3. The results for the block model volume, tonnage and grade are as follows:

Table 4.15: Resource estimation report for the full wireframe by the NNP method

Volume (m^3)	Tonnage (tonnes)	Mean grade (%)
6,230,098.95	18,690,296.85	35.36

Applying the 30% Fe grade cut-off, the mineral resource of the project was estimated using the nearest neighbour polygon method in grade categories as follows:

Table 4.16: Estimation after applying the 30% grade cut-off (NNP method)

Category	Volume (m^3)	Tonnage (tonnes)	Density (kg/m^3)	Grade (%)
30 – 35	1,819,155.68	5,457,467.03	3	32.57
35 – 40	1,558,336.46	4,675,009.37	3	37.53
40 – 45	722,937.96	2,168,813.87	3	42.02
45 – 50	370,319.90	1,110,959.71	3	46.69
50 – 55	301,793.62	905,380.85	3	52.02
55 – 60	101,480.34	304,441.03	3	56.26
60 – 65	45,000	135,000	3	60.32
Total	**4,919,024.18**	**14,757,072.54**	**3**	**38.53**

4.8.3 Inverse distance weighting (IDW)

4.8.3.1 IDW (power 2) interpolated block model

The block model was interpolated using the IDW method. In the first case, a power2 was used to estimate the grade blocks. The inverse distance weighting method estimates by averaging the nearby sample weights by the distance from the point that is being estimated. (**Figure 4.21** and **Figure 4.22**) show the block model in a plan view and a view looking due north, respectively.

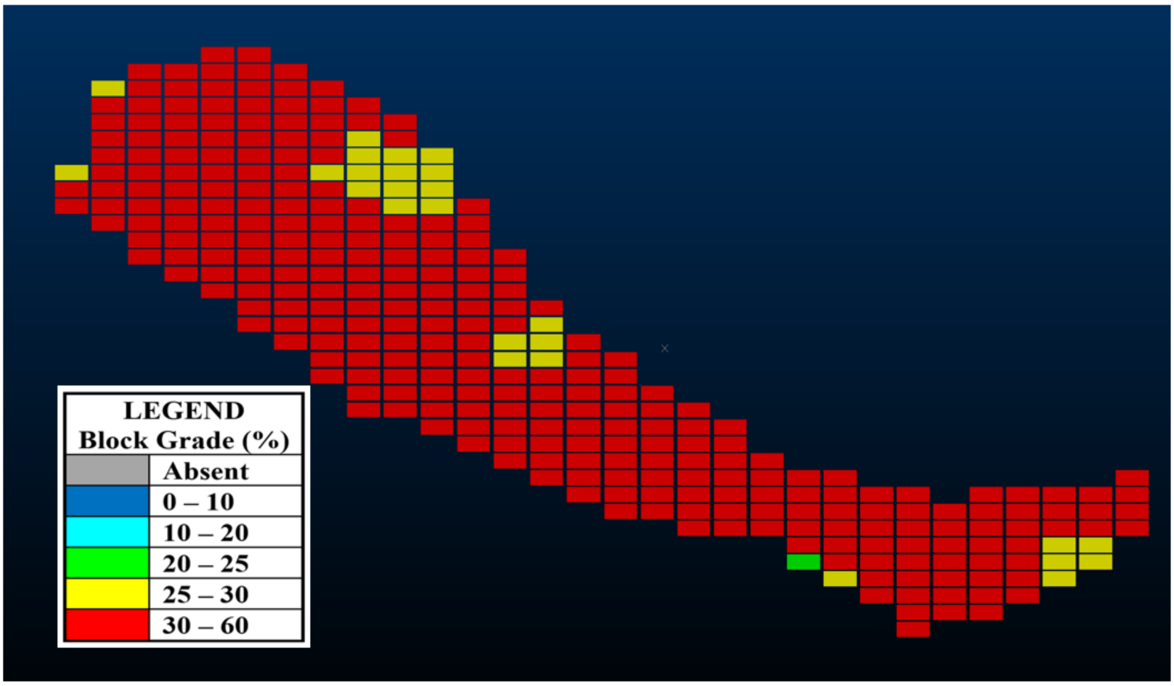


Figure 4.21: Plan view of block model interpolated by the IDW power2 method

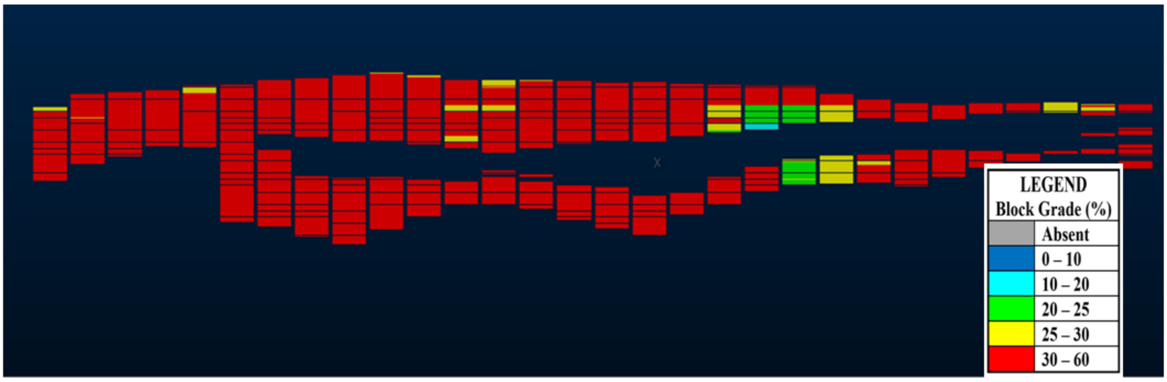


Figure 4.22: A due north view of the block model interpolated by the IDW power2 method

The parameters used for IDW (power2) estimation are shown in **Table 4.17**:

Table 4.17: Parameters used for IDW (power2) estimation

Parameter	**Value**
Length of search ellipse in the x-direction (m)	250
Length of search ellipse in the y-direction (m)	250
Length of search ellipse in the z-direction (m)	40
Minimum samples used for estimation	3
Maximum samples used for estimation	20

4.8.3.1.1 IDW (power2) Resource estimation report

The mineral resource was estimated using a global density of 3.00kg/m3. The results for the block model volume, tonnage and grade are as follows:

Table 4.18: Resource estimation report of the full wireframe by the IDW (power2) method

Volume (m^3)	**Tonnage (tonnes)**	**Mean grade (%)**
6,230,098.95	18,690,296.85	34.63

Applying the 30% Fe grade cut-off, the mineral resource of the project was estimated using the inverse distance weighting IDW power2 method in grade categories as follows:

Table 4.19: Estimation after applying the 30% grade cut-off (IDW power2 method)

Category	**Volume (m^3)**	**Tonnage (tonnes)**	**Density (kg/m^3)**	**Grade (%)**
30 – 35	3,170,013.19	9,510,039.58	3	32.91
35 – 40	2,117,648.13	6,352,944.40	3	36.95
40 – 45	357,954.39	1,073,863.16	3	41.50
45 – 50	102,675.05	308,025.14	3	47.25
50 – 55	10,000	30,000	3	51.54
Total	**5,758,290.92**	**17,274,872.76**	**3**	**35.22**

4.8.3.2 IDW (power 3) interpolated block model

The block model was interpolated using the IDW method. In the second IDW case, a power3 estimates the grade blocks. The inverse distance weighting method estimates by averaging the nearby sample weights by the distance from the point that is being estimated. (**Figure 4.23** and **Figure 4.24**) display the block model in a plan view and a view looking due north, respectively.

