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Nickel Laterite Resource Estimation Using Inverse Distance Weighted (IDW) and Ordinary Kriging (OK) Methods in East Luwu Regency, South Sulawesi, Indonesia

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ABSTRACK

Nickel is a major mining commodity in Indonesia with abundant reserves, especially in Sulawesi which contributes to the national economy through the stainless steel and electric vehicle sectors. This study aims to analyze the estimation of nickel laterite resources in East Luwu Regency using the Inverse Distance Weighted (IDW) and Ordinary Kriging (OK) methods to analyze the quality and effective methods for estimating nickel laterite resources. The data used were 2.616-grade samples for each borehole interval and analyzed through descriptive statistics, variogram fitting, estimation model building, and laterite nickel resource estimation analysis. The estimation results of the IDW method with Cut-off Grade (COG) showed the volume and tonnage acquisition in the limonite zone of 4.593.710 m^3, 5.896.667 tons, while in the saprolite zone of 5.058.249 m^3, 6.317.770 tons. The Ordinary Kriging (OK) method shows the acquisition of volume and tonnage in the limonite zone of 4.602.227 m^3, 6.203.349 tons, while in the saprolite zone of 5.674.171 m^3, 6.647.641 tons. Based on the estimation results, the OK method obtains larger volume and tonnage results than the IDW method. This happens because the OK method uses the principle of spatial correlation of data. It not only focuses on the closest distance but can also cover data from the entire research area.

1. INTRODUCTION

Nickel is an important mining commodity that contributes significantly to the economy, especially as a raw material for stainless steel. In nature, nickel is generally found in the form of sulfide and oxide compounds (laterite ores), which are divided into two zones, which are saprolite with high levels in the bedrock and limonite zones with nickel levels above it [1].

Nickel is becoming a key ingredient in electric vehicle batteries, replacing fossil fuels. Indonesia, with its abundant nickel reserves, benefits from such events, leading to increased national nickel production and its contribution to the country's economy [2]. According to the Ministry of Energy and Mineral Resources (2022), the potential nickel resources in Sulawesi are very large with reserves in 2020 estimated at 2,6 billion tons of ore spread across Central, Southeast, and South Sulawesi. One of the main nickel-producing areas is East Luwu Regency, South Sulawesi. The nickel ore commodity in the region contributes significantly to increasing regional income through Gross Regional Domestic Product (GRDP). This great potential is supported by the presence of fault structures, rock formations, and mineral-rich alluvial deposits in the region. [3].

Resource estimation is an important step in obtaining IUP/IUPK approval in accordance with KEPMEN ESDM No.84.K/MB.01/MEM.B/2023. In the context of nickel laterite, detailed exploration is required to accurately determine the grade, volume, tonnage, and quality of the resource. The resource estimation used is the Inverse Distance Weighted (IDW) method, which assumes that the value at a sample location can be estimated based on the distance and known values around it using the distance-weight average concept. The IDW method has the advantage that points that have a long distance from the sample point, so that they have a small spatial correlation, can be deleted or removed from the calculation. [4].

Another frequently applied method is Ordinary Kriging (OK) using similar data in other locations to estimate. The Ordinary Kriging method estimates the variogram parameters, which are sill, nugget effect, and range. The OK method is consistent in all directions and produces estimates with Best Linear Unbiased Estimator (BLUE) properties [5]. Previous research shows that IDW and OK methods are often used in mine resource estimation involving nickel [6],[7]. However, most researchers only focus on one type of method without comparing the results between the estimation methods. Therefore, this study aims to compare the IDW and OK methods in nickel laterite resource estimation and determine the resource classification at mine X, East Luwu Regency, in order to determine the resource quality more comprehensively.

2. LITERATURE REVIEW

2.1 Nickel Laterite

Nickel laterite is formed by the chemical weathering of ultramafic rocks rich in ferromagnetic minerals such as olivine, pyroxene, and amphibole. Nickel-forming rocks come from dunite rock units that form nickel laterite. The mineral composition of dunite is olivine, which contains high Mg. Pyroxene contains orthopyroxene. Chromite is the main composition of nickel [8].

The weathering process involves the interaction of water, air, and temperature changes that cause the decomposition of the host rock into Fe, Mg, and Ni compounds. These compounds move downward in solution, forming minerals such as geothite, limonite, hematite and deposits in fractures such as granite and chrysopras. The laterite nickel deposits are divided into three main zones, namely the limonite zone located at the top, red-brown to dark yellow in color, the saprolite zone is a light yellow to greenish active weathering zone, rich in nickel hydrosilicate minerals, bedrock is a basic zone consisting of parent rocks such as igneous, sedimentary, or metamorphic rocks [9].

