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Hurricane sample replacement using the inverse distance weighted method

Vitaliy L. Ruposov^a✉^a*Irkutsk National Research Technical University, Irkutsk, Russia*

Abstract. The article discusses the method of hurricane sample replacement taking into account the spatial relationship of other routine samples. This sample is presented as the result of selecting sampling parameters with the mineral content above average values determined using the proposed methodology. The approach is based on geostatistical findings regarding the spatial dependence of sampled subsurface areas within a single geological block. The feature of the proposed methodology is the calculation of the studied indicator taking into account all samples for the evaluated block including the hurricane one. The approach is based on the method for determining weighting coefficients from the inverse distance weighted method. The method has been tested using the exploration data from a placer gold deposit. All key parameters of the proposed method, such as the radius and number of additional points created, as well as the power coefficient of the weighting function are analyzed. Several indicators are identified that will influence the results of mineral reserves calculations taking into account a hurricane sample and when it is replaced by the values calculated using the proposed methodology. The article analyses a situation in which the study object is selected incorrectly. It is demonstrated how the replacement of an outlier value can affect the assessment results for a given geological block. Examples of replacing similar samples are provided along with the assessment of the impact on the change in estimated reserves for a placer gold deposit. A conclusion is drawn regarding the error in determining the hurricane sample with the comparison of the impact on the exploration results and geological block assessment. The article is based on the study of a geological block tested by vertical boreholes, in which the gold content was determined. The results were obtained by modeling the process of determining the values to be used to replace the selected sample. The conducted analysis shows the effect of volume changes for various parameter variants of the proposed method. The article is illustrated with grade-interpolated plots and graphs showing curves for various parameters of calculated indicators.

Keywords: hurricane sample, geostatistics, inverse distance weighted method, exploration of solid mineral deposits

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Научная статья

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Замена ураганной пробы с использованием метода обратных взвешенных расстояний

В.Л. Рупосов^a✉^a*Иркутский национальный исследовательский технический университет, Иркутск, Россия*

Резюме. В статье рассмотрена методика замены ураганной пробы с учетом пространственной взаимосвязи других рядовых проб. Такая проба представлена как результат выбора показателей опробования с содержаниями полезного компонента выше рядовых значений, определение ее произведено по предложенной методике. Подход основывается на выводах геостатистики о пространственной зависимости опробуемых участков недр в рамках одного геологического блока. Особенностью предлагаемой методики является расчет исследуемого показателя с учетом всех проб по оцениваемому блоку, включая и саму ураганную. В основу подхода взят способ определения весовых коэффициентов из метода обратных взвешенных расстояний. Апробация метода произведена на примере данных разведки россыпного месторождения золота. Исследованы все основные параметры предлагаемого метода, такие как радиус и количество создаваемых дополнительных точек, а также степенной коэффициент весовой функции. Определены несколько показателей, которые повлияют на результаты подсчета запасов полезного ископаемого с учетом ураганной пробы и при ее замене на рассчитанные значения по предлагаемой методике. Проведен анализ ситуации, когда объект исследования выбран неверно, и показано, как замена выделяющегося из ряда значения может повлиять на результаты оценки данного геологического блока. Приведены примеры замены подобных проб и оценка влияния на изменение подсчитанных запасов россыпного месторождения золота. Сделан вывод об ошиб-



ке определения ураганной пробы с сопоставлением влияния на результаты разведки и оценки геологического блока. Статья основана на исследовании геологического блока, опробованного вертикальными скважинами, в которых определялись содержания золота. Результаты получены с использованием моделирования процесса определения значений, которые будут использоваться для замены выбранной пробы. Проведенный анализ показал эффект изменения объемов для различных вариантов параметров предлагаемого метода. Публикация проиллюстрирована планами с интерполяцией по содержаниям и графиками с кривыми при различных параметрах расчетных показателей.

Ключевые слова: ураганная проба, геостатистика, метод обратных взвешенных расстояний, разведка месторождений твердых полезных ископаемых

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Introduction

The large heterogeneity of the occurrence of many minerals [1, 2] requires the use of methods to reduce the high contrast content of the useful component. Modern sampling methods make it possible to obtain samples of variety orientation and to assess the content of chemical elements and the composition of rocks qualitatively [3]. The reliability of sampling increases along with the capabilities of modern laboratories, which reduces the amount of processed material [4]. The borehole drilling method makes it possible to obtain samples of various locations and orientations, which reduces the number of workings and improves the quality of sampling¹. In this regard, each sample obtained during exploration has a high value and reliability of determination, which does not exclude the appearance of values that are out of the general range of sampling and can be considered hurricane-like [5]. In this case, it should be understood that a given sample is an element of the heterogeneity of the natural occurrence of minerals associated with a very high fluctuation in the content of the useful component in the selected samples, therefore, a simple approach of ignoring or replacing this value with non-standard parameters is unacceptable. It is necessary to form approaches to replacing this value, taking into account the heterogeneity of the natural environment². On the other hand, the preservation of an out-of-line sample can also negatively affect the calculations of mineral reserves, as it leads to their increase or decrease [6]. This is most often due to the fact that a single sample does not carry a high reliability of determining

