THE IMPORTANCE OF DILUTION FACTOR FOR OPEN PIT MINING PROJECTS*

Anoush Ebrahimi, P. Eng., Ph.D.
Principal Consultant at SRK Consulting
22nd Floor, 1066 West Hastings Street,
Vancouver, BC, V6E 3X2, Canada
(Corresponding author: aebrahimi@srk.com)

* *This article is the modified version of the paper that has been submitted to World Mining Congress, Montreal 2013 under the name of "AN ATTEMPT TO STANDARDIZE THE ESTIMATION OF DILUTION FACTOR FOR OPEN PIT MINING PROJECTS".*

ABSTRACT

Mining dilution is one of the most important factors affecting the economy of mining projects. While we do our best to identify and calculate all the other cost items of a project, no matter how small, it is common to make general assumptions about dilution instead of quantifying it. This is usually due to insufficient budget, time for studies and also lack of a well-defined methodology that can be used. Instead of quantifying dilution in mining studies it is common to assume a general dilution such as 5% for massive deposits and 10% for tabular shape deposits. While these figures may be a good starting point in early stages of mining studies, it does not take in to consideration the complexity of the problem. Dilution factor varies within a single mine for different benches and zones. This is due to changes we see in grade distribution and shape of ore body. It also varies based on commodity price. It is necessary to make sure that these variations are taken into account when designing or evaluating a mine.

Dilution increases the operating costs in the mill by increasing the tonnage of material to be milled. In addition to its direct impact on short term income of a mine, dilution causes significant changes in other factors that on the long term reduce the overall value of the project. For example, it prolongs the mine life by reducing mill's effective capacity. It also reduces the feed grade. In most cases, lower feed grade means lower mill recovery. Dilution also increases the cut-off grade which in turn reduces the overall ore utilization of a mine.

In some cases, to take advantage of economies of scale, mining operations tend to plan for higher mining rates. Moving to a larger scale of operation means less selectivity, hence more dilution. This is true for all kind of deposits. High level and uncontrolled dilution may ultimately defeat the purpose of increasing production rates.

If not impossible in theory it is nevertheless extremely difficult and expensive to eliminate dilution in practice. Some amount of dilution is practically unavoidable in most mining operations (Scoble and Moss, 1994). Although completely avoiding dilution may be impossible, we can measure and control it. By better understanding the root causes of the dilution and planning accordingly, it can be controlled and reduced.

Ore losses and dilution are present at all stages of mining and while several models can investigate the influence of dilution it is its quantification that poses the most serious challenge (Pakalnis et al., 1995). This paper introduces a methodology to quantify dilution factor in open pit mines. The proposed approach makes use of general mining software available in most mining companies. Therefore it is amenable to most mining operations and provides a readily available tool for understanding mining dilution for operators and consultants. To illustrate the methodology the author uses an example from a hypothetical mine.

Dilution varies in different mines based on the deposit characteristics, operational aspects and economic cut-off grade. For instance, shape of the deposit, bench height, equipment size, and market conditions will have an impact on the level of dilution in a mine. It is paramount for mining projects to have a better understanding of dilution right from the beginning. In times like today, where mining operations must operate at peak efficiency, it is even more crucial to be able to calculate and have a better grasp of all the parameters influencing the economics of a project including dilution. In order to produce better project evaluations, dilution studies should be an integral part of any project.

KEYWORDS

Open Pit, Dilution, Selectivity, Mining studies, Mine design, and Mine evaluation

INTRODUCTION

Uncertainty and risk are inherent characteristics of mining projects. This is due to uncertainty in market conditions, resource models, and mining factors such as tonnages, grades and dilution. To reduce the risk of investment, mining companies dedicate a large amount of time and money during studies to estimate grades and tonnages as well as measuring the mining conditions and costs. Due to difficulties in measuring some of the important design parameters such as dilution, still there are factors that can be overlooked. With a holistic approach to design a mine that includes quantifying dilution in early stages of work, a good mining study will reduce the risk of investment and operation.