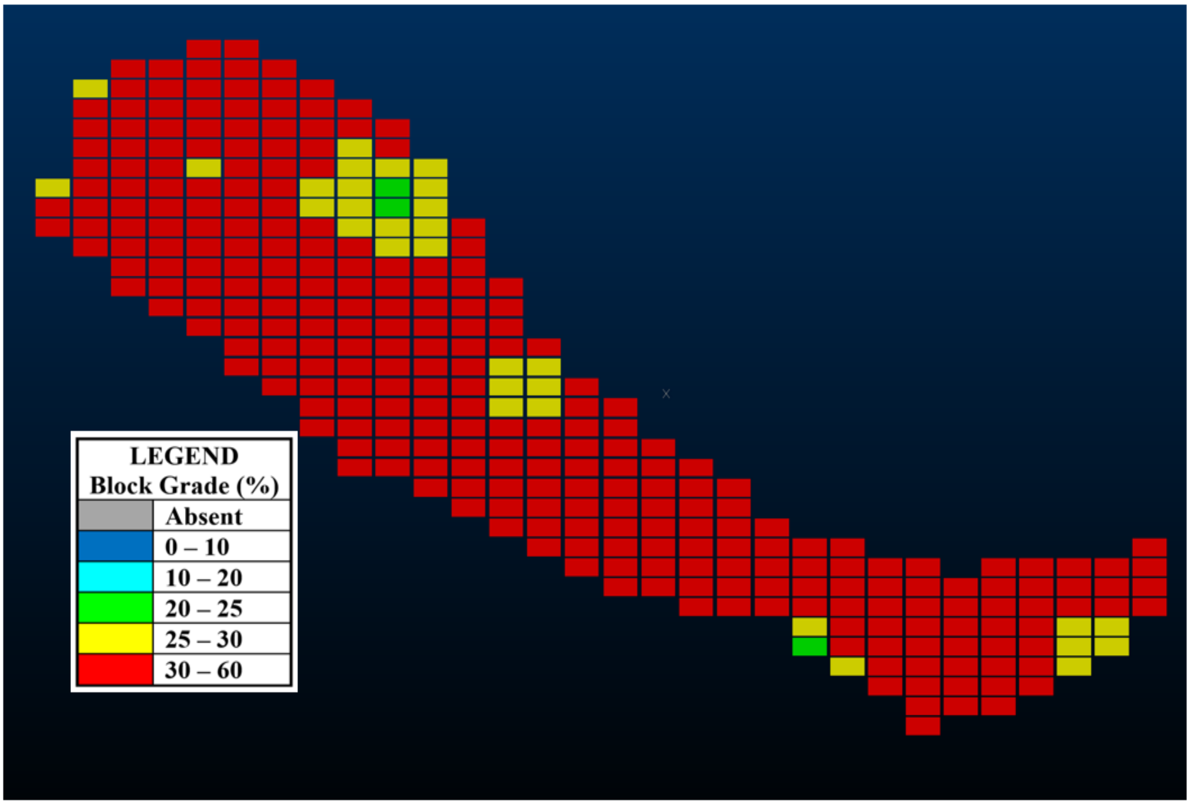


Figure 4.23: Plan view of block model interpolated by the IDW power3 method

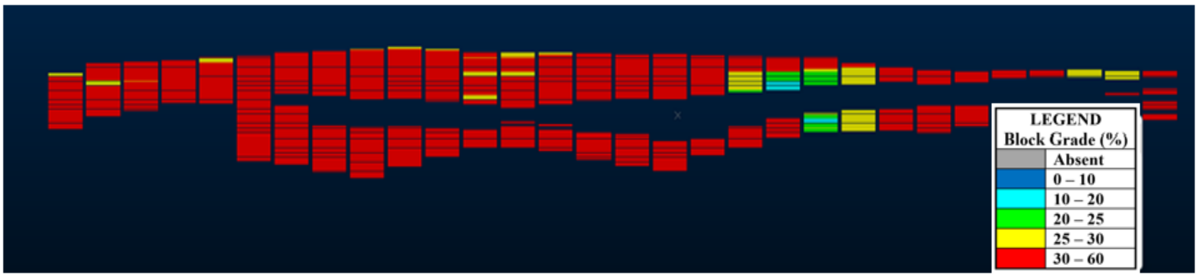


Figure 4.24: A due north view of the block model interpolated by the IDW power3 method

The parameters used for IDW (power3) estimation are shown in **Table 4.20**:

Table 4.20: Parameters used for IDW (power3) estimation

Parameter	Value
Length of search ellipse in the x-direction (m)	250
Length of search ellipse in the y-direction (m)	250
Length of search ellipse in the z-direction (m)	40
Minimum samples used for estimation	3
Maximum samples used for estimation	20

4.8.3.2.1 IDW (power3) Resource Estimation report

The mineral resource is estimated using a global density of 3.00kg/m3. The results for the model volume, tonnage and grade are as follows:

Table 4.21: Resource estimation report for the full wireframe by IDW (power 3) method

Volume (m^3)	Tonnage (tonnes)	Mean grade (%)
6,230,098.95	18,690,296.85	34.74

Applying the 30% Fe grade cut-off, the mineral resource of the project is estimated using the inverse distance weighting IDW power3 method in grade categories as follows:

Table 4.22: Estimation after applying the 30% grade cut-off (IDW power3 method)

Category	Volume (m^3)	Tonnage (tonnes)	Density (kg/m^3)	Grade (%)
30 – 35	3,064,380.94	9,193,142.83	3	32.84
35 – 40	1,984,944.94	5,954,834.81	3	37.10
40 – 45	450,007.57	1,350,022.72	3	42.21
45 – 50	109,860.66	329,581.98	3	47.42
50 – 55	49,181.31	147,543.94	3	52.11
Total	**5,658,375.59**	**16,975,126.76**	**3**	**35.53**

4.9 Results Comparison of Estimation Methods

A comparison was made with the geostatistical ordinary kriging method and the basic estimation methods to achieve this research's objective three (3). The comparison was through four means: visualization of grade blocks, statistical comparison, correlation coefficient comparison, and grade-volume-tonnage results comparison.