the contents and, therefore, its value is usually extended to a certain volume in samples, and with a high deviation from ordinary samples, it leads to an increase in the error of the evaluation work. For some methods of calculating reserves, the error of one sample can strongly affect the total reserves of the deposit [7–10]. For example, the polygon method is based on the zone of influence of a single sample on a subsurface area. At the same time, this method does not use averaging of indicators, but relies only on the value of the sample, which default parameters apply to the entire space around this value that is the centre of the polygon. If we imagine a situation where a nugget got into a borehole during the exploration of a placer deposit (even the control sample gave high values of gold grade, which is associated with selective grinding), then according to the polygon method, the entire space around this sample should contain nuggets, but, as practice shows, more often there are no nuggets in this subsurface area. If you use methods of calculating reserves, where there is averaging over a small amount of data, the error will persist. For example, the reserves of the triangle method will also be calculated with a deviation from the true values. In the triangle method, the averaging of contents of fossil fuels occurs only for three values, which are the vertices of the triangle, so the impact of the hurricane sample here will also be high.

In this case, an out-of-the-range value will distort the volume of reserves for all triangles that have this vertex as one of the three points. Such a situation has no effect on the reliability and validity of the obtained exploration results

¹ Komlev A.S. *High-frequency combined sampling of ores and enrichment products: dis. ... D.Sc. (Technology): 2.8.9.* Yekaterinburg: Ural State Mining University; 2024, 433 p.

² Filonyuk V.A. *Fundamentals of risk factor management in the development of mineral deposits: textbook. handbook for universities.* Irkutsk: Irkutsk State Technical University; 2014, 113 p.



for the borehole or sample, therefore, such a value should be taken into account. Simple replacement of this value without analyzing it is incorrect [5, 9, 11].

The purpose of this study is to determine a way to replace the hurricane sample with a value that takes into account the statistical and spatial features of the distribution of the useful component in the subsurface.

Materials and methods

The analysis of the hurricane sample is divided into two stages: at the first stage, we determine what relates to this indicator; at the second stage, we replace this sample with the calculated value [5].

The first stage is described in the previous article [12]. It was necessary to provide some characteristics of the proposed method for detecting such a sample, especially for deposits with high content variability. The article proposed to search for the highest low-frequency modal values. To identify them it is necessary to divide values into classes according to the proposed formula, which takes into account the heterogeneity of the data by adding the coefficient of variation into the formula:

$$k = \frac{1,5 + \frac{1}{\log_5 V}}{\sqrt{n}},$$

where V is the coefficient of variation, and k is the number of classes for a sample with n dimensions.

When calculating, the number of classes increases depending on the value of the relative spread (V). Another feature of the proposed method is the analysis of low-frequency modal values. At the same time, it is necessary to take into account the presence of a natural increase in concentrations, justified by a series of samples with high values and located in close proximity to each other. A series of such samples cannot be classified as a hurricane samples, even if they are much higher than the average value in the series. But a single low-frequency sample with a spatial environment of unremarkable samples can be classified as a hurricane sample, as shown in the article on the example of exploration of a placer deposit.

To illustrate this approach, Figure 1 shows a plot that identifies two hurricane samples. An example is a placer gold deposit with borehole sampling along exploration lines with high het-

erogeneity of mineralization. At the same time, the highest values on the plot related to boreholes no. 75 and 74 cannot be attributed to them for this method of determining hurricane samples, since they are located next to each other and with high values of boreholes no. 73 and 76, thus forming an area of a regular increase in mineral content. But boreholes which samples showed high values (more than 20,000 mg/m³) can be classified as hurricane boreholes, since they are located in a relatively isolated area and surrounded by samples with high values. Such objects include boreholes no. 20 and 15.

After you have detected hurricane samples, you need to move on to the next stage. The article presents the results of a study of methods for replacing selected values with calculated ones.

There are several approaches to taking hurricane samples into account in the literature. The first approach is a method for determining and excluding such values when calculating reserves. In this case calculating the average mineral content in the deposit is acceptable without excluding such a sample [5]. In the earliest works on this problem, it was proposed to replace this sample with a new one, which should be selected under the same conditions and with very similar geometric parameters. This was often impossible due to the completion of the field work of the exploration stage, when the required equipment may no longer be available in the field or it is very difficult to repeat a geometrically close sample. Now we can add the economic feasibility of such work to this, especially when each exploration process has a high reliability of obtaining a result.

The second approach is to replace such a sample with the value of a certain indicator. This approach makes it possible to reduce the reserves calculation error, since the sample is not completely removed, but replaced with a certain calculated value. In this case, the accuracy of reserves accounting does not suffer due to changes in the geometry of the blocks of calculating minerals. There has been a wide discussion about the method of calculating such an indicator, which can reasonably replace a hurricane sample [5, 13–15]. The justifications of many methods are based on statistical methods, especially great attention is paid to random distributions. For example, D.I. Shamansky proposed replacing the value