Financial models calculate revenues by using tonnage and grade of ore which is determined during mine design. Tonnage and grade are calculated using a resource model, dilution, and mine recovery factors. Reconciliation between what is actually mined and what was designed has been a concern of mining companies for a long time. The inherent uncertainty in resource modelling, no matter how dense the sampling program, is one of the main sources of discrepancies. Another source of discrepancies is the dilution factor which is applied in reserve calculation. Estimating a reliable dilution factor can reduce the discrepancy between design and operation and consequently can lower the overall risk of mining projects.

Underestimating dilution may pose a significant risk to a project. For example a ten percent error in copper grade may result in a 60% change in the net present value (NPV) of a project (Parker 2012).Inaccurate dilution is a source of error for grade and tonnage sent to the mill.

DEFINITION

Dilution refers to the waste material that is not separated from the ore during the operation and is mined with ore. This waste material is mixed with ore and sent to the processing plant (R.M. Jara 2006, A. Sinclair 2002). Dilution increases tonnage of ore while decreasing its grade. Dilution can be defined as the ratio of the tonnage of waste mined and sent to the mill to the total tonnage of ore and waste combined that are milled. It usually expressed in percent format. This can be expressed as:

$$Dilution = \frac{Waste\ Tonnes}{(Ore\ Tonnes + Waste\ Tonnes)} \times 100 \qquad (1)$$

For example if 10 tonnes of waste rocks (and/or below cut-off grade mineralized rocks) are mined with 90 tonnes of ore and all (100 tonne) being sent to mill, dilution is calculated to be 10.0%. According to this definition X percent of dilution in a mine suggests that X percent of the feed is not economically profitable to be processed. This X amount should not be sent to the crusher and proper actions must be taken in the mine to separate them from the feed as much as possible.

Referring to a mining block, dilution happens in two different areas. Sometimes within a mining block there are waste inclusions or low grade pockets of ore that cannot be separated and are inevitably mined with the mining block. This is called internal dilution. *Internal dilution* is difficult if not impossible to avoid. The amount of internal dilution varies in different types of deposits. Lithology and grade distribution are important factors in internal dilution. *External dilution* also called *contact dilution* refers to the waste outside of the orebody that is mined within the mining block. External dilution varies based on geology, shape of orebody, drilling and blasting techniques, scale of operation and equipment size. This is the type of dilution that can be controlled using proper equipment and mining practices. Figure 1 shows a mining block in a bench of an open pit mine with different types of dilutions.

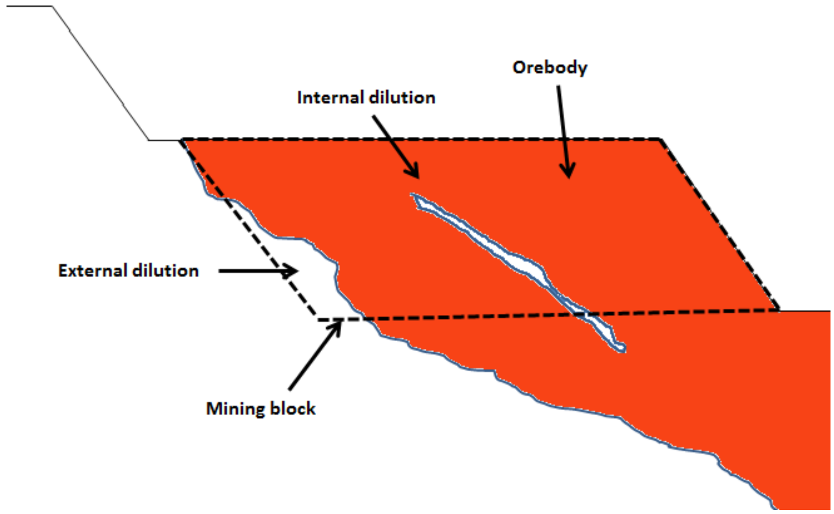

Figure 1A mining block in an open pit and different types of dilution

MINE VALUE DIMINUTIONS DUE TO DILUTION

1. One of the main consequences of dilution is the reduction of mill feed grade. Lower feed grade means less income. For marginal grade ore, dilution may reduce the grades to a degree that it becomes uneconomic to be processed, in other words dilution may turn an ore block to waste. The feed grade after dilution can be calculated using the equation (2).