2.2 Inverse Distance Weighted (IDW) Method

The Inverse Distance Weighted (IDW) method is an interpolation method that assumes each input point has a local influence and decreases with distance. It is influenced by the inverse distance obtained from mathematical equations and can be adjusted to the relative influence on each sample point.

The formula used in this Inverse Distance Weighted (IDW) method is [11]:

$$Z^* = \sum_{i-1}^{N} \omega_i Z_i$$

The formula used to find the weight is:

$$\omega_i = \frac{h_i^{-p}}{\sum_{j=0}^{n} h_i^{-p}}$$

The formula used to determine the interpolation point is:

$$h_i = \sqrt{(x - x_i)^2 + (y - y_i)^2}$$

2.3 Experimental Semivariogram

The experimental semivariogram is a part of geostatistics that contributes to the visualization, modeling, and explanation of spatial correlation between points in the form of error variance at a location (s) and locations separated by a distance (s+h) [12].

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

Description:

$\gamma(h)$	=	the semivariogram value for distance (h)
$Z(S_i)$	=	the value of the variable measured at the location
$Z(S_i + h)$	=	the measured variable value of the location $(S_i + h)$

2.4 Variogram Model

The Variogram model is a part of the geostatistical analysis that describes the spatial correlation of data points between locations. Variations in variable values can change as the distance between observation points increases. To determine the parameters of the experimental semivariogram, the following variogram model can be use as follows:

a. Spherical Model

$$\gamma(h) = \{C_0 + C\,(\frac{3}{2}\frac{\|h\|}{a} - \frac{1}{2}\frac{\|h\|^3}{a^3})\} \text{ for } 0 < \|h\| \leq a$$

$$C_0 + C \text{ for } \|h\| \geq a \text{ and } 0 \text{ for } h = 0$$

b. Eksponensial Model

$$\gamma(h) = C_0 + C\ [1 - exp - \frac{3h}{a}]$$

c. *Gaussian* Model

$$\gamma(h) = C_0 + C\ [1 - exp - \frac{-3h}{a}]$$

2.5 Ordinary Kriging (OK) Method

The Ordinary Kriging method is a calculation method that assumes that random variables at a particular location concerning similar data at other locations have a constant value, but the average value is unknown[13]. With the following description:

a. Find the predicted value Z* on loation X_0

$$Zx = \sum_{i=1}^{n} \lambda_i Z_{xi}$$

b. Considering the unbiased condition

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

The linear equation formula in ordinary kriging is based on the semivariogram (γ(h)) in the equation between sample points. From the three equations mentioned, a system of kriging equations can be obtained, i.e.:

$$\begin{cases} \sum_{j=1}^{n} \lambda_j \gamma(x_i - x_j) + \mu = \gamma(x_i - x_0) \\ \sum_{j=1}^{n} \lambda_j = 1 \end{cases}$$

3. RESEARCH METHODOLOGY

3.1 Research Location

The research was conducted in East Luwu District, South Sulawesi Province. The area of East Luwu Regency is 6.944.88 km2. The East Luwu region is geomorphologically divided into three landform units, including structural slope units, hills units, and denudational valley units. The geology of East Luwu district has many karsts and is within the scope of the ultramafic rock area or ultrabasic rocks originating from plate collisions.

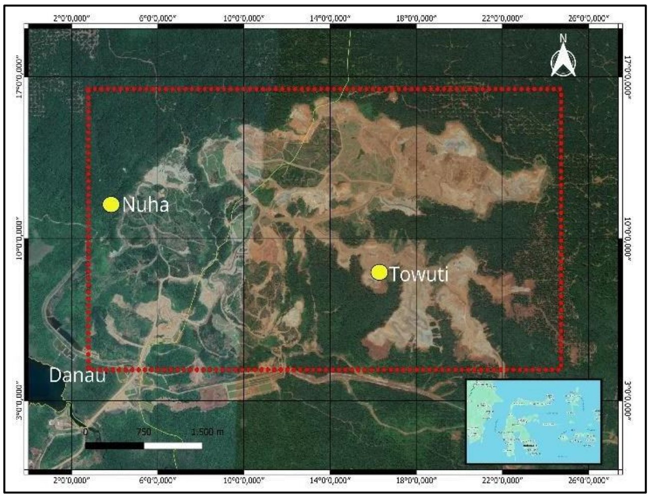

Figure 1. Research location map

3.2 Data Processing

The data used was obtained from exploration drill log data, which includes nickel grade at each drill hole interval and lithology data containing information on the location of limonite, saprolite, and bedrock zones. The data obtained is then processed, and the estimated value of nickel and other minerals in each zone (domain) is produced. The data processing process includes:

