# ACCOUNTING FOR DILUTION IN RESOURCE ESTIMATION

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## ABSTRACT

The full economic evaluation of a mining project requires a block model that provides an estimate of the tons and grades of available resources. The model must be representative of the mineralization to be found at the time of mining for specified extraction periods and within acceptable error margins.

In an operating mine, there may be a reasonable understanding and estimates of actual dilution and ore loss. This paper discusses the issue from the perspective of a project at a feasibility or pre-production level of development.

Three types of dilution are discussed. Internal dilution (or change of support) is function of the spatial distribution of the mineralization and its relation to the operation's selectivity. Geologic contact dilution is the unavoidable mixture at contacts or boundaries of material with different geologic characteristics, grades, or metallurgical performance. Operational planned and unplanned dilution should also be considered, sometimes incorporated by factoring the resource model, but more accurately by mimicking the grade control process.

The resource estimation process always carries uncertainty, which is sometimes significant, and usually caused by several factors. These include quantity and quality of drill hole information; quantity and quality of geologic data; grade estimation methodology; dilution and mining recovery factors applied; etc.

A key decision is to whether estimate as accurately as possible the in-situ geologic resource or to estimate the tons and grade of the material to be fed to the processing plant. The geologic modeling and grade estimation methods used are conditioned by this decision.

## BIOGRAPHY

Mr. Rossi has a BS in Mining Engineering from San Juan University, Argentina, an MSc in Geostatistics from Stanford University, USA, and about twenty years experience in geostatistics, ore resources estimation, and computer and optimization studies for the mining and environmental industries.

He has been Principal Geostatistician for GeoSystems International, Inc. for the past 15 years, where his responsibilities include project management and development of geostatistical ore resources and reserves estimates, conditional simulations for orebody optimization, and different aspects of computer modeling. Mr. Rossi has completed ore resource and reserves estimates to support Long- and Short-term mine planning, grade control, mine property evaluation in North and South America, Australia, Europe, Africa, and Asia. Prior to GeoSystems International, Mr. Rossi was Senior Geostatistician for Mineral Resources Development, Inc. (MRDI) and a geostatistician with Fluor Daniel, Inc. Mr. Rossi is the author of over 30 papers, and has taught numerous short courses in English and Spanish at graduate level and for geologists and mining engineers.

## INTRODUCTION

The full characterization of the geologic resources and mining reserves of any deposit is required before completing an economic evaluation of any mining project. Reserve reporting, pit or stope designs, financing, and operational and remediation planning are based on the estimated resources. The consequences of potential estimation errors and omissions are significant, and can result in serious economic losses. Experience has shown that ignoring or incorrectly estimating potential dilution and ore losses at the time of estimating resources is one of the main causes of failure of resource models.

This discussion argues the importance of incorporating an appropriate amount of dilution to the "undiluted" resource model, such that a recoverable reserves model is eventually obtained. The requirement would therefore be that the resource model should accurately predict the tonnage and grade produced at the mine of mining. Any model that does not provide a reasonable estimate of recoverable resources will result in a sub-optimal estimate of the tonnage and grade available for mining. This is true regardless of the project's stage of development.

## DILUTION AND ORE LOSS

There are at least three types of dilution and ore losses that need to be considered: internal dilution, also known as change of support or volume-variance correction; geologic contact dilution; and operational dilution and ore loss.

- **Internal dilution** takes into consideration the mixtures of grades within pre-defined volumes. Many deposits exhibit grade populations that are positively skewed, implying that only a small proportion of samples have interesting grades. A small volume of rock is likely to have a more homogeneous distribution of grade within itself compared to a larger volume. When larger volumes of rock are considered, there will be more mixtures of high and low grades. The block size that is typically relevant is the Selective Mining Unit (SMU), defined as the smallest volume at which the operation can separate ore and waste. It is an indication of mine selectivity.

- **Geologic contact dilution** is defined as the dilution and ore loss resulting from the extraction of material of different geologic characteristics. It occurs at the transition (contact) between different grade domains. It has local impact, and for high tonnage, massive base metals deposits the impact of geologic contact dilution will be small, although it can impact the positioning of a final pit wall or stope. Contact dilution can be the most consequential dilution type in deposits with more complicated geometries, such as veins, skarn, or stratigraphically controlled deposits with significant folding and faulting.