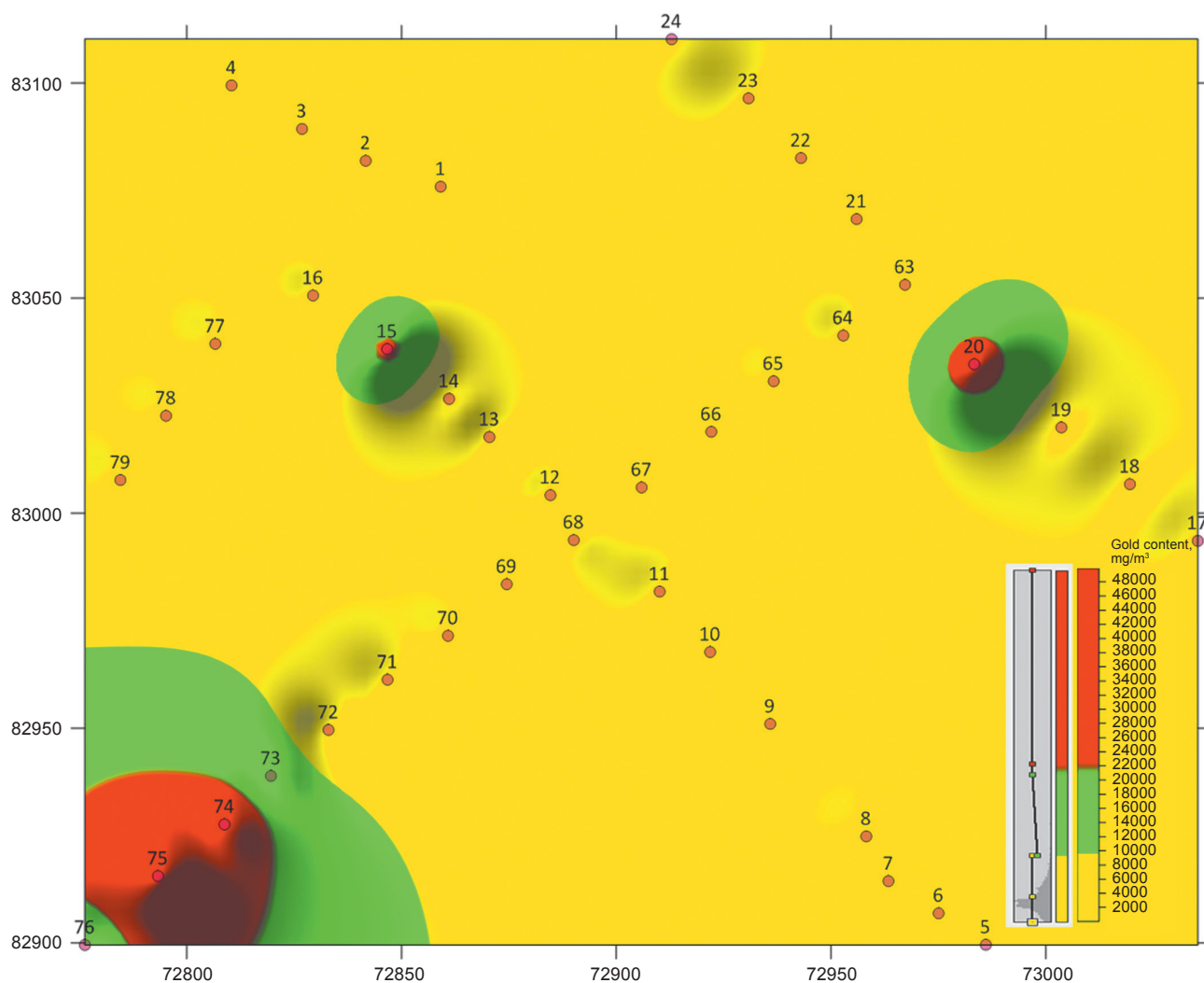


Fig. 1. Gold grade change plot for boreholes with the identification of samples related to hurricane samples
Рис. 1. План изменения содержания золота по скважинам с определением проб, относящихся к ураганным

from the empirical distribution of a random variable with a normal distribution. V.I. Smirnov recommended replacing it with the average value for the sample [5]. N.V. Volodomonov proposed replacing the hurricane sample with a calculated value based on the average content for all samples, taking into account the increase values according to the introduced indicator, the limit of the effect of this sample on the average is 20 %. A similar approach to replacing an out-of-order sample with a calculated indicator can also be found in other authors, for example, V.I. Kuzmin, V.M. Gudkov, G.I. Vilesov, Iv. Khristov, D. Dimokov, Tsv. Boyadzhiev, B.Ya. Yufa, G.A. Bazanov, I.V. Frantskiy and many others³ [3–5, 9, 11, 14, 15]. The influence of the spatial position of the sample can

be found in the works of P.L. Kallistov [5], where he suggests classifying a hurricane sample, which is two or more times higher in content than the sample closest to it. In terms of spatial analysis, the effects of such a sample deserve additional consideration, which was noted in the approach of G.I. Vilesov [5]. There is a feature in his method of replacing a hurricane sample related to the spread of the influence of such a value. It is proposed to distribute this content not over half the distance between neighboring samples, but over a part of this distance corresponding to the probability of a hurricane value, calculated as the ratio of conditional reserves for such samples to the sum of conditional reserves for hurricane and ordinary samples.

³ Frantskiy I.V., Bazanov G.A. *Mathematical statistics and geometrization of deposits: textbook*. Irkutsk: Irkutsk Polytechnic Institute; 1975, 249 p.