4.9.1 Visual comparison of grade blocks

A visual comparison was made of the estimated grade blocks by OK, NNP, IDW2, and IDW3 methods (**figure 4.25**). The red colour shows a grade value of 30% and above, the yellow colour shows a grade value between 25% to 30%, the green colour shows a grade value between 20% to 25%, and the blue colour shows 0% to 20%. Based on the figure, the block estimates of both IDW methods (IDW2 and IDW3) are more closely related to the geostatistical ordinary kriging interpolated blocks than that of the NNP method. The NNP method introduces numerous underestimated blocks of lower grade (shown in green and blue) due to the means of interpolation: applying the grade of the nearest or closest sample to the block. It is seen that the IDW2 method is most closely related to the OK method with the estimated blocks following a more similar color pattern. The IDW3 method introduces minor but visible green blocks representing lower interpolated ore grades.

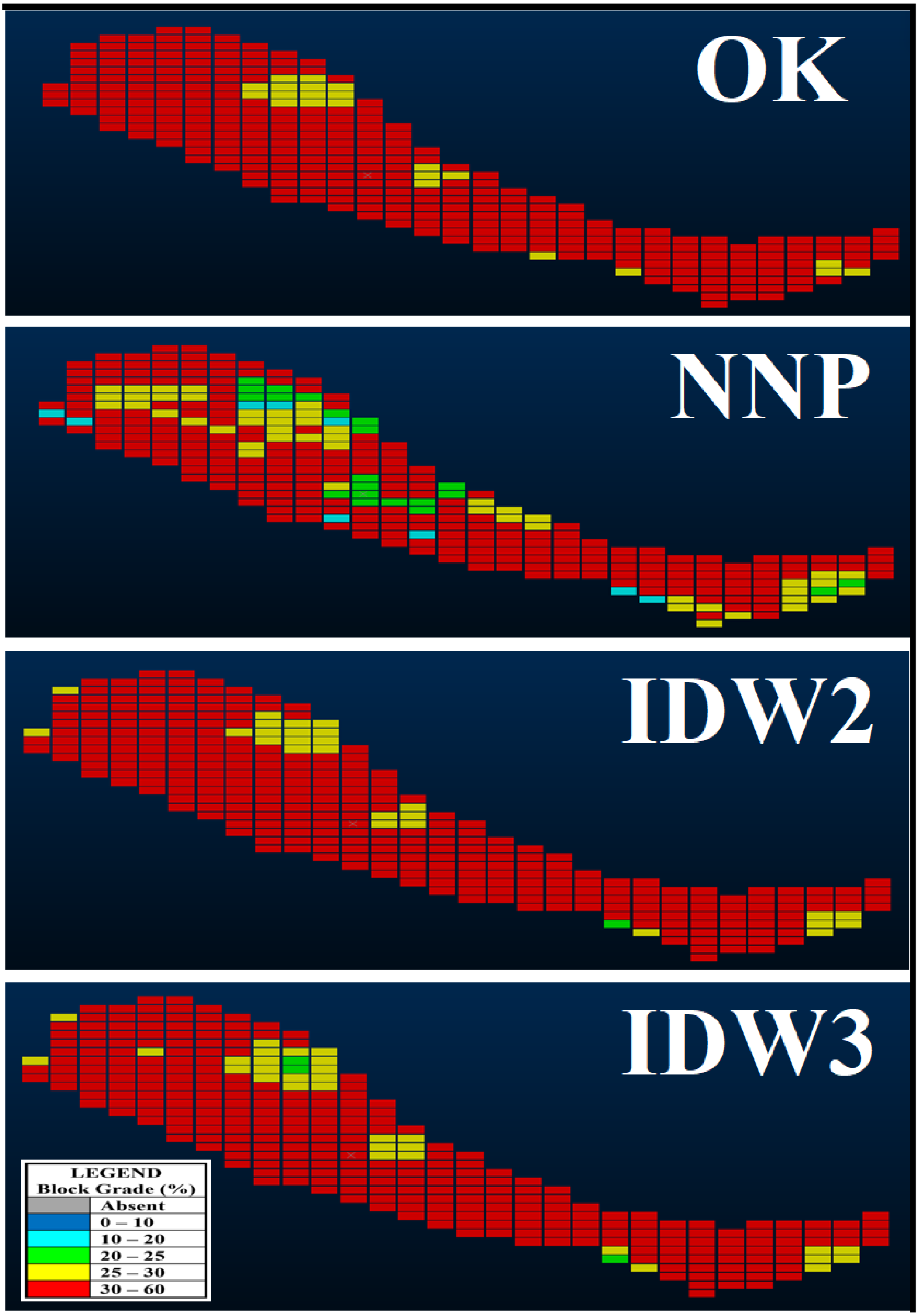


Figure 4.25: A plan view visual comparison of the estimation methods

4.9.2 Statistical comparison

The summary statistics from the four estimation methods were compared. A minimum grade of 16.914 was reported by OK and 16.986 by IDW3, respectively. The IDW2 method reported 18.793 as a minimum grade, and the NNP reported the lowest, 8.34. The OK and IDW2 methods produced close maximum grade values of 51.707 and 52.944. The IDW3 method produced 54.914, and the NNP a high 60.320. The range values were OK method, 34.793; NNP, 51.980; IDW2, 34.151; and IDW3, 37.928. The NNP range value was slightly higher due to a very low minimum grade value and a very high maximum grade value. The OK and NNP methods showed a comparable mean of 35.003 and 35.173. The IDW2 and IDW3 methods reported a mean of 34.435 and 34.537. A similar median (50th percentile) of 34.477 for the OK method and 34.119 for the IDW2 method were reported. IDW3 method reported a median of 34.038, and the NNP reported 34.930. The IDW2 method reported the best variance and best standard deviation, 13.872 and 3.725, respectively. The OK method reported 18.633 and 4.317, while the IDW3 reported 19.044 and 4.364. A high variance of 71.627 and a high standard deviation of 8.463 was reported for the NNP method. A CV value lower than 0.5 (good comparison similarity) was reported for all methods, with OK having 0.123; NNP a higher, 0.241; IDW2, 0.108; and IDW3, 0.126.

Though the NNP method showed a closely similar mean to the OK results, the two IDW methods performed better. Considering the similarity parameter (CV), variance, STD, range, maximum and minimum, the IDW methods (IDW2 first, then IDW3) showed a closer value to the OK results. The NNP is the least compared. **Table 4.23** presents a comparison of the summary statistic, while (**Appendix 5**) presents a comparison of the full statistics.