- **Operational mining dilution** refers to both dilution and ore loss that occurs at the time of mining, because the precision with which the equipment can follow dig lines is limited, even with Global Positioning Systems (GPS). If the ore and waste contacts correspond with geologic contacts, the operational and contact dilution can be the same. But more generally the contacts of ore and waste that occur at the time of mining are defined in economic terms, and they do not necessarily follow geologic contact zones.

Also, another factor to be accounted for is the "Information Effect". This term does not refer to dilution or ore loss, but rather refers to the fact that, at the time of mining, the information used to decide which portion of the deposit is ore and which is waste is based on different (and more) information than that available when performing an ore resource evaluation. Therefore, the additional information could account for potential discrepancies between the resource model and actual production.

Note that the ore/waste selection is always made with an estimate of the true but unknown grades. This is called imperfect selection, in this sense that an estimation error is always present. Additionally, the selection process is not "free", meaning that each block (SMU) is not selected as ore or waste independently of other blocks in the vicinity. There may be also geometrical or other mining constrains that restrict the accessibility of each SMU.

**Internal Dilution**

Internal dilution is modeled using geostatistical tools for volume-variance correction. The classical methods for volume-variance correction are the Affine Correction, the Indirect Lognormal, and the Discrete Gaussian methods. These methods generally intend to correct a sample distribution into an SMU block distribution, and are generally applicable to small scale changes. References for additional details on the methods are Journel and Huijbregts (1978), and Isaaks and Srivastava (1989).

The relationship between volumes and variances is shown in Figure 1. The variance decreases as the volume increases due to the "averaging out" of high and low values, with the point (samples) distribution always having the larger variance. The averaging is affected by the size and shape of the volume, the spatial continuity of the variable, and the averaging process. The mean does not change with a change in volume for most grades in mining, since they average arithmetically. There are exceptions, however, mostly when considering geotechnical and geo-metallurgical variables.

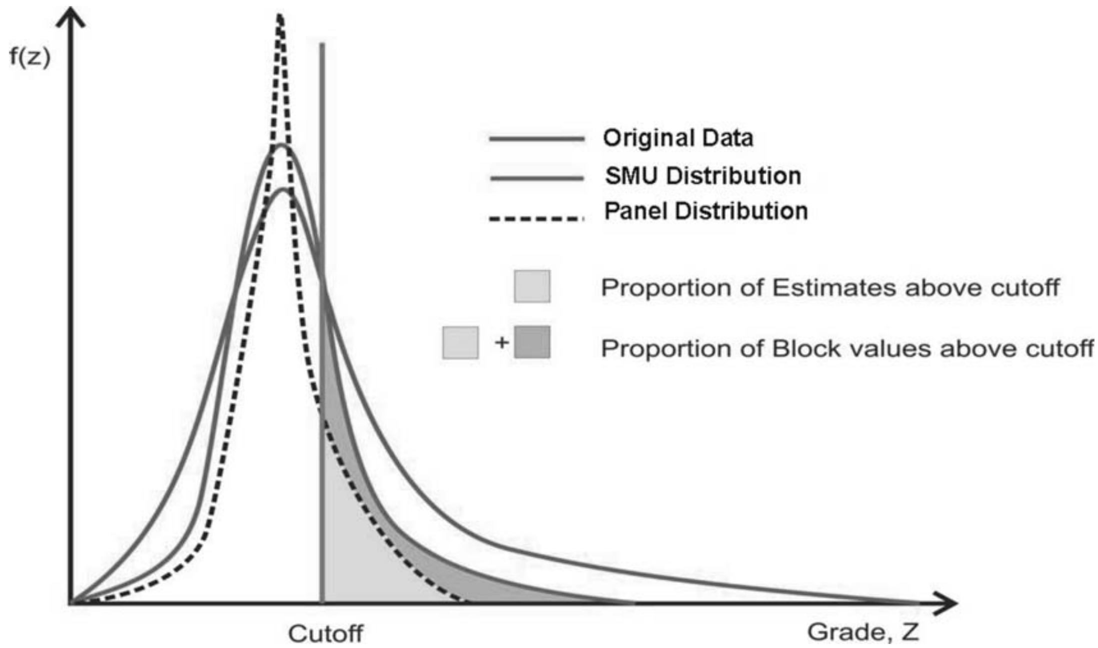


**Figure 1:** Schematic showing volume-variance relations for original data, SMU-sized distribution, and a larger panel distribution.

The amount of correction or decrease in variance is a function of the spatial distribution of the variable, and the block size (or selectivity) chosen as the SMU. It is possible to predict the expected distribution of the SMU blocks using for example one of the methods mentioned above, but they have limitations derived from the theoretical assumptions. The most important ones are (Rossi and Parker, 1993):

- The Permanence of Distribution assumption (Affine and Indirect Lognormal corrections; this assumption is strong, since the variance of a distribution cannot be changed without changing its shape. However, for small variance corrections, it can be an acceptable assumption.