In the conducted studies, it is proposed to replace this sample based on an analysis of its spatial position in the studied subsurface. The value replacing this sample should take into account both the content of all samples obtained during the exploration of this ore block and their location in space. The main assumption is the geostatistical concept of the dependence of mineralization of geological blocks on the spatial geometry of ore-bearing structures [16–19]. To form an approach for replacing such samples, the inverse distance weighting method was applied [20]. This method is based on the geostatistical assumption that all samples obtained for a selected geological block or ore body can have an effect on the interpolated point.

The spatial position of the samples limits this effect. The further the samples are geometrically away from the determined point, the less influence there is on the calculated value. This method is implemented through the calculation of special coefficients. Most often, such a coefficient is the inverse distance, raised into a power coefficient. Most software designed for this type of interpolation suggests squaring the distance by default. This study has shown

that other values of the power coefficient can be used, including the range from 0 to 1.

Here is a method for calculating the indicator value, which can be used to replace a hurricane sample (Fig. 2).

The inverse distance weighting method is based on the assumption that the closest sample to the interpolated point is the most influential, and the furthest sample is the least influential. The weight is determined using the inverse distance, raised to the power of γ . The formula for calculating weights using the inverse distance weighting method:

$$\lambda_i = \frac{1}{d_i^\gamma}, \quad (1)$$

where λ_i is the weight with which the i^{th} sample is taken into account; γ is the power coefficient; d_i^γ is the distance between the interpolated point and the i^{th} sample, which is calculated using the formula:

$$d_i = \sqrt{(x_i - x_{uj})^2 + (y_i - y_{uj})^2}, \quad (2)$$

where x_i and y_i are the coordinates of the i^{th} point; x_{uj} and y_{uj} are the coordinates of the interpolated point.

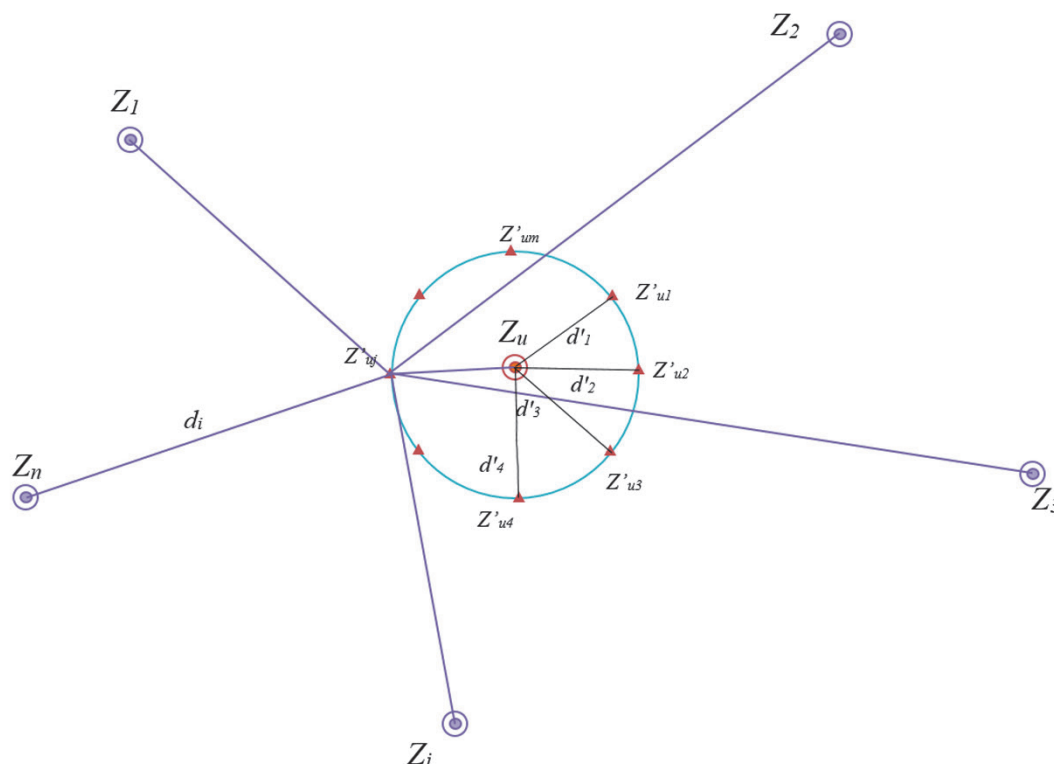


Fig. 2. Hurricane sample recalculation scheme:

$Z_{1-3, i, n}$ – ordinary samples; $Z_{um, u1-u4, uj}$ – additional calculation points; Z_u – hurricane sample

Рис. 2. Схема пересчета ураганной пробы:

$Z_{1-3, i, n}$ – рядовые пробы; $Z_{um, u1-u4, uj}$ – дополнительные расчетные точки; Z_u – ураганная проба



A feature of the proposed method is the creation of a series of interpolated points placed around the hurricane sample in a circle, each such point as a result of the process of determining the calculated value through inverse weighting distances is independent. The selected sample is also involved in the calculation of the interpolated value. This approach is demonstrated in Figure 2. To use the method, it is necessary to calculate both the value Z_{uj} for each additional point and the position of the point on the plan. To do this, we use the formula for calculating the determined indicator Z_{uj} :

$$Z_{uj} = \frac{\sum_{i=1}^n Z_i \lambda_i}{\sum_{i=1}^n \lambda_i}, \quad (3)$$

where Z_i is the value of the studied indicator for the i^{th} sample; λ_i is the weighting coefficient for this sample; $\sum_{i=1}^n \lambda_i$ is the total sum of the weights.