Table 4.23: Summary statistics comparison of methods used for estimation

NAME	**OK (%)**	**NNP (%)**	**IDW2 (%)**	**IDW3 (%)**
Total Samples	1686	1686	1686	1686
Minimum	16.914	8.340	18.793	16.986
Maximum	51.707	60.320	52.944	54.914
Range	34.793	51.980	34.151	37.928
Mean	35.003	35.173	34.435	34.537
Variance	18.633	71.627	13.872	19.044
Standard Deviation	4.317	8.463	3.725	4.364
Coefficient of Variation	0.123	0.241	0.108	0.126
50th Percentile	34.477	34.930	34.119	34.038

4.9.3 Correlation Coefficient

A comparison of the correlation coefficient using the coefficient values and the scatter plot (or regression plot) showed a very high correlation between the IDW2 and IDW3 methods (**Figure 4.26**). This is because the two methods are similar and are expected to produce nearly similar estimates. The only distinguishing factor of the IDW2 and IDW3 methods is the power factor. A high correlation value of 0.991, very nearly 1, is reported. The IDW methods grade values and the OK method grade values showed a better correlation coefficient than the NNP method. The IDW3 reports a coefficient of 0.876, and the IDW2 reports a coefficient of 0.862. A lower coefficient of 0.687 is reported to compare NNP grade values with those produced by the OK method. The NNP method, when compared with the IDW2 method, reported 0.695 and 0.720 when compared with the IDW3 method.

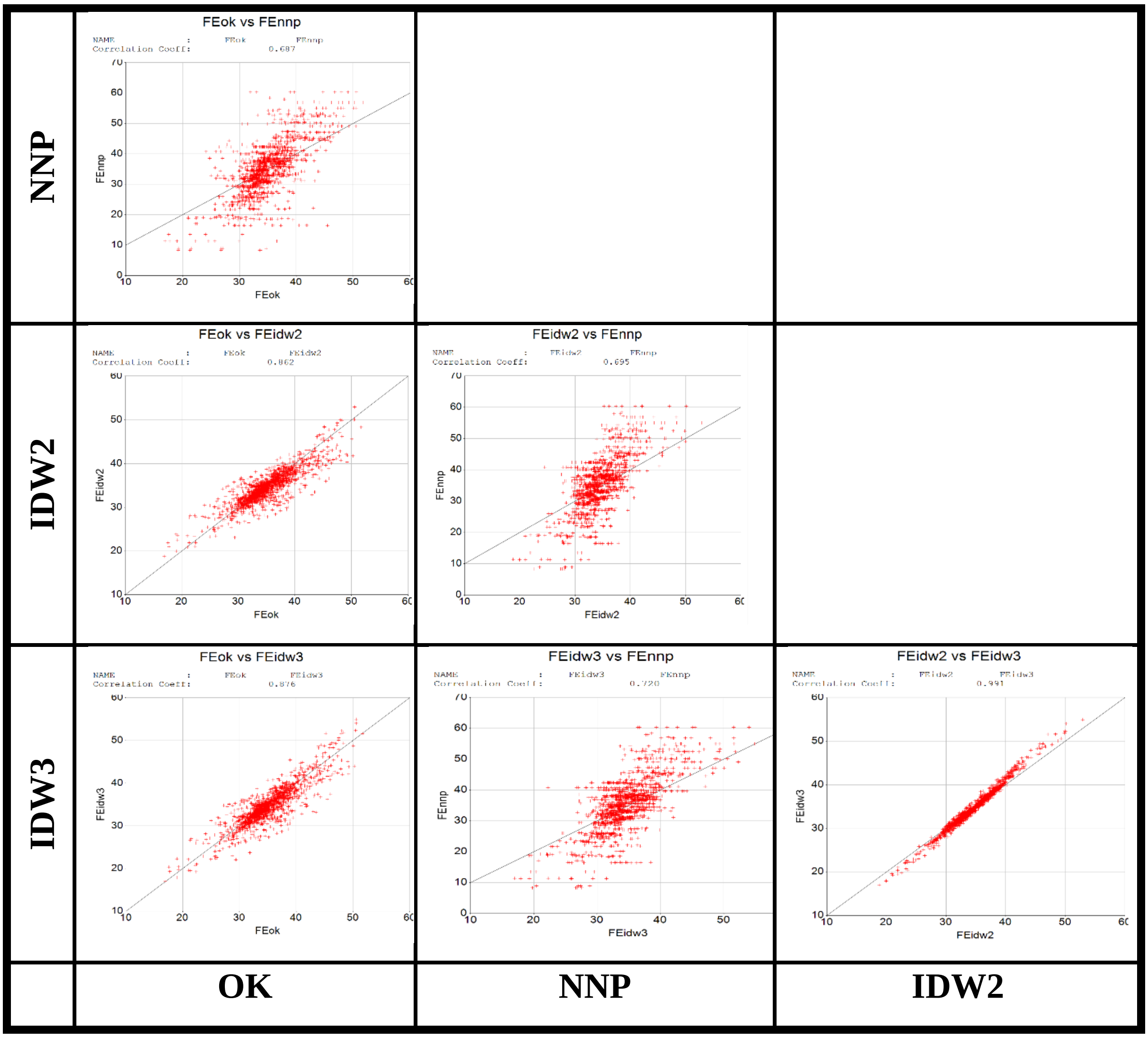


Figure 4.26: Comparison of estimation methods by the correlation coefficient

4.9.4 Resource results comparison

4.9.4.1 Comparison of Grade estimates

The interpolated grade values were compared after applying a 30% grade cut-off. The OK method reported a grade total of 35.90%, the IDW3 method reported 35.53%, the IDW2 method reported 35.22%, and the NNP method reported 38.53%. A higher grade value was reported by the NNP method since the method considers only a single known point to interpolate an unknown point. It is even noticed that the NNP method reported two grade categories (55% - 60% and 60% -65%) not reported by the other three (3) methods: OK, IDW2 and IDW3. Compared to the OK method, the two IDW methods were underestimated by a little margin. The NNP method overestimated grade values. The IDW3 method reported a closer total grade value to the OK method, followed by the IDW2 and NNP methods. For each grade category comparison, the IDW2 method reported results closer to the OK method in two categories: 30% - 35%, and 50% - 60%. The NNP method also reported a closer result to the OK method in two categories: 40% - 45% and 45% - 50%. The IDW3 method reported a closer result to the OK method in a single category: 35% - 40%. (**Table 4.24**) shows a grade category comparison for all methods. (**Appendix 6**) shows the histogram curve for the interpolated grade.

In summary, the IDW2 and NNP methods showed comparable results in two grade categories. The IDW3 method showed a more comparable result to the OK method in a single grade category and the total estimated grade value.

Table 4.24: Grade values comparison of methods used for estimation

Category	**OK (%)**	**NNP (%)**	**IDW2 (%)**	**IDW3 (%)**
30 – 35	33.03	32.57	32.91	32.84
35 – 40	37.14	37.53	36.95	37.10
40 – 45	42.06	42.02	41.50	42.21
45 – 50	46.78	46.69	47.25	47.42
50 – 55	50.60	52.02	51.54	52.11
55 - 60		56.26		
60 – 65		60.32		
Total	**35.90**	**38.53**	**35.22**	**35.53**

4.9.4.2 Comparison of Volume estimates

The calculated block volume results were compared for all the methods. The IDW2 method reported the highest calculated block volume of 5,758,290.92m^3, the IDW3 method reported 5,658,375.59m^3, the OK method calculated the total volume to 5,723,145.24 m^3, and the NNP method reported the lowest calculated volume of 4,919,024.18m^3. A lower volume was reported by the NNP method since only blocks that showed a 30% grade cut-off was categorized and calculated. It is also noticed that the NNP reported two volume categories (55% - 60% and 60% - 65%) not reported by the other three (3) methods: OK, IDW2 and IDW3. The IDW2 method reported a closer total volume value to that of the OK method, followed by the IDW3 method and then finally the NNP method. For volume category comparison, the IDW3 method reported closer results to the OK method. The results of the IDW3 method had the least difference in all categories.