1) The Sediment Cross-Section Model
The sediment cross-section model is a cross-section model generated from the drill log database. It is useful for determining the value and model of the resource to be estimated.
2) Descriptive Statistical Analysis
Statistical analysis aims to analyze the relationship between data. The results obtained are mean, median, standard deviation, and variance. The results obtained will then be plotted into a variogram.
3) *Fitting* Variogram
After performing descriptive statistical analysis, the next step is to perform variogram fitting by entering the descriptive statistical analysis results to determine the sill and range for kriging estimation.
4) Resource Estimation
Resource estimation aims to estimate the Ni grades, volume, and tonnage in each estimation method. The results of the resource estimation are then analyzed and compared between the Ordinary Kriging and Inverse Distance Weighted methods.

4. RESULTS AND DISCUSSION

4.1 Descriptive Statistics Analysis

The descriptive statistical analysis in this study uses data on nickel (Ni) levels at each borehole interval, the data used is 2.616. Descriptive statistical analysis functions in analyzing the relationship between data without regard to the location of the drill point. The results of this descriptive statistical analysis are Mean, Median, Range, and Variance. The descriptive statistical value, sill, and range are used for variogram parameter analysis. The range value in the variogram is generated from the acquisition of variance, maximum, median, and minimum values in descriptive statistics.

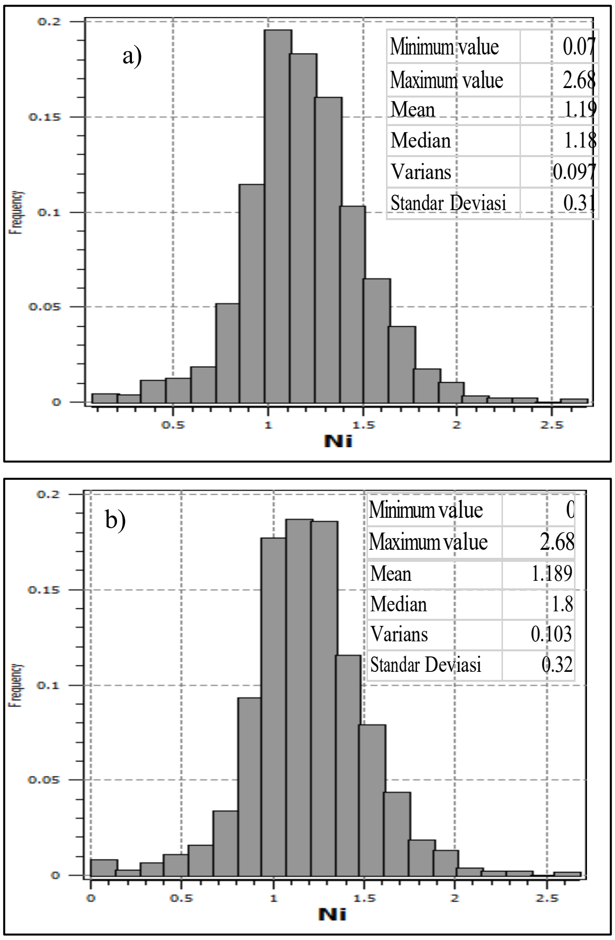

Figure 2. Descriptive statistics on: a) limonite zone and b) saprolite zone

Descriptive statistics in Figure 2 show that the most significant variance is in the saprolite zone. The variance value in Figure 2 is 0,097% in the limonite zone and 0,103% in the saprolite zone. Variance in descriptive statistical analysis is used to obtain information about the consistency or heterogeneity of nickel content. The mean value in the descriptive statistical analysis shows that the average nickel content in the study zone is 1,19% for the limonite zone and 1,189% for the saprolite zone. The standard deviation value shown in Figure 2 shows that the limonite zone has a value of 0,31%, and the saprolite zone is 0,32%. The standard deviation represents how much nickel content is distributed in each zone. The minimum value represents the value with the lowest grade in each zone. The limonite zone obtained a minimum value of 0,07%, while the saprolite zone was 0%. The maximum value represents the value with the largest grade available in each zone. The limonite zone obtained a minimum value of 2,68%, while the saprolite zone was 2,68%. The statistical analysis of the limonite and saprolite zones showed a difference in results. The saprolite zone produces a greater value than the limonite zone. This indicates a difference in the distribution of nickel content values. The variation of nickel content in the limonite zone tends to be close together, so the distribution is more consistent.