$$Feed_g = \frac{Ore_g + Waste_g \times Dilution}{1 + Dilution} \qquad (2)$$

Where:

- $Feed_g$ is the Mill feed grade
- Ore_g is the grade of ore in ground
- $Waste_g$ is the grade of waste rock
- $Dilution$ is the dilution (a value between 0 to 1)

The same unit must be used for all grades in this equation.

Table 1 shows the effect of 10% dilution on ore grade for a gold mine for one tonne of ore. Assaying showed that waste rocks have a small amount of gold. The gold grade in waste rocks is 0.05 gram per tonnes. The milling cut-off grade for this operation is calculated to be 0.30g/t. It means that a tonne of ore with 0.3g/t can be sent to the mill and be expected to generate a small amount of profit. Ten percent dilution in this mine will reduce the grade of ore from 0.3g/t to 0.28g/t which is below cut-off grade and will not be able to return a profit. This block will be considered as waste after 10% dilution.

Table 1 – Effect of Dilution on Ore Grade in a Gold Mine

Original Ore (g/t)	Dilution (%)	Waste Au (g/t)	Mill Feed (g/t)
0.50	10%	0.05	0.46
0.40	10%	0.05	0.37
0.30	10%	0.05	0.28
0.20	10%	0.05	0.19

Based on the discussion above, it can be expected that due to higher milling cut-off grade, caused by dilution, the overall reserve of the mine will decrease within a given pit.

2. Due to dilution, energy and materials that are used in the processing plant to treat the waste portion of the feed are wasted. As a result, the mill unit operating cost increases directly by the amount of the dilution factor. For example in a project whose processing cost has been estimated at $18/t,a 10% dilution means $1.80is spent processing waste in the mill for every tonne of feed. For a 30,000 tonne a day operation this amount of dilution means $54,000 is wasted every day.

3. Occupying part of the processing capacity by sending waste rocks to the plant prolongs mine life. As a result it delays cashing the value of mineable resource on time as planned. A longer mine life obviously lowers the net present value (NPV) and internal rate of return (IRR). For example consider a mine that has the potential to generate $20M/year net revenue by milling certain amount of ore for up to 10 years. This is after $100M initial capital investment. Assuming a 10% dilution the mine life increases to 11 years from 10 years. With a simple calculation it is possible to compare mine economics for two cases of mining operation, with dilution and without dilution. For this example there will be 21.0% decrease in NPV (at 10% discount) and an 8.6% decrease in IRR after 10% dilution.

SOURCES OF THE PROBLEM

A combination of physical parameters of orebody, grade distribution, mining conditions and operational issues cause dilution. Factors affecting dilution can be divided as deposit related and mine operation related.

Deposit related factors are inherent features of the resource and comprise lithology, structural geology, the grade distribution, dip, thickness, and general shape of deposit. As we collect more information about the deposit and its features we can expect better performance in all aspects of operation and planning including reducing dilution. One of the causes of reconciliation issues in mines is inadequate information about the resource model.

Factors that are related to mine operation comprise the mining method, mine geometry, mining direction, equipment size, and the skill of operators. These factors can be adjusted and controlled by miners. In order to minimize dilution in the mine design stage we need to understand the features of the resource model and optimize the mining factors to match them.

SOLUTION

Although dilution cannot be avoided, it can be quantified and then controlled. In most cases, quantifying dilution is so challenging that calculating it will become the main part of the solution. In mining operations, to calculate dilution the information obtained from samples on conveyor belts (after crusher) can be compared with resource/reserve models that are developed using drill data. This is the best way of calculating the actual dilution occurring in a mine. The accuracy of the calculation of course depends on the accuracy of sampling and resource modeling.