In summary, the IDW2 method showed a more comparable result to the OK method when considering the total volume calculated. The least difference was realized with the IDW2 total calculated volume result. The IDW3 method performed better in all grade categories with volume results showing the least difference when compared to the grade categories calculated volume results of the OK method. The NNP method calculated volume results are the least compared. **Table 4.25** compares the calculated volume results by all the methods used for estimation.

Table 4.25: Volume values comparison of methods used for estimation

Category	OK (m^3)	NNP (m^3)	IDW2 (m^3)	IDW3 (m^3)
30 – 35	2,911,922.27	1,819,155.68	3,170,013.19	3,064,380.94
35 – 40	2,043,831.98	1,558,336.46	2,117,648.13	1,984,944.94
40 – 45	559,933.54	722,937.96	357,954.39	450,007.57
45 – 50	177,457.30	370,319.90	102,675.05	109,860.66
50 – 55	30,000	301,793.62	10,000	49,181.31
55 - 60		101,480.34		
60 – 65		45,000		
Total	**5,723,145.24**	**4,919,024.18**	**5,758,290.92**	**5,658,375.59**

4.9.4.3 Comparison of Tonnage estimates

A comparison was made of the calculated tonnage results for all the methods. The volume and tonnage results produced a similar comparable pattern. The IDW2 method reported the highest calculated block tonnage of 17.274Mt, the IDW3 method reported 16.975Mt, the OK method reported 17.169Mt, and the NNP method reported the lowest calculated tonnage of 14.757Mt. A lower tonnage was reported by the NNP method since only blocks that showed a 30% grade cut-off was categorized and calculated. It is also noticed that same with the volume calculation, the NNP method reported two tonnage categories (55% - 60% and 60% - 65%) not reported by the other three (3) methods: OK, IDW2 and IDW3. The IDW2 method reported a closer total tonnage value to that of the OK method, followed by the IDW3 method and then finally the NNP method. For grade category comparison of calculated tonnage figures, it is the IDW3 method that reported closer results to the OK method in all categories. The IDW3 method produced results with the least comparable difference.

In summary, the IDW2 method showed comparable figures for total tonnage calculated, while the IDW3 method showed comparable figures when considering the categories. The NNP method produced the least comparable results. **Table 4.26** compares the calculated tonnage results by all the methods used for estimation.

Table 4.26: Tonnage values comparison of methods used for estimation

Category	**OK**	**NNP**	**IDW2**	**IDW3**
30 – 35	8,735,766.80	5,457,467.03	9,510,039.58	9,193,142.83
35 – 40	6,131,495.95	4,675,009.37	6,352,944.40	5,954,834.81
40 – 45	1,679,800.63	2,168,813.87	1,073,863.16	1,350,022.72
45 – 50	532,371.90	1,110,959.71	308,025.14	329,581.98
50 – 55	90,000	905,380.85	30,000	147,543.94
55 - 60		304,441.03		
60 – 65		135,000		
Total	**17,169,435.71**	**14,757,072.54**	**17,274,872.76**	**16,975,126.76**

4.10 Cross-validation of methods of estimations

Objective four of the research was achieved by cross-validating all methods of estimation to confirm validity, precision and accuracy. The ordinary kriging method was primarily validated using the slope of regression values, which compares actual grade value to estimated grade values. Combined, all methods were validated by wireframe volume comparison, standard error comparison, and global or grade mean difference values.

4.10.1 The slope of Regression for Kriging estimates validation.

The ordinary Kriging geostatistical method is used in most resource evaluation studies since the method can be easily validated through numerous means to prove the accuracy and precision of the Kriged estimates. In this study, validation was carried out on the estimated block kriging model by the calculated slope of regression values for each interpolated block. The slope regression compares the actual grade with the estimated kriged grade (Z/Z*). The goal is to have a mean slope of regression value close to 1. (**Figure 4.27**) shows a histogram of the calculated slope of regression values with 85% of the kriged estimates showing good correlation and having values lying between 0.5 to 1 and mean regression value of 0.792