4.2 Resource Estimation Using Inverse Distance Weighted

The Inverse Distance Weighted (IDW) method is an interpolation technique used to estimate resources or variables at unmeasured locations based on data available at nearby locations. IDW assumes that values at unmeasured locations can be predicted by calculating a weighted average of the measured values in the vicinity. The weight assigned to each measured value is inversely proportional to the distance between the measurement point and the estimation location; the closer the measurement location is to the estimation location, the greater the weight assigned. [14]. The resource estimation of the limonite zone using the IDW method is presented in Table 1.

Table 1. The total nickel (Ni) resource recovery in the limonite zone by IDW method

Grade	Grade interval	Volume (m^3)	Tonnage (ton)	Average grade(%)
G2	0,4 – 0,6	35.039	19.133	0,55
G	0,6 – 0,8	41.961	29.228	0,70
E2	0,8 – 1,0	465.281	422.810	0,91
E	1,0 – 1,2	1.459.750	1.624.279	1,12
D	1,2 – 1,4	2.168.172	2.823.313	1,30
C	1,4 – 1,6	906.320	1.351.913	1,49
B	1,6 – 1,8	59.320	96.892	1,63
A	1,8 – 2,0	148	270	1,82
Grand Total		**5.135.991**	**6.367.838**	**1,269**

The laterite nickel resources shown in Table 1 obtained average grade results ranging from 0,55 - 1,82. The largest volume was produced at the 1,3% level of 2.168.172 m^3, and the resulting tonnage was 2.823.313 tons. The results of nickel resource estimation in the limonite zone using the Inverse Distance Weighted (IDW) method shown in Table 1 obtained the volume of nickel is 5.135.991 m^3. The tonnage obtained from nickel in the limonite zone is 6.367.838 tons. The average optimal nickel content is vulnerable at 0,55 – 1,82, obtaining an average Ni of 1,269%. Nickel (Ni) grade was obtained through previous research conducted [15]. Nickel grade indicates the quality of the grade obtained from resource estimation using the Inverse Distance Weighted (IDW) method. The quality of nickel with large levels is shown in grades A to E. Meanwhile, nickel with low levels is shown in grades E2 to G2.

Table 2. Total nickel (Ni) resource recovery in saprolite zone by IDW method

Grade	Grade interval	Volume (m^3)	Tonnage (ton)	Average grade(%)
I	0,2 – 0,4	891	343	0,385
G2	0,4 – 0,6	42.547	22.534	0,535
G	0,6 – 0,8	34.305	23.219	0,683
E2	0,8 – 1,0	465.867	423.878	0,913
E	1,0 – 1,2	1.465.203	1.625.930	1,113
D	1,2 – 1,4	2.140.844	2.787.679	1,304
C	1,4 – 1,6	919.867	1.371.713	1,493
B	1,6 – 1,8	66.320	108.298	1,633
A	1,8 – 2,0	148	272	1,830
Total		**5.135.992**	**6.363.866**	**1,270**

The laterite nickel resources shown in Table 2 obtained average grade results ranging from 0,385 – 1,830. The largest volume was produced at a level of 1,304%, amounting to 2.140.844 m^3, and the resulting tonnage was 2.787.679 tons. The results of nickel resource estimation in the saprolite zone using the Inverse Distance Weighted (IDW) method shown in Table 2 obtained the volume of nickel is 5.135.992 m^3. The tonnage obtained from nickel in the limonite zone is 6.367.866 tons. The average optimal nickel content is susceptible to 0,385 – 1,830, obtaining an average Ni of 1,270%. Nickel (Ni) grade was obtained through previous research conducted [15]. Nickel grade indicates the quality of the grade obtained from resource estimation using the Inverse Distance Weighted (IDW) method. The quality of nickel with large levels is shown in grades A to E. Meanwhile, nickel with low levels is shown in grades E2 to G2.

The estimation results using the IDW method in Table 1 and Table 2 show differences in the results of each zone. In the limonite zone, the overall block volume is 5.135.991 m^3 with a tonnage of 6.367.838 tons and an average overall grade of 1,269%. Meanwhile, the saprolite zone obtained a level of 5.135.992 m^3 with a tonnage of 6.363.866 tons and an average overall grade of 1,270%. According to Ilham et al. (2021), the difference in grade, volume, and tonnage in the limonite and saprolite zones is influenced by the nature of the Ni element. Nickel has semi-mobile properties and limited mobility, so the nickel element will collect in the saprolite zone.