In the case of mining studies, where no operation data are available, suitable techniques must be used to estimate dilution. Quantifying dilution during the study stage is necessary in order to have a better economic evaluation of the project. In addition to achieving a more accurate economic evaluation, quantifying dilution helps to improve mine design. If the study shows significantly high dilution it is a starting point to mitigate it by changing the mine plans. Dilution can be reduced by adjusting the mine design and operation related factors to best match the deposit related factors. For example by reducing bench height it may be possible to mine more selectively. Obviously for this case we must also realize that reducing the bench height will increase unit production cost due to smaller scale of operation. The bottom line is that to improve the economy of a mine a series of factors such as bench height, selectivity and production rate must be optimized together.

This paper tries to introduce a technique for estimating dilution in open pit mines using computer software as well as proposing a standard procedure for the work.

QUANTIFYING DILUTION IN OPEN PIT MINES

Computer programs have changed the way we design mines. There is a large amount of commercial software readily available in the market. Most can handle the methodology described in this paper. This methodology can be used to quantify dilution in existing operations as well as for studies.

When working on a mining project it is necessary for the designer to keep in mind that every mining project is different. It is difficult if not impossible to formulate a generic solution that can be applied for all mining projects. Every deposit has its unique characteristics and must be dealt with differently. We need to be creative, ingenious and practical in using tools to solve mining problems. The following section explains the steps that can be taken to quantify dilution in open pit mines.

Methodology

1. Understanding the geology is the starting point for quantifying dilution. Create or use a geological block model that contains at least the following information: grade(s), specific gravity and rock types. If the deposit is a poly-metallic deposit then it helps to calculate and include metal equivalent grade. Preferably, block size should be equal to the bench size. If the grades are reported as in-situ grade (inside the 3D geology model, partial models) then the ore body percentage values must be calculated and included as well.
2. Using operating costs, recoveries, and prices, calculate cut-off grade(s). Note that for different prices there will be different cut-off grades. Dilution is a function of metal price. It is time consuming to calculate dilution for each cut-off grade (price) however calculating dilution for at least three prices including the base case price is recommended. If it is possible to develop an equation that relates dilution to metal prices then it is useful to use it instead of a single dilution factor in mine design. In some of the optimization programs there are tools and tricks that can be used to apply variable dilution factors. For base metals, equation (3) can be used to calculate the milling cut-off grade.

$$cut\ off\ grade = \frac{((processing\ operating\ cost + G\&A) \times (1 + dilution))}{(recovery * (metal\ price - selling\ cost) \times 22.046)} \qquad (3)$$

Where:

- G&A is General and Administration cost by $/t milled
- Processing operating cost by $/t milled
- Dilution is by percent
- Recovery is by percent
- Metal price and selling cost are by $/lb
- 22.046 is the conversion factor for $/lb to $/%
- Cut-off grade is in %

3. Create a series of grade shells from the constrained block model using the cut-off grades that are calculated in the previous stage. These grade shells basically characterize 3D shapes of the orebody above cut-off grades and will be used to create sections and plans.