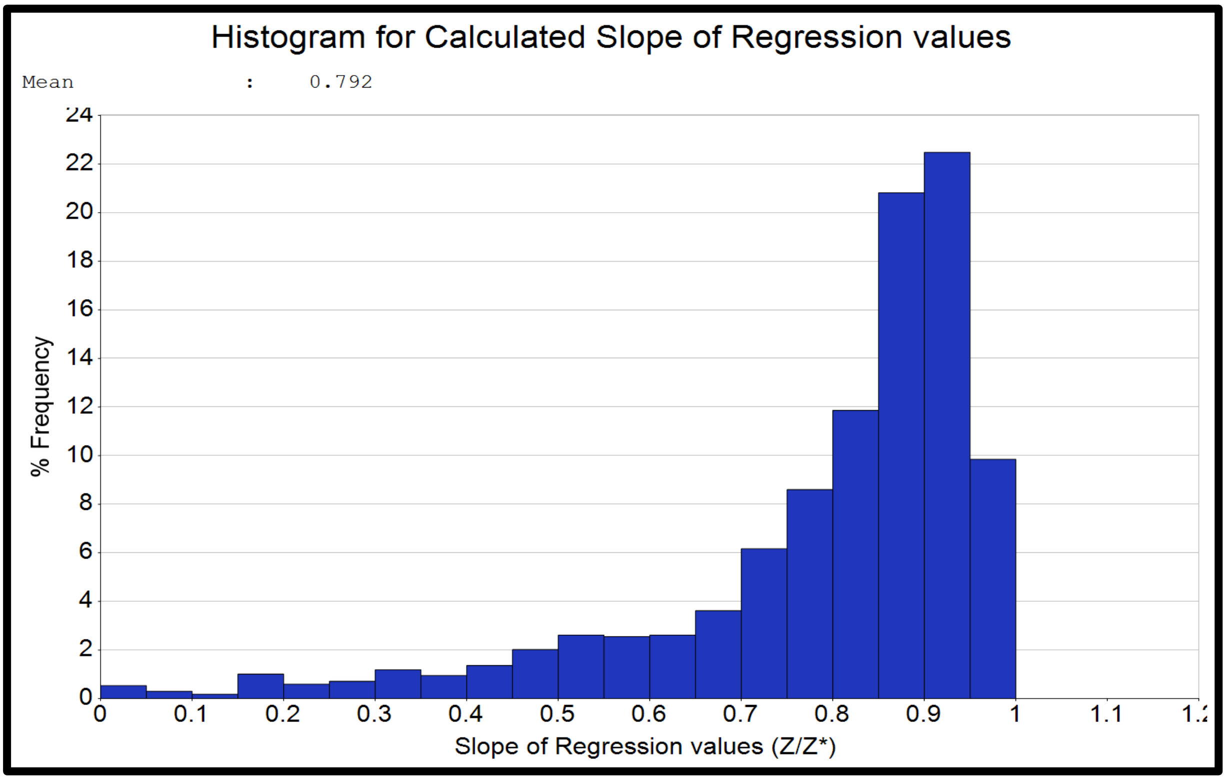


Figure 4.27: Histogram for the calculated slope of regression values

4.10.2 Validation of block model and wireframe (3D model)

For validation of the block model, a comparison was made with the volume estimate of the wireframe (3D Model). The block model estimate is expected to be lower than the wireframe volume estimation. This first validation of lower block model volume was met successfully. Finally, and importantly, the difference or variance when comparing the estimated (wireframe volume) and calculated (block model volume) block model is expected to be lower than 2%. A variance of 0.29% shows the high accuracy of our block model by using volume comparison. (**Table 4.27)** shows the result from the block model and wireframe validation.

Table 4.27: Validation of block model and wireframe by comparing volume results

Volume comparison (m^3)	**Estimated vol (wireframe vol)**	**Calculated vol (block model vol)**	**Difference**	**% diff**
	6,248,455.49	6,230,099.17	18,356.31	0.29%

4.10.3 Validation by the standard error

Validation using calculated standard error values showed high accuracy since all estimation methods had very low values close to zero. The IDW2 method showed the highest accuracy in terms of standard error comparison. The IDW2 and IDW3 methods showed closer values to the OK standard error, proving the IDW methods were more accurate than the NNP method. (**Table 4.28**) shows the standard error for all four (4) grade interpolation methods.

Table 4.28: Validation by calculated standard error results

	OK	**NNP**	**IDW2**	**IDW3**
Standard Error	0.105	0.206	0.091	0.106

4.10.4 Validation by Global mean grade difference (samples against models)

Validation was completed by comparing the input sample distribution of the drill hole and the estimated block model grade distribution of all four (4) methods used in the study. The mean % difference of all models was less than 5% meaning acceptable results with high accuracy. The NNP method produced the highest mean % different of 2.76%, followed by the OK method with 2.21%. IDW2, and IDW3, had a lower mean difference of 0.64%%, and 0.96%, respectively. The OK method produced a slightly higher mean difference than the IDW methods which is due to the overall goal of the technique, which is to minimize error or produce error close to zero, thereby introducing smoothing. (**Table 4.29**) compares input samples and model estimates for all the methods.

Table 4.29: Distribution of Input samples and model estimates for all methods

	Samples	**OK**	**NNP**	**IDW2**	**IDW3**
No. of Records	359	1686	1686	1686	1686
No. of Samples	359	1686	1686	1686	1686
Minimum	3.36	16.914	8.340	18.793	16.986
Q1	30.31	32.609	30.770	32.287	32.200
Median	34.36	34.477	34.930	34.119	34.038
Q3	38.56	37.197	39.660	36.336	36.698
Max	60.32	51.707	60.320	52.944	54.914
Mean	34.41	35.17	35.36	34.63	34.74
Mean Diff v Model	**-**	**-0.76**	**-0.95**	**-0.22**	**-0.33**
%Mean Diff v Model		**-2.21**	**-2.76**	**-0.64**	**-0.96**
Std. Dev	9.35	4.317	8.463	3.725	4.364
Variance	87.47	18.633	71.627	13.872	19.044
%Coefficient of Variation	27.18	12.30	24.10	10.8	12.60

CHAPTER FIVE: CONCLUSION AND RECOMMENDATION

The results of mineral resource modelling, mineral resource estimation using the geostatistical ordinary kriging method and basic estimation methods (IDW and NNP), comparative study of estimation methods and cross-validation of results for the Gofolo Hill Iron Ore deposit in Western Liberia, Grand Cape Mount County have been presented in this study. The objective of this final chapter is to provide a conclusion and recommendations.

5.1 Conclusion

A conclusion is drawn based on the four specific objectives of this research project which are described below as follows:

The first specific objective of this research was to produce a 3D geological model or wireframe of the spatial distribution of the ore deposit parameters and reveal how they extend laterally. Using a grade shell modelling method (that is, modelling after a grade cut-off of 30% Fe), a geological 3D model showing two layers, an upper main orebody and a lower orebody, was produced to reveal the size, shape and depth of the Gofolo Hill iron ore deposit.

The second objective was to qualitatively and quantitatively estimate the mineral resources of the deposit. This objective was achieved using the geostatistical ordinary kriging method, IDW power 2, IDW power 3 and NNP estimation methods by applying a 30% Fe cut-off grade and a global density of 3.00kg/m3. The geostatistical ordinary kriging result was calculated to 17.169Mt of ores at an average grade of 35.90% Fe. The grade and tonnage result of the basic estimation methods are as follows: IDW2 method reported 17.274Mt at a mean grade of 35.22%, the IDW3 method reported 16.975Mt at a mean grade of 35.53%, and the NNP method reported 14.757 at a mean grade of 38.53%. The estimation results are classified as inferred resources due to the drill spacing of 2000m x 60m.

The third objective was to determine a comparison between the geostatistical ordinary kriging method and the basic estimation methods (IDW2, IDW3 and NNP). This objective was realized by using four means of comparison: visualization of grade blocks, statistical comparison, correlation coefficient comparison and results (grade-volume-tonnage) comparison. The visual comparison of blocks shows that the OK and IDW methods produce nearly the same block estimates showing a larger homogenous zone of mineral blocks above the 30% grade cut-off, with just a minor zone of blocks estimated to fall between 25% – 30% Fe. It was observed that the NNP method showed a close comparison with the OK method in a statistical parameter:

mean, but the OK methods were better in most parameters such as results similarity (or the coefficient of Variation), variance, standard deviation, maximum, minimum and median which proves that the IDW methods are more related to the OK estimates than the NNP method, The test for correlation of results using the scatter plot (regression plot) and correlation value revealed a high correlation of OK estimates with IDW3 estimates, followed by IDW2, and finally, NNP. The grade results comparison showed that the IDW methods performed better with each showing comparable results in two categories and the NNP showing a comparable result with the OK method in a single category. The volume and tonnage comparison followed a similar pattern: the IDW2 method had the closest comparable results in the total calculated values, and IDW3 showed more comparable results when considering grade step categories. The NNP method is the least compared.