To determine the coordinates of an additional point on the plan, we use the formulas:

$$x_{ui} = x_u + d'_j \cos \alpha'_j, \quad (4)$$

$$y_{ui} = y_u + d'_j \sin \alpha'_j, \quad (5)$$

where x_u and y_u are the coordinates of the hurricane sample; d' is the distance from this sample to the interpolated point; the directional angle α'_j is determined by the formula:

$$\alpha'_j = \left(\frac{360}{m} \right) j, \quad (6)$$

where m is the number of additional points for interpolation.

After additional points are found, we calculate the value that will be used to replace the hurricane sample. The calculation is carried out according to the formula:

$$Z'_u = \frac{\sum_{j=1}^m Z_{uj}}{m}. \quad (7)$$

In this method, the replacement of the hurricane sample is carried out taking into account all the obtained samples, including the replaced sample, which makes it possible to take into account all the data obtained without exception. The calculated value will take into account the heterogeneity of the ore field and the complexity of its structure.

This method depends on several parameters, the value of which can greatly affect the calculation results of the replaced hurricane sample. The following critical parameters can be distinguished:

- the value of the power coefficient in the calculation of weights;
- the distance of the interpolated points from the selected sample;
- the number of additional interpolated points.

The Results and discussion

Studies were conducted at a real object with exploration data on a placer deposit to determine the effect of the above parameters on the results of using the proposed method.

The effect of the number of additional points arranged evenly in a circle around the hurricane sample was estimated by calculating the obtained result using formulas (1)–(7) for various options. The points on the circle were taken in the amount from 4 to 26 units and the replaced values were calculated using the above formulas (4) and (5) for each option with 1 step. A graph based on the calculation results is shown in Figure 3.

The graph shows that after 10 additional points, the value of the calculated indicator becomes almost the same. Therefore, we take the number of points on the circle, taking into account a 20 % increase in reliability, equal to 12 pcs.

The next direction of the analysis was two indicators: a power function and the distance from the selected sample. The distance analysis was performed taking into account the size of the exploration grid, since otherwise the influence of surrounding samples would be higher than the influence of hurricane sample, and then you can replace this indicator simply with the value of the nearest borehole. To do this, the distance to the nearest sample was determined and the influence of the radius size of the circle on the selected sample was analyzed. Radii were studied from the location of the hurricane sample to half the distance to the nearest borehole.

The power coefficient was studied by calculating an indicator that replaces this sample for different values of the radius according to formulas (1), (3) and (7). Therefore, data on the analysis of the influence of the radius from the hurricane sample and the power function were combined into a single set of curves shown in the Figures below. The power indicator was studied in the period from 0.5 to 6 with unequal step. The results obtained for sample of the borehole no. 15 are shown in Figure 4. As can

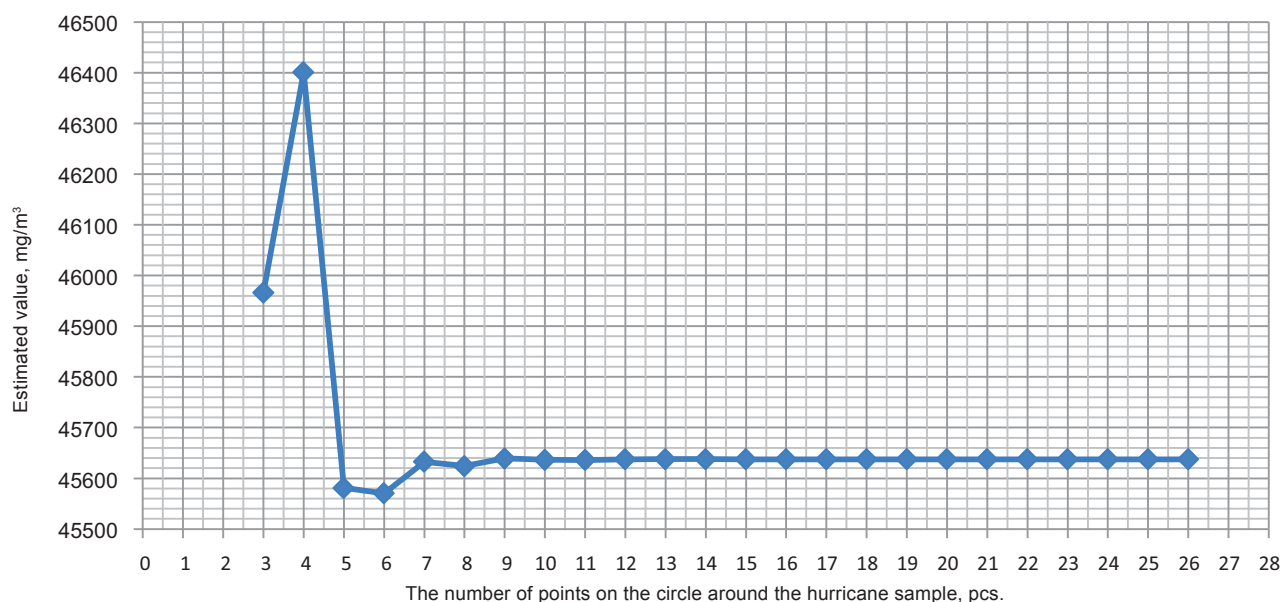


Fig. 3. Analysis of the number of points around the hurricane sample
Рис. 3. Анализ количества точек вокруг ураганной пробы