4. Create a set of horizontal sections (plans) of the grade shells, pit walls, and topography. The number of sections depends on the level of study and also the variation in the shape of the orebody. For higher level studies such as feasibility studies it is better to check more points than in the early stages of the project when there is less time and money available. For deposits with complex shapes, a higher number of sections are required compared to simple geology models.
5. Think about the mining operation and estimate the minimum size of blocks (ore/waste) that can be separated from surrounding rocks when blasting. Define the outline of ore blocks for each section (bench). Narrow branches of ore that stretch out of the main orebody zones and cannot be mined efficiently must be separated from the ore outline. Small pieces of waste blocks that are too small to be separated from ore must be accounted for. Identify internal waste (interburden).
6. Due to both blasting and loading issues, part of waste rock outside of the outlined ore blocks will be loaded into trucks and hauled to the mill. Considering the scale of operation, offset the ore outline by expanding it to a reasonable distance – for example a 2m offset for mine operations with 10m bench height. Make sure to trim outlines by topography and pit boundaries if it is applicable.
7. Use outlines created in the previous step to calculate areas of mineable ore and diluted area for every bench. Using the calculated areas we estimate the total ore that can be mined from the bench and also total waste that is mixed with ore and sent to the mill.
8. Dilution is calculated using the information obtained in the previous step and equation (1).If the specific gravity of the rocks is similar for the entire model, using only areas to calculate dilution is enough; otherwise, the specific gravity must be applied to the areas before calculating dilution.
9. To complete the dilution study we need to calculate the grades within different outlines. This is possible using the block model and outlines.
10. If time and budget allow, repeat the previous steps using a different cut-off grade (price). For mining evaluation practices, the price that is used in the financial model must be the basis for cut-off grade calculation and grade shell creation.

Example

As an example, a hypothetical gold deposit (modeled and imitated from a few real deposits) called North Gold Project is used. This example shows how the methodology works. This is a typical large disseminated low grade gold deposit within an assemblage of sedimentary, volcanic and metamorphic host rocks. The deposit is crossed by a few mafic dykes. It is assumed that the specific gravity for ore and waste are similar. The topography is relatively flat and the average is about 550m, and the deposit has been explored down to -50m. Based on a preliminary study, the input parameters introduced in Table 2 have been estimated to initiate mine deign. The input parameters for this illustrative example are for a 40kt/day operation scenario in northern Canada.

Table 2 – The input parameters to initiate mine design

Item	Value	Unit
Mining cost	2.05	$/t mined
Processing cost	15.25	$/t milled
General and Administration cost	2.50	$/t milled
Gold Price*	1,300	$/oz
Processing recovery	95	%
Preliminary dilution	10	%

*after deductions such as selling cost

Using the input parameters in Table 2 a series of milling cut-off grades has been calculated. The cut-off grades vary from 0.43g/t to 0.66g/t. The cut-off grade for the base case gold price ($1,300/oz) is 0.49 gram per tonne. Figure 2 shows the cut-off grade for gold prices ranging from $1,000/oz to $1,500/oz. Cut-off grade decreases as the gold price increases.

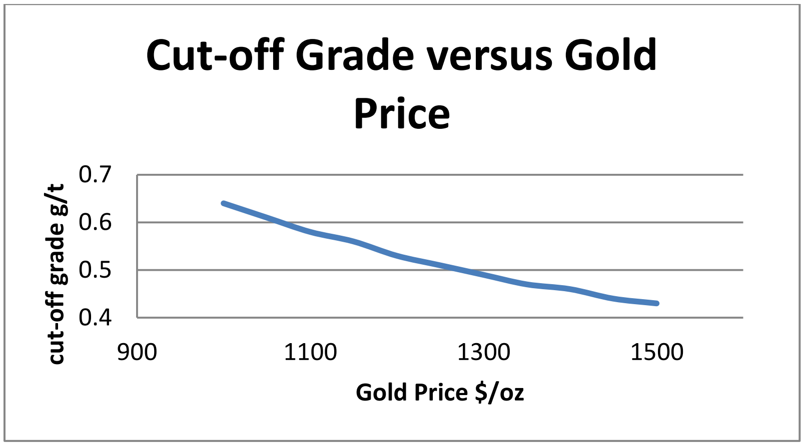

Figure 2 – Different cut-off grades based on different gold prices

Using cut-off grades calculated in the previous stage, six grade shells were created from the block model for gold prices ranging from $1,000/oz to $1,500/oz with $100/oz intervals. The base case price is $1,300/oz gold. Three sections have been produced for the base case grade shell at 50m, 250m and 450m depths. All sections are below topography. At the -250m bench, additional sections were created using all other 5 gold grade shells. In total 8 sections have been studied in this example - 6 of them at the-250m bench.