The fourth objective was to validate all methods of estimation. This was achieved using available cross-validation methods for the Datamine Studio RM software. All estimation methods were cross-validated by block-wireframe volume results comparison, standard error comparison and global estimate comparison. The Kriging estimates were further validated by a histogram of the slope of regression values with a mean of 0.792. The block-wireframe volume comparison (comparing estimated wireframe volume and calculated block volume) shows high accuracy with a per cent difference of 0.29% (acceptable being 2% and below) for all methods. Global estimate and calculated mean estimate for all methods showed a mean percent difference (actual %Fe versus estimated %Fe) less than 5%.

5.2 Recommendation

From the completed research study, the following recommendations have been reached:

The study recommends that other deposits within strike length, such as Gofolo north-east, Koehnko, and Zaway, which sum to the “Mofe Creek project”, be fully estimated and a full feasibility study be completed on the project for exploitation of the mineral resource.

Based on the estimated results, the study suggests that an evaluation considering the geological domain be done parallelly for further results comparison. This can only be possible with an updated geological database, as about 40% of the lithology (geology) table lacks a lithological code.

The study recommends that infill drilling be completed on the deposit to reduce the current 200m by 60m drill hole grid spacing, thereby improving the classification of the resource from the inferred category to the measured category.

The study recommends that a multivariate analysis involving Fe, Al_2O_3, and SiO_2 be completed on the project and that deleterious substances such as phosphorous and sulphur be studied to adequately inform a mineral extraction decision.

It is recommended that more prospected and explored (drilled) iron ore deposits within the Precambrian geological provinces (Liberian age province and Eburnean age province) of Lberia be evaluated quantitatively and qualitatively.

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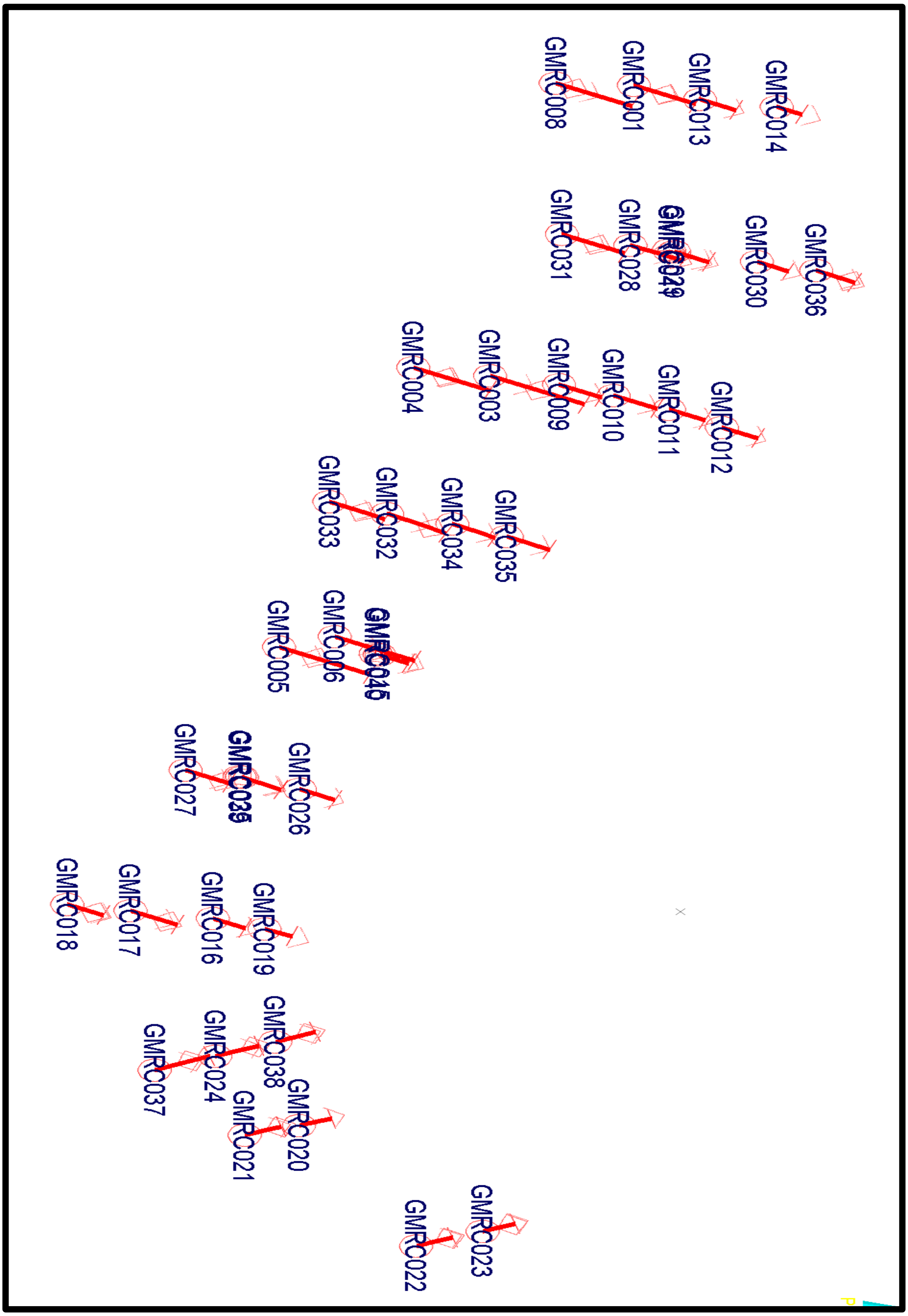
List of Appendices

Appendix 1: Drill hole collar data with added survey data details

BHID	X COLLAR (m)	Y COLLAR (m)	Z COLLAR (m)	DIP (°)	Azimuth (BRG)	Depth (m)
GMRC001	252609.612	761556.35	77.857	-50	24	102
GMRC003	253025.088	761417.343	99.159	-50	24	156
GMRC004	253013.267	761342.892	79.973	-50	24	127
GMRC005	253413.106	761212.985	84	-50	24	150
GMRC006	253398.211	761266.93	95	-50	24	132
GMRC008	252606.533	761480.761	61.058	-50	24	126
GMRC009	253037.811	761484.0257	106.1379516	-50	24	70
GMRC010	253053.3233	761536.8102	111.2037476	-50	24	72
GMRC011	253073.1337	761590.3662	111.6660779	-50	24	60
GMRC012	253098.9508	761641.5664	109.7252669	-50	24	60
GMRC013	252629.6505	761620.3772	92.08198942	-50	24	60
GMRC014	252640.393	761694.5553	78.41349564	-50	24	42
GMRC015	253424.232	761310.4282	103.4974462	-50	24	48
GMRC016	253801.2539	761148.8718	84.81219921	-50	24	54
GMRC017	253790.1537	761069.3356	84.63638075	-50	24	78
GMRC018	253781.2859	761008.1387	72.93936518	-50	24	60
GMRC019	253816.3912	761199.0458	78.53794822	-50	24	48
GMRC020	254097.5674	761232.41	84.15896663	-50	340	54
GMRC021	254111.4073	761179.7985	83.25478573	-50	340	60
GMRC022	254269.96	761345.743	80.226	-50	340	60
GMRC023	254249.035	761409.957	75.806	-50	340	54
GMRC024	253998.3627	761151.4089	88.48696284	-50	340	72
GMRC025	253599.2683	761177.0175	92.93178051	-50	24	66
GMRC026	253616.3541	761233.1061	98.98545846	-50	24	60
GMRC027	253589.2077	761122.5556	84.56513267	-50	24	72
GMRC028	252838.3925	761553.1492	100.4473365	-50	24	90
GMRC029	252847.5593	761595.5288	101.7197278	-50	24	60
GMRC030	252861.8401	761675.4878	91.76746601	-50	24	54
GMRC031	252822.6967	761486.7883	82.25143581	-50	24	104
GMRC032	253222.3451	761317.6027	91.5052002	-50	24	96
GMRC033	253205.2217	761261.654	82.51014201	-50	24	96
GMRC034	253237.0198	761380.8278	105.7927231	-50	24	72
GMRC035	253254.892	761433.2614	103.6822558	-50	24	72
GMRC036	252874.4514	761732.8852	82.89909361	-50	24	66
GMRC037	254018.419	761092.5666	83.41227707	-50	24	89
GMRC038	253978.1412	761209.2948	82.49940714	-50	24	66
GMRC039	253598.3589	761174.9489	92.5037134	-90	24	77
GMRC040	253422.729	761306.561	102.77	-90	24	72
GMRC041	252845.1998	761590.3892	101.9437359	-90	24	90