be seen in the graph, a high dependence of the results exists both on the power in a weight function of the inverse weighting distance method and on the radius at which twelve additional interpolated points are located. The maximum decrease in the hurricane sample occurs only for the power coefficients 0.5, 0.6 and 0.7, while the effect of increasing the distance of the last three metres is insignificant. The graph also showed that high powers (when the power coefficient is higher than 3) do not differ significantly from each other and, therefore, it is impractical to apply powers above 3. The power of 1 is when the weight values correspond to the inverse distances, the curve is close to a linear relationship, therefore, only the distance from the hurricane sample exists almost according to an linear law.

This method of replacing a hurricane sample turned out to be very flexible. Depending on the purpose and type of deposit, the value can be drastically reduced using half or even just 1/3 of the distance from such a sample and the power of 0.5 or 0.6. At the same time, the reduction of the selected sample for the given example occurred from 23674 to 4400 mg/m³, that is by 81 %. The smallest decrease in this sample for the maximum radius is possible with a power coefficient of 3, which is equivalent to 8200 mg/m³, so that the value of the replaced hurricane sample will decrease by 65 %.

For this type of deposits belonging to the third group of complexity, a curve with a power coefficient of 0.6 and a distance of 14 m

from the location of the hurricane sample can be used. The replacement value for the selected sample will be 5100 mg/m³ or 78 % of the original value.

To assess the impact of replacing the hurricane sample, we calculate the volume of the surface of the contents relative to the zero value using the Surfer software. The total volume of the «ingot» without replacing the selected sample turned out to be 268.3×10^6 mg. When replacing this sample from 23674 to 8200 mg/m³, the volume of the «ingot» turned out to be 248.3×10^6 mg, the difference was 7.5 %. Without taking this sample calculating reserves using a linear method will overestimate the amount of gold in the deposit by more than 5 %, which is higher than the acceptable margin of error. The plan with an interpolated surface is shown in Figure 5, a.

An analysis of the case was carried out when the selected sample is not a hurricane sample (for example, borehole no. 75 in Figures 1 and 5). This borehole, as mentioned above, is not hurricane, as it is surrounded by samples with a high gold grade, which is clearly visible on the plan, where another borehole falls into the red zone of very high concentrations, and two boreholes located in the immediate vicinity fall into the green zone of high concentrations. In case of incorrect selection of such a sample, the method should not have a strong impact on the total reserves of the mineral. To substantiate this statement, the variability of the calculated indicator was analyzed depending