- The change in variance can be characterized using the variogram model; variogram models are highly sensitive to certain parameters or characteristics of the data, including the presence of extreme values and how they are dealt with, spatial clustering, the parameters used to obtain the experimental variograms, and the mathematical function used to obtain the model: traditional variogram, correlogram, some form of relative variogram, etc.

- The block size of interest is defined as the SMU of the operation; but it is always considered a cube or regular dimensions applied to all grade domains; this is an idealized concept. In reality, SMU do not exist, and the operation selects ore and waste panels of irregular sizes and shapes, depending on the geometry of the deposit, the short-term mine plan, and the mining equipment used. Figure 2 shows an example of a partial bench in a porphyry Cu mine. The theoretical SMU is 20 x 20 x 15m; there are very few ore and waste panels that come close to the SMU size, and their sizes and shapes are extremely variable.

- The variance correction is applied by grade domain or globally, without attempting to take into account local deviations in sub-areas of the domains. If the defined grade domains are not as stationary as the classical methods require the change of support will not result in a good prediction of the SMU distribution.

There are other non-traditional methods available, as discussed in Rossi and Parker (1993); however, the method that is considered most effective and unbiased if correctly applied is conditional simulations (Rossi, 2000).

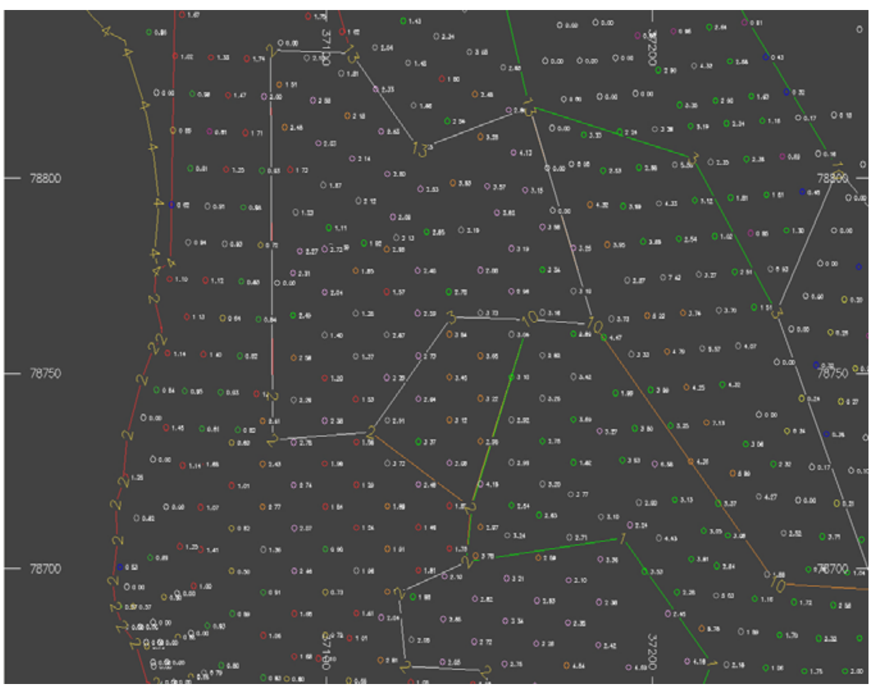


**Figure 2:** Partial view of blast holes and ore/waste selection panels in a Cu mine. The theoretical SMU is 20 x 20 x 15m; blast hole spacing is approximately 8 x8 m.

**Geologic contact dilution**

Contact dilution can be characterized for individual geologic zones or estimation domains by the ratio of contact volume (CV) to the overall extraction volume (V), CV/V, as measured by the volume represented by blocks with geologic contacts to the overall volume of the unit. This unit-less factor provides an indication of how important contact dilution may be. It can be incorporated into the block model using two conceptually similar techniques:

1) The sub-cell (or variable-cell) method, which is applied at the time of building the block model to provide a better definition of the geologic contacts. These sub-cells are then re-blocked to the parent block size of the model to provide the diluted grades and maintaining the proportions of each geologic unit within each block.

2) A direct calculation of the proportion of each unit within each block, storing the percentage of each unit within the block. This is generally more involved, but provides for better resolution and most importantly an option if using mining software without the capability of defining variable block sizes.