4.3 Variogram Model

Fitting variograms helps minimize errors in the resource estimation process. The variogram fitting process is done by inserting a lag (the lag is obtained based on the distribution of the data and the average distance from the borehole). The type of variogram used is an omnidirectional variogram, which helps provide an overall picture of the spatial relationship of data without considering specific directions. The reason for using omnidirectional variograms is the limitation of particular directions. The results of variogram fitting can be seen in Figure 3.

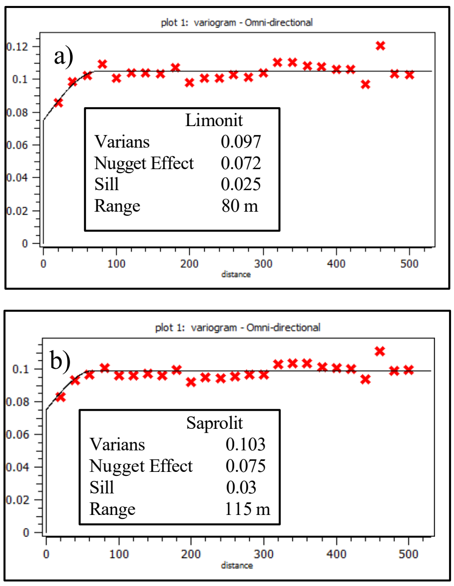

Figure 3. Nickel (Ni) variogram fittings on: a) limonite zone and b) saprolite zone

The results of fitting variograms are sill, range, and nugget effect. The sill obtained from the variogram fitting process is 0,025% for the limonite zone and 0,03% for the saprolite zone, and the nugget effect obtained is 0,072% for the limonite zone and 0,075% for the saprolite zone. The range value obtained from the variogram fitting process is 80 m for the limonite zone and 115 m for the saprolite zone.

The nugget effect shows the variability of data at a short distance; if the nugget effect value is greater, the variance between data at a short distance will be greater. The size of the nugget value can be adjusted by minimizing the sampling distance. The correlation between the nugget effect, sill, and range is that they work together to describe patterns of spatial variability in the data. The nugget effect in the variogram shows unexplained local variability, the sill shows the maximum limit of variability, and the range shows the distance at which spatial variability stabilizes.

The fitting variogram results show that nickel homogeneity is shown in the limonite zone because the variance gain is lower than in the limonite zone. This shows that the distribution of nickel content in the limonite zone is more uniform. The nugget effect shown by the limonite zone is of higher consistency. The difference in sill shows that the limonite zone produces more homogeneous grades because the limonite zone has a more complex decomposition process. The difference in range results shows that the spatial relationship between data points is limited, so the variation in nickel content is more concentrated at a closer distance. The spatial relationship between data points in the saprolite zone is broader.

4.4 Resource Estimation Using Ordinary Kriging (OK)

Estimation using the Ordinary Kriging method is a geostatistical method that requires spatial data at the sampled locations and variograms that are useful in determining values at unsampled locations, these values depend on their proximity to the sampled locations. The results of the variogram fitting that has been done are then entered into the software database for estimation.

Table 3. Total nickel (Ni) resource recovery in limonite zone by OK method

Grade	Grade interval	Volume (m^3)	Tonnage (ton)	Average grade(%)
G2	0,4 – 0,6	31.211	17.251	0,56
G	0,6 – 0,8	42.297	29.311	0,70
E2	0,8 – 1,0	460.258	418.954	0,91
E	1,0 – 1,2	1.404.586	1.556.134	1,11
D	1,2 – 1,4	2.270.086	2.961.364	1,31
C	1,4 – 1,6	899.602	1.326.697	1,48
B	1,6 – 18	27.805	45.458	1,64
A	1,8 – 2,0	148	284	1,91
Total		**5.135.993**	**6.355.453**	**1,27**

The laterite nickel resources shown in Table 3 obtained average grade results ranging from 0,56 – 1,91. The largest volume was produced at the 1,31% level of 2.270.086 m3, and the resulting tonnage was 2.961.364 tons. The results of nickel resource estimation in the limonite zone using the Ordinary Kriging (OK) method shown in Table 3 obtained the volume of nickel is 5.135.993 m^3. The tonnage obtained from nickel in the limonite zone is 6.355.5453 tons. The average optimal nickel content is susceptible to 0,56 – 1,91, obtaining an average Ni of 1,27%. Nickel (Ni) grade was obtained through previous research conducted [15].