Appendix 2: Drill holes showing borehole ID and location



Appendix 3: Full statistics for twin holes

a) Full statistics for GMDD001 and GMRC006

NAME	GMDD001 (%)	GMRC006 (%)
Total Samples	21	21
Minimum	36.418	35.660
Maximum	59.390	60.320
Range	22.972	24.660
Total	1053.050	1027.310
Mean	50.145	48.920
Variance	53.387	69.439
Standard Deviation	7.307	8.333
Standard Error	1.594	1.818
Coefficient of Variation	0.146	0.170
Skewness	-0.679	-0.204
Kurtosis	-1.023	-1.585
Geometric Mean	49.568	48.183
Sum of Logs	81.970	81.375
Mean of Logs	3.903	3.875
Logarithmic Variance	0.024	0.031
Log Estimate of Mean	50.171	48.936
Correlation Coefficient	0.758	0.758
5th Percentile	36.418	35.660
10th Percentile	37.050	37.360
25th Percentile	40.774	39.520
50th Percentile	54.009	52.410
75th Percentile	55.800	56.880
90th Percentile	56.383	58.420
95th Percentile	58.557	58.960

b) **Full statistics for GMDD007 and GMR013**

NAME	GMRC007 (%)	GMDD013 (%)
Total Samples	21	21
Minimum	17.334	18.590
Maximum	58.467	56.510
Range	41.132	37.920
Total	830.940	838.560
Mean	39.569	39.931
Variance	134.988	97.532
Standard Deviation	11.618	9.876
Standard Error	2.535	2.155
Coefficient of Variation	0.294	0.247
Skewness	-0.331	-0.506
Kurtosis	-0.840	-0.258
Geometric Mean	37.577	38.489
Sum of Logs	76.154	76.658
Mean of Logs	3.626	3.650
Logarithmic Variance	0.114	0.082
Log Estimate of Mean	39.790	40.095
Correlation Coefficient	0.825	0.825
5th Percentile	17.334	18.590
10th Percentile	18.428	21.700
25th Percentile	30.208	33.600
50th Percentile	40.480	40.660
75th Percentile	48.510	47.290
90th Percentile	52.673	50.350
95th Percentile	55.416	54.010

Appendix 4: Full statistics for raw sample data and clipped mineralized hole data

a) Full statistics for 2m composited raw sample data

NAME	**VALUE (%)**
Total Samples	1525
Minimum	0.940
Maximum	60.320
Range	59.380
Total	31201.810
Mean	20.460
Variance	162.999
Standard Deviation	12.767
Standard Error	0.327
Coefficient of Variation	0.624
Skewness	0.486
Kurtosis	-0.466
Geometric Mean	15.671
Sum of Logs	4196.519
Mean of Logs	2.752
Logarithmic Variance	0.675
Log Estimate of Mean	21.966
Correlation Coefficient	-
5th Percentile	3.060
10th Percentile	4.720
25th Percentile	9.280
50th Percentile	19.210
75th Percentile	30.160
90th Percentile	37.680
95th Percentile	41.730

b) Full statistics for 2m composited clipped mineralized hole data

NAME	VALUE (%)
Total Samples	359
Minimum	3.360
Maximum	60.320
Range	56.960
Total	12354.720
Mean	34.414
Variance	87.466
Standard Deviation	9.352
Standard Error	0.494
Coefficient of Variation	0.272
Skewness	-0.029
Kurtosis	0.912
Geometric Mean	32.874
Sum of Logs	1253.869
Mean of Logs	3.493
Logarithmic Variance	0.109
Log Estimate of Mean	34.717
Correlation Coefficient	-
5th Percentile	18.320
10th Percentile	22.810
25th Percentile	30.330
50th Percentile	34.360
75th Percentile	38.550
90th Percentile	45.380
95th Percentile	52.410

Appendix 5: Full statistics comparing the results of all methods used for data analysis

NAME	OK (%)	NNP (%)	IDW2 (%)	IDW3 (%)
Total Samples	1686	1686	1686	1686
Minimum	16.914	8.340	18.793	16.986
Maximum	51.707	60.320	52.944	54.914
Range	34.793	51.980	34.151	37.928
Total	59015.001	59302.020	58057.677	58229.567
Mean	35.003	35.173	34.435	34.537
Variance	18.633	71.627	13.872	19.044
Standard Deviation	4.317	8.463	3.725	4.364
Standard Error	0.105	0.206	0.091	0.106
Coefficient of Variation	0.123	0.241	0.108	0.126
Skewness	0.285	0.015	0.400	0.500
Kurtosis	1.966	0.850	2.492	2.596
Geometric Mean	34.733	34.019	34.234	34.262
Sum of Logs	5981.413	5946.371	5956.995	5958.386
Mean of Logs	3.548	3.527	3.533	3.534
Logarithmic Variance	0.016	0.075	0.012	0.016
Log Estimate of Mean	35.008	35.312	34.437	34.541
Correlation Coefficient	0.687	0.687	0.991	0.991
5th Percentile	28.875	19.780	29.032	28.146
10th Percentile	30.575	24.810	30.506	30.239
25th Percentile	32.609	30.770	32.287	32.200
50th Percentile	34.477	34.930	34.119	34.038
75th Percentile	37.197	39.660	36.336	36.698
90th Percentile	40.151	45.450	38.794	39.436
95th Percentile	43.167	50.290	40.736	42.046

Appendix 6: Histograms of grade values for all methods (OK, NNP, IDW2, IDW3)