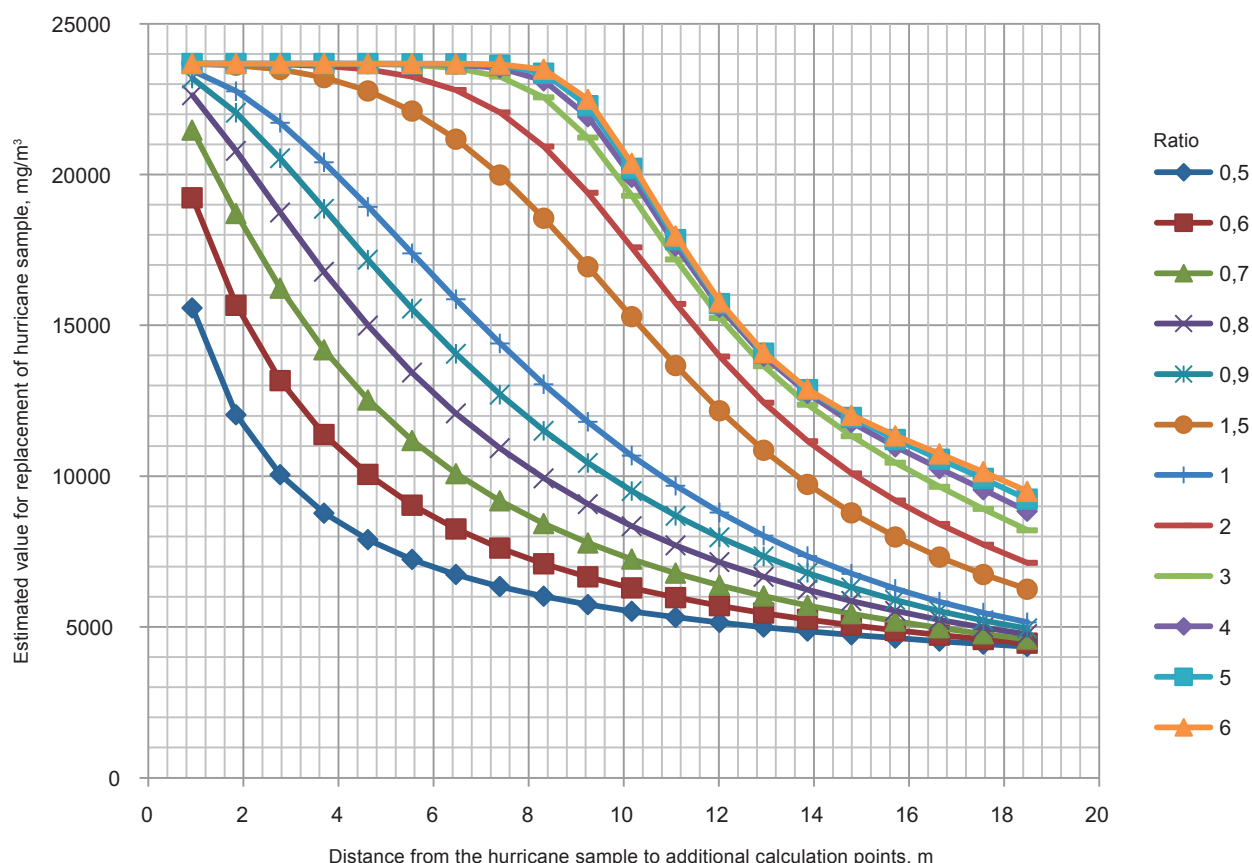


Fig. 4. Calculated replaced hurricane sample value vs distance and degree as a function of weighting coefficients for the borehole no. 15
Рис. 4. Зависимость расчета значения заменяемой ураганной пробы от расстояния и степени в функции весовых коэффициентов для скважины № 15

on the power and distance from the selected sample. The obtained results are summarized in a graph in Figure 6.

As can be seen in the graph, the behavior of the power functions remains similar to the graph in Figure 4, therefore, the effect of the method is stable for different cases. So, for example, for powers above 3, the curves merge. The difference between the resulting minimum value of 10340 and the pseudo-hurricane sample of 50323 mg/m³ is 79.5 %, which is lower than for a truly hurricane sample of borehole no. 15. If we take the values at a power coefficient of 0.6 and a distance of 14 m, then in Figure 6 we will find the value of 14200 mg/m³, which will be a decrease in the value of the selected pseudo-hurricane sample by 71.7 %, which is less than when replacing the true hurricane sample by 6 %.

As can be seen in Figure 5, *b*, the replaced value of the pseudo-hurricane sample ceased to be ultra-high, but it remained high at the same time. Calculated the volume of the resulting surface in the amount of 228.9×10⁶ mg and

compared with the volume of the original surface, equal to 268.3×10⁶ mg, we conclude that there was a significant decrease (by 14.7 %). Consequently, this method, if a hurricane sample is chosen incorrectly, may reduce the indicators of mineral reserves unreasonably, which does not make the method fully universal and does not remove individual responsibility for choosing such a sample from the specialist who calculates reserves.

Conclusion

The proposed method allows not only to replace samples of this type, taking into account the content of the studied geological block, but also to assess the influence of the geometric location of the sampled subsurface areas. The geostatistical approach to estimating a spatial variable makes it possible to make calculations using all the obtained results of sampling, taking into account the high reliability and good quality of the results obtained at all stages of exploration. It is unacceptable to exclude samples from the evaluation of the block due to

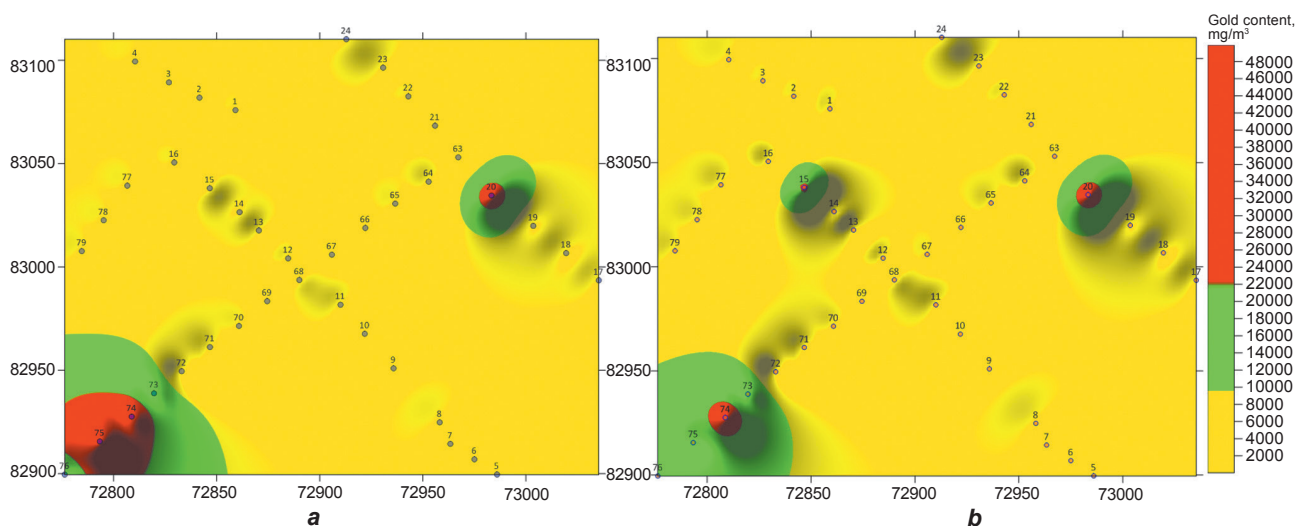


Fig. 5. Gold grade change plot boreholes with interpolation when replacing hurricane samples no. 15 (a) and 75 (b) according to the proposed methodology
Рис. 5. План изменения содержаний золота по скважинам с интерполированием при замене ураганных проб № 15 (a) и 75 (b) по предлагаемой методике