Table 4. Total nickel (Ni) resource recovery in saprolite zone by OK method

Grade	Grade interval	Volume (m^3)	Tonnage (ton)	Average grade(%)
I2	0,0 – 0,2	547	480	0,121
I	0,2 – 0,4	297	390	0,305
G2	0,4 – 0,6	73.531	54.563	0,503
G	0,6 – 0,8	87.453	84.300	0,697
E2	0,8 – 1,0	778.930	444.292	0,883
E	1,0 – 1,2	1.681.359	1.848.861	1,103
D	1,2 – 1,4	2.280.172	2.972.551	1,306
C	1,4 – 1,6	905.273	335.376	1,477
B	1,6 – 1,8	28.289	46.276	1,637
A	1,8 – 2,0	148	285	1,922
Grand Total		**5.835.999**	**6.787.374**	**1,25**

The acquisition of nickel laterite resources, as shown in Table 4, obtained average grade results ranging from 0,121 – 1,922. The largest volume was produced at 1,306% of 2.280.172 m^3, and the resulting tonnage was 2.972.551 tons. The results of nickel resource estimation in the saprolite zone using the Ordinary Kriging (OK) method shown in Table 4 obtained the volume of nickel is 5.835.999 m^3. The tonnage obtained from nickel in the limonite zone is 6.787.374 tons. The average optimal nickel content is vulnerable to 0,56 – 1,92, obtaining an average Ni of 1,25%.

The classification of resources in Table 3 and Table 4. shows the difference in yields from each zone. In the limonite zone, the overall block volume is 5.135.993 m^3 with a tonnage of 6.355.453 tons and an overall average grade of 1,27%. In comparison, the saprolite zone obtained a level of 5.835.999 m^3 with a tonnage of 6.787.374 tons and an average overall grade of 1,25%. The difference occurs due to the weathering process of ultrabasic parent rock, rich in silicate minerals such as olivine and serpentine, which contain nickel.

The results obtained are differences in volume, tonnage, and grade. The grade obtained in the limonite zone is greater than the saprolite zone because there is a wide variability in the saprolite zone, resulting in a smaller average grade than the limonite zone. According to Ilham et al. (2021), the difference in content, volume, and tonnage in the limonite and saprolite zones is influenced by the nature of the Ni element. Nickel has semi-mobile properties and limited mobility, so the nickel element will collect in the saprolite zone. Minerals rich in nickel will be concentrated, and the levels in the saprolite zone will be more varied.

4.5 Classification of Nickel Laterite Resources Using Relative Kriging Standard Deviation (RKSD)

The classification of nickel laterite resources can be represented by the level of geological confidence represented by the error rate in geological modeling and resource estimation based on kriging variance. According to SNI 2019, resource classification includes inferred, indicated, and indicated resources. Resource classification can be obtained from the calculation of Kriging Relative Standard Deviation (RKSD). Blackwell's theory states that values ≤ 0,3 are considered indicated, 0,3-0,5 indicated, and 1 ≥ suspected. Ronaldo (2020), in his research, mentioned that Blackwell's RKSD method tends to produce more indicated resources and is considered less realistic. For more accurate results, RKSD is used with the Snowden method, where RKSD values ≤ 0,5 are considered measured, 0,5-1 are considered indicated, and 1 ≥ are considered inferred.

Table 5. Limonite zone laterite nickel (Ni) resource classification

Classification	Total Block	Dimensions block	Total volume (m^3)	Density (g/cm^3)	Tonnage (ton)
Inferred	4	7,8125	31,25	0.89	27,8125
Indicated	21	7,8125	164,0625	0.89	146,015
Measured	2.534	7,8125	19.796,875	0.89	17.619,218

The nickel resource classification in Table 5 shows that the measured resource classification results are greater due to geological variability; according to research conducted by Musrifin et al. (2021), geological diversity, such as the meeting of tectonic plates, and other factors such as faults. The complexity causes lithologic variation, which can affect the distribution of nickel. The distribution of nickel minerals can influence the classification of resources, as well as the level of material density in the limonite zone.

Table 6. Classification of saprolite zone nickel (Ni) resources

Classification	Total Block	Dimensions block	Total volume (m^3)	Density (g/cm^3)	Tonnage (ton)
Inferred	4	7,8125	109,375	0,89	97,3437
Indicated	21	7,8125	210,937	0,89	187,734
Measured	2.534	7,8125	19.671,8	0,89	17.508,9

The results of the resource classification in the saprolite zone in Table 6 show that measured resources are greater due to geological variability; according to research by Musrifin et al. (2021), geological diversity, such as the meeting of tectonic plates and other factors such as faults. Geological diversity in the research area can affect the distribution of nickel. The distribution of nickel minerals can influence the classification of resources, but there are different results for the saprolite and limonite zones with the categories of suspected and indicated resources. The saprolite zone produces a larger block of estimated and measured resources than the limonite zone. This is due to geological characteristics.