An additional approach is to add an empirical factor to the block model by defining a transitional zone in contact areas, and affecting the grades of the blocks within the transition zone with an additional factor. In general, this method has been proven difficult to calibrate and overly subjective, and is not recommended.

**Operational mining dilution**

One possible estimate of this type of dilution for both underground and open pit mines can be obtained by simple geometric calculations. In the case of an open pit mine, dilution and ore loss are incorporated in the resource model considering a specific bench height and assuming an angle of repose for the material. The total metal lost depends on the characteristics of the contact, including the grade of ore lost and the grade of the diluting material. Quantification of dilution for underground deposits from a mine planning perspective can be found in Pakalnis et al. (1995).

Another possible source of dilution and ore loss is blast heave and movement, which shifts the position of the modeled dig-lines. Some research has been done in this area (Yang and Kavetsky, 1990, and Harris, 1997), but to date there are very few practical ways of accurately quantifying and accounting for this source of dilution.

Ore loss and dilution also occurs when the extracted material is transported to the wrong destination: waste sent to the mill, or ore sent to the dumps. Control equipment such as GPS and truck dispatch systems has reduced the likelihood of this error, but in many operations destination control can be a significant problem. Both planned and unplanned ore losses and dilution are accounted for using factors derived from production reconciliation (Mine Call factors), and applied to the resource model globally. Reconciliation in itself can be very misleading, and factoring globally the resource model does not allow for much prediction refinements; therefore, Mine Call factors are mostly useful for material accounting.

A geostatistical conditional simulation study can be used to help predict dilution and ore loss (Guardiano et al, 1995, GeoSystems International, 1999, 2007). The same conditional simulation study can address all three types of dilution, providing the best technology available at this time, but the amount of work involved is significant, with also considerable implementation challenges.

All ore loss and dilution calculations should be incorporated into the resource model itself, which would then truly be a recoverable resource model. The more traditional option of mine planning engineers using subjective factors to account for dilution could thus be avoided.

**GRADE-TONNAGE CURVES**

Each dilution type discussed impacts the expected resource grade-tonnage curve. The impact is generally less significant at a 0 cutoff, compared to higher economic or operational cutoffs. Since the relative impact of dilution is higher for higher cutoffs, this author does not recommend the use of global factors to account for any form of dilution.

Figure 3 shows a series of grade-tonnage (GT) curves from an Au operation in South America. The deposit is a massive, porphyry-type Au-Cu deposit, with a fairly continuous distribution, compared to more typical epithermal- or vein-type Au deposits. Figure 3 shows the GT curves corresponding to a model without any dilution; the theoretical grade-tonnage curve that incorporates the internal dilution according to a Discrete Gaussian Model for volume-variance correction; the grade-tonnage curve that incorporates additionally geologic contact dilution after re-blocking the original sub-celled model; and the final resource model that incorporates both internal and contact dilution.

Some interesting aspects derived from Figure 3 are:

- The GT curves cross over, depending on the grade ranges considered. It is therefore difficult to obtain a generalized conclusion about the consequences of each type of dilution. It will depend on the deposit, grade distribution within the geologic domains considered, and cutoff grades of interest.

- It is therefore inappropriate to apply a single factor to a resource model (even if it is by geologic domain) to account for dilution. In many instances, a factor as applied by mining engineers is considered more a safety factor to account for resource model deficiencies. But the end result is generally a distorted and even less representative grade-tonnage curve.

- The difference between the undiluted model and the final resource model is about 4% relative in tonnage for a 0.3g/t Au cutoff, and about 8% relative for a 0.7g/t Au cutoff. With respect to grade, the relative differences are 9% for the 0.3g/t cutoff and 14% for the higher 0.7g/t cutoff.

- The model that incorporates contact dilution has a more constant difference with the undiluted model across most cutoffs. The relative difference in grade with respect the resource model is about 4% for most cutoffs.

- Note that the Discrete Gaussian model (model with internal dilution) has a higher grade for lower cutoffs compared to the model with contact dilution. That is, even in the case of a massive deposit and fairly homogeneous grade distribution contact dilution can be significant, more so than internal dilution.

The different grade-tonnage curves will result in different economics and cash flow predictions for the operation. A simplistic analysis would be to assume that there is a linear relationship between the economic impact of differences in grades and tonnages above cutoff and the classical revenue function. Although in general this assumption is not valid and is also limited because it assumes that those differences are valid at every location within the deposit, it serves as a basic example to illustrate the potential consequences of ignoring or underestimating dilution.