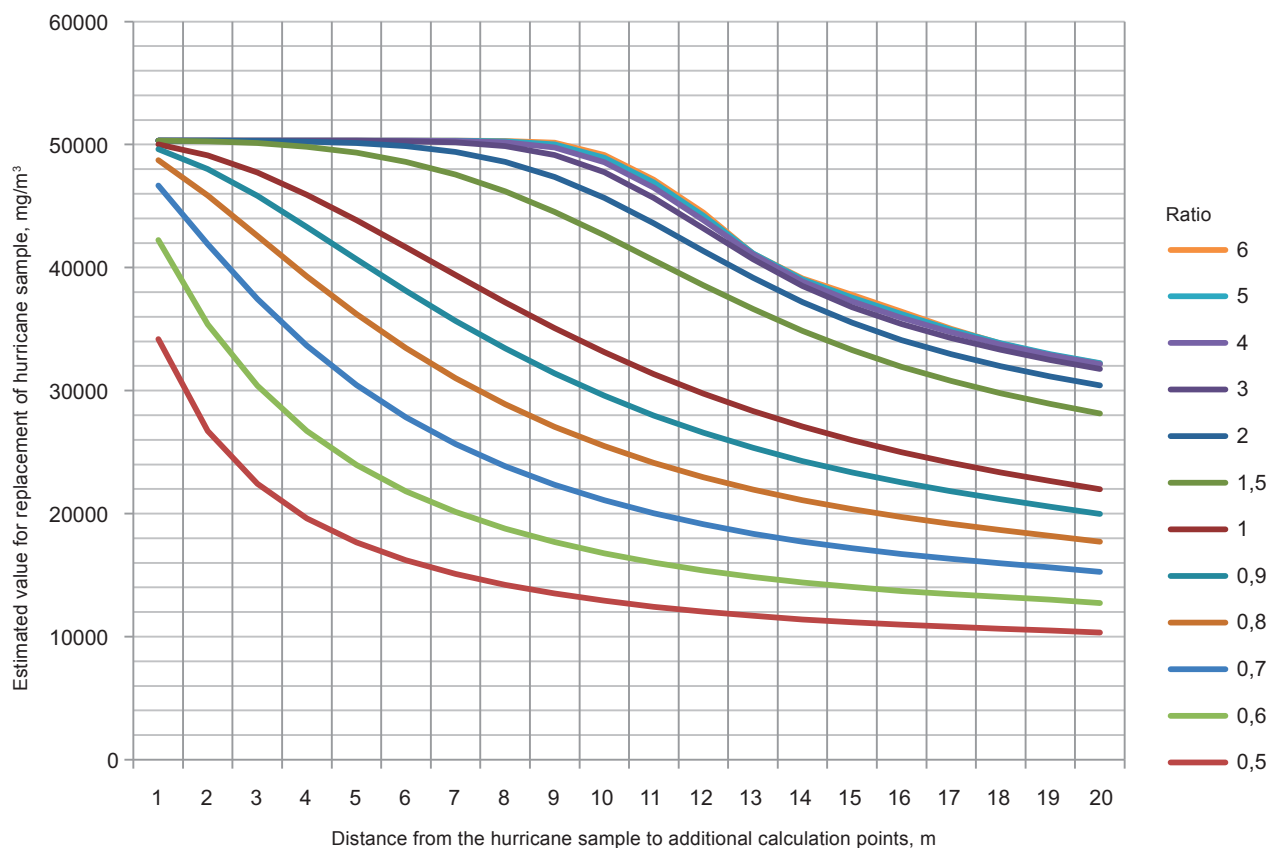


Fig. 6. Calculated replaced hurricane sample value vs distance and degree as a function of weighting coefficients for the borehole no. 75
Рис. 6. Зависимость расчета значения заменяемой ураганной пробы от расстояния и степени в функции весовых коэффициентов для скважины № 75

their value being out of the general range at this stage of technology development, therefore, replacement should take into account the existence of a hurricane sample. The calculated value should be justified not only by the content, but also by the geometry of the

orientation of the samples in the estimated subsurface space. The proposed method for replacing such samples is based on the weight coefficients of the inverse weighting distance method, meets all the requirements and can be used for various deposits of solid minerals.



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Information about the author / Информация об авторе

**Vitaliy L. Ruposov,**

Cand. Sci. (Geol. & Mineral.), Associate Professor,
Associate Professor of the Department of Mine Surveying and Geodesy,
Institute of Subsoil Use,
Irkutsk National Research Technical University,
Irkutsk, Russia,

✉ ruposov@istu.edu

<https://orcid.org/0000-0003-2202-9034>

Рупосов Виталий Леонидович,

кандидат геолого-минералогических наук, доцент,
доцент кафедры маркшейдерского дела и геодезии,
Институт недропользования,
Иркутский национальный исследовательский технический университет,
г. Иркутск, Россия,

✉ ruposov@istu.edu

<https://orcid.org/0000-0003-2202-9034>

Contribution of the author / Вклад автора

The author performed the research, made a generalization on the basis of the results obtained and prepared the copyright for publication.

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