The results from Tables 5 and 6 show that the limonite zone produces a larger resource classification than the saprolite zone. The difference in results occurs because of the difference in compressive strength values in the limonite and saprolite zones during exploration drilling. According to Kumalasari (2023), the compressive strength of the limonite zone is higher at around 0,0655 kg/cm^3 compared to the saprolite zone, which is around 0,056 kg/cm^3. This is also due to the higher material density in the limonite zone compared to the saprolite zone.

4.6 Comparison of Inverse Distance Weighted (IDW) Method with Ordinary Kriging (OK)

The results obtained from each estimate are then categorized based on COG (cut-off Grade). The COG value in each mineralization zone is different: 1,0% in the limonite zone and 0,8% in the saprolite zone. The Cut-off Grade (COG) value was obtained from previous research conducted by Irzan MZ et al. (2018), referring to PT Vale Indonesia. The results of the nickel resource estimate can be seen in Table 7.

Table 7. Nickel (Ni) resource estimation results with limonite zone COG values

Category	Grade interval	Volume(m^3)		Tonnage (ton)		Average grade(%)	
		IDW	OK	IDW	OK	IDW	OK
Low Grade	1,0 – 1,2	1.459.750	1.404.586	1.624.279	1.55.6134	1,12	1,11
	1,2 – 1,4	2.168.172	2.270.086	2.823.313	2.961.364	1,3	1,31
Medium Grade	1,4 – 1,6	906.320	899.602	1.351.913	1.326.697	1,49	1,48
	1,6 – 1,8	59.320	27.805	96.892	45.458	1,63	1,64
High Grade	1,8 – 2,0	148	148	270	284	1,82	1,91
Total		**4.593.710**	**4.602.227**	**5.896.667**	**6.203.349**	**1,30**	**1,29**

The results of the nickel resource estimation using COG in Table 7 show that the low-grade category resources with the highest-grade interval are 1,0 – 1,2% using the Inverse Distance Weighted (IDW) method with an average grade of 1,12%. The acquisition of medium-grade category resources with the highest-grade interval of 1,6-1,8% using the Ordinary Kriging (OK) method with an average grade of 1,64%. Furthermore, the high-grade category, the resource category with the highest-grade value, is shown in the interval of 1,8 – 2,0% with an average grade of 1,91%. The total obtained from the results of nickel estimation in the limonite zone shows that the Ordinary Kriging method obtained higher results, which are 4.602.227 m^3 for a volume of a tonnage of 6.203.349 tons.

Tabel 8. Nickel (Ni) resource estimation results with saprolite zone COG values

Category	Grade interval	Volume(m^3)		Tonnage (ton)		Average grade(%)	
		IDW	OK	IDW	OK	IDW	OK
Low Grade	0,8 – 1,0	465.867	778.930	423.878	444.292	0,913	0,883
	1,0 – 1,2	1.465.203	1.681.359	1.625.930	1.848.861	1,113	1,103
	1,2 – 1,4	2.140.844	2.280.172	2.787.679	2.972.551	1,304	1,306
Medium Grade	1,4 – 1,6	919.867	905.273	1.371.713	1.335.376	1,493	1,477
	1,6 – 1,8	66.320	28.289	108.298	46276	1,633	1,637
High Grade	1,8 – 2,0	148	148	272	285	1,830	1,922
Total		**5.058.249**	**5.674.171**	**6.317.770**	**6.647.641**	**1,27**	**1,26**

The results of the nickel resource estimation with COG in Table 8 show that the low-grade category resources with the highest-grade interval are 1,0 – 1,2% using the Inverse Distance Weighted (IDW) method with an average grade of 1,11%. The acquisition of medium-grade category resources with the highest-grade interval of 1,6-1,8% using the Ordinary Kriging (OK) method with an average grade of

1.64%. Furthermore, the high-grade category, the resource category with the highest grade value, is shown in the interval 1,8 – 2,0% with an average grade of 1,922%. The total obtained from the nickel estimation results in the limonite zone shows that the Ordinary Kriging method obtained higher results, namely 5.674.171 $m^3$for volume and 6.647.641 tons. However, the overall average grade produced is greater using the IDW method, which is 1,27%.

From the results that have been obtained, there is a difference between the initial results and the final results based on the COG of nickel. Cut-off Grade on nickel acts as a parameter in determining the minimum limit of nickel content that is feasible to mine. COG also plays a role in mineral resource management, deciding which is possible to mine and which may not be mined. The minimum level limit in the limonite zone is 1,0%; if there are levels below 1,0%, it is considered waste, as is the saprolite zone, with a COG of 0,8%. Waste is waste generated from the nickel mining process.