Figure 2 shows the -250m sections for various prices (cut-off grades).Moving from $1,000/oz section to $1,500/oz section, it can be seen that the smaller pieces of mineralized blocks in the $1,000/oz gold price section fuse and form larger pieces in higher gold price sections. It also can be seen that the internal waste shrinks as the gold price increases. Due to this unification of scattered blocks and shrinking of interburden, it can be expected that dilution reduces for higher prices.

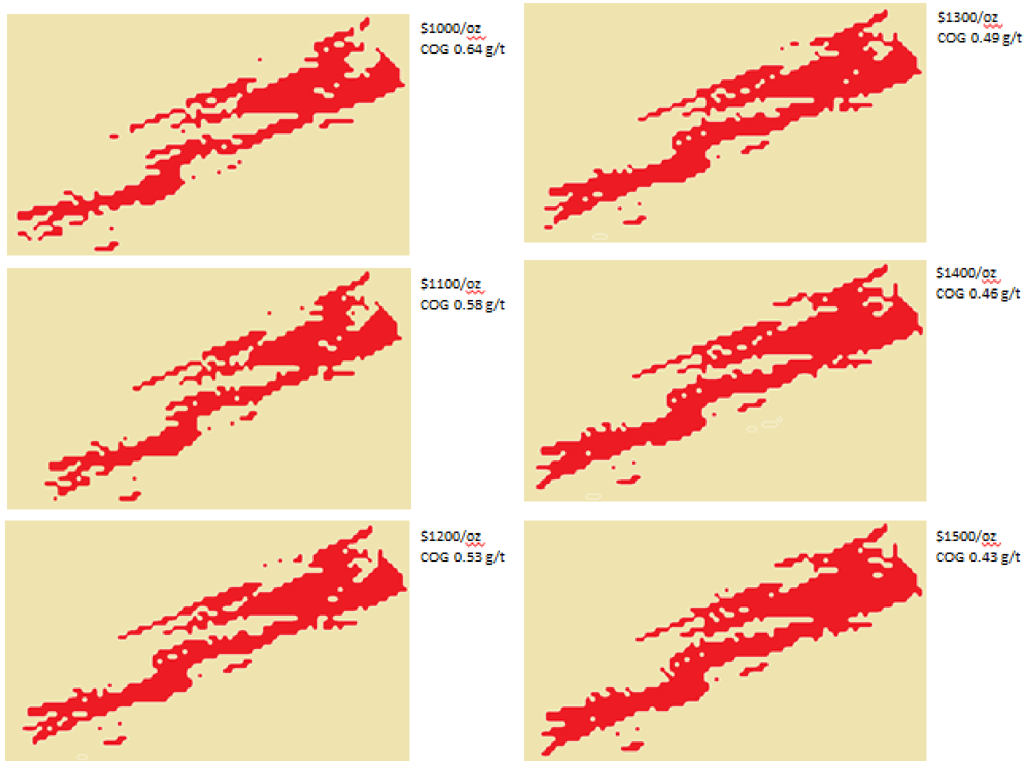

Figure 2 – Effect of gold price on the shape of mineable resource in an open pit bench

In each section outline for mineable ore, interburden and contact waste areas have been developed. Figure 3 shows the -250m section for the base case gold price ($1,300/oz). The small circles in the figure are 10m in diameter. Resources in this section are above 0.49g/t AU which is the cut-off grade for the base case gold price. It is assumed that if the interburden materials are smaller than 10m in size they cannot be separated from the ore and are marked by a separate color. Larger than 10m interburden is considered to be segregated from ore in operation.

Due to operational considerations, a 2m contact waste has been added to the orebody outline. This can be seen as an envelope around the orebody. This amount of waste also has been included into the dilution material. Pieces of ore that are isolated from the main zone and are too small to be recovered are considered as ore loss. This work has been done on all 8 sections. Using these outlines, the areas and grades for each section have been measured and recorded in an Excel file.