For a 0.7g/t cutoff grade, the differences between the undiluted and the resource model is about -8% in tonnes and +14% in grade. Thus, the undiluted model overestimates metal content by about 6%. Assume the operation feeds 40,000 tonnes/day (common for massive or porphyry-type deposits) at an average grade of 1.0g/t; the overall gold recovery (mining plus metallurgy) is 80%; and its cash flow results in a net operational gain of US$ 200.00 per ounce of gold sold. Thus, the 6% difference in metal content between the two models is about 62 ounces of gold per day, net of recovery. For the operational margin assumed, it results in a *net* shortfall of US$ 12,400 per day, or US$ 4.5M per year.

This simple calculation is intended as an illustration, and does not take into account differences in the mine plan resulting from the lower metal content, differences in costs due to material movement, plant efficiencies, differences in capital and financial costs, etc.

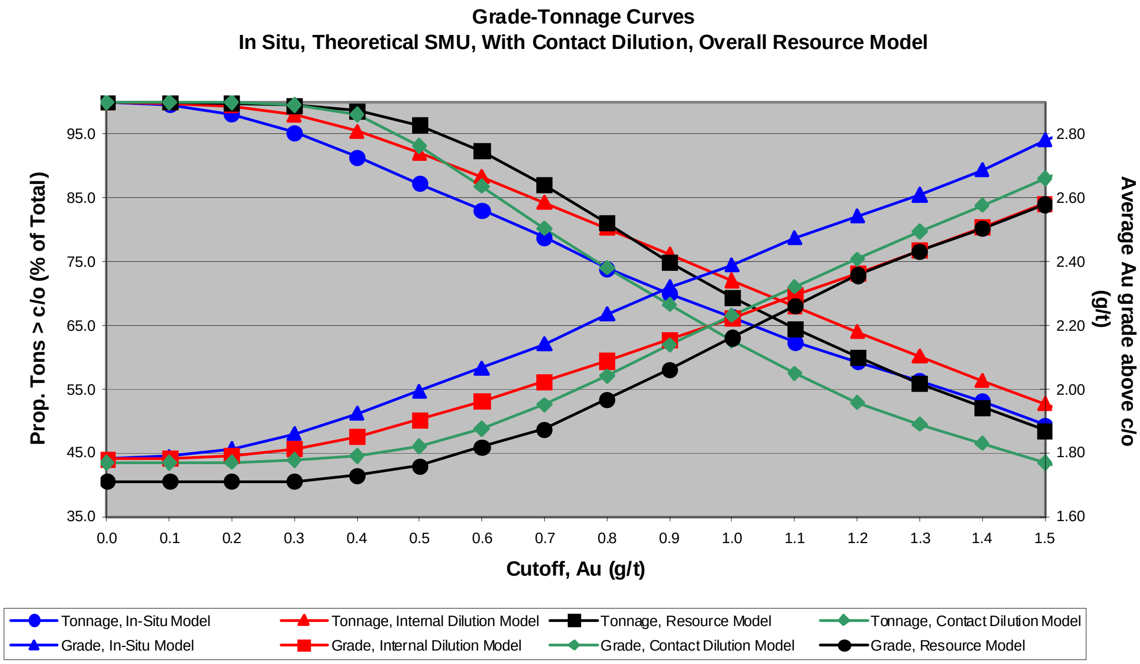


**Figure 3:** Grade-tonnage curves for models that incorporate different amounts of dilution. Cutoffs of interest are 0.3g/t and 0.7g/t.

## CONCLUSIONS

The most important conclusions to be derived from this work are:

1. The resource model should include different types of dilution, expected to be encountered at the time of mining. In this sense, the model should be a recoverable resource model, as opposed to a geologic in situ model.

2. The dilution incorporated into the resource model should be clearly reported, including estimates of the different types of dilution; also, whether allowances have been made for operational dilution.

3. Applying global factors to account for dilution in resource models is not advised because the factors do not discriminate the dilution according to geologic environments, and also are not based on grade ranges or cutoffs.

4. There are methods (classical and non-traditional) that can be used to incorporate internal dilution; likewise, geologic contact dilution can be explicitly accounted for. Operational dilution can also be added, based on geometric calculations, or operational experience derived from, for example, production drilling. In all cases, the relevant methods, estimates, and assumptions should be reported.

5. Production reconciliation and short-term models can be used to evaluate the adequacy of dilution estimates.

6. The economic consequences of expected dilution can be significant and should be accounted for at the time of economic evaluations.

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