The results obtained from the comparison using COG show that the IDW method produces higher grades, but for the volume and tonnage produced, the OK method is higher. This is because the OK method takes into account all areas, including low grades. The OK method produces smaller grades because of smoothing in the variogram, which tends to reduce extreme grades and results in a more realistic grade distribution. The IDW method gives greater weight to the closest data points. The result will be affected by extreme grades, resulting in higher grades in certain areas.

Based on these estimates, the OK method has a larger estimated volume and tonnage compared to the IDW method. However, there is a difference in results in the IDW estimate where the resulting grade is higher. This is due to the inability of the IDW method to capture geological variations, resulting in an overestimation. Meanwhile, OK has the BLUE (Best Linear Unbiased Estimator) principle. According to research conducted by Falah et al. (2024), the BLUE principle is divided into three, namely Best, which is an estimate with the smallest error variance. Linear is a combination of samples around it. Unbiased is the average estimation error is zero. Data distribution at low levels is often more dispersed. The IDW method cannot capture patterns because it only uses the distance principle, resulting in a higher average value.

Table 9. Comparison of nickel (Ni) estimation results with IDW and OK methods

Method	Volume of Ni (m^3)		Tonnage of Ni (ton)		Average Grade of Ni (%)	
	Limonite	Saprolite	Limonite	Saprolite	Limonite	Saprolite
IDW	4.593.710	5.058.249	5.896.667	6.317.770	1,30	1,27
OK	4.602.227	5.674.171	6.203.349	6.647.641	1,29	1,26

Based on the results of the analysis, it is found that the OK method is more suitable for the research location because the volume, tonnage, and grade results obtained from the Ordinary Kriging method are more proportional. The IDW method can provide a high-grade estimate but is less representative of tonnage and volume. According to Asy'ari et al. (2013), the OK method can minimize estimation errors with the principle of unbiased, thus avoiding overestimation or underestimation in data with high variability. The accuracy of the OK method depends on the variability of the data, the number of observation points, and the variogram that determines the spatial relationship between points.

The selection of the Ordinary Kriging method in resource estimation has an accuracy that depends on data variability and the number of observation data points; there are variograms that help in determining the spatial relationship between data points. The OK method is more proportionally used because tonnage is calculated based on a wider distribution of material. The resulting grade is calculated by taking into account the spatial relationship between data. The IDW method considers zones with high grades, resulting in smaller tonnages.

5. CONCLUSIONS AND SUGGESTIONS

5.1 Conclusions

The conclusions obtained from the nickel laterite resource estimate are:

1. The actual average grade of nickel laterite in the limonite zone is 1,19%, and the saprolite zone is 1,189%. The variance obtained in the limonite zone is 0,097%, and the saprolite zone is 0,103%. The variance is used in variogram fitting to determine the sill, nugget effect, and range values. The nugget effect value (γh) of the limonite zone = 0,072 and the saprolite zone = 0,075. The sill obtained is 0,025 in the limonite zone and 0,03. The range value obtained is 80m for the limonite zone and 115m for the saprolite zone.
2. The estimation results of the Inverse Distance Weighted (IDW) method are shown from the estimated resources. The results obtained using the IDW method in the limonite zone obtained 4.593.710 m^3 and 5.896.667 tons with an average grade of 1.30%, in the saprolite zone obtained 5.058.249 m^3 and 6.317.770 tons with an average grade of 1,270%.
3. The results of the resource estimation using the Ordinary Kriging (OK) method in the limonite zone are 4.602.227 m^3 and 5.889.937 tons with an average grade of 1,29%, in the saprolite zone 5.674.171 m^3 and 6.647.641 tons with an average grade of 1,26%.
4. The ordinary kriging method obtained proportional volume, tonnage, and grade distributions. The Ordinary Kriging (OK) method is more capable of considering the distance between points with a variogram that describes the distribution and correlation between data points compared to the IDW method, which only affects the distance without comparing the spatial correlation between data points.

5.2 Suggestion

Suggestions from the research on nickel laterite resource estimation using the Inverse Distance Weighted (IDW) and Ordinary Kriging (OK) methods are the nickel laterite estimation results that have been obtained, the need for further analysis for the benefit of production operations such as feasibility studies. The classification of nickel laterite resources needs to be processed using Excel. Manual calculation using Excel can identify the classification of resources in each estimation block produced by Ordinary Kriging (OK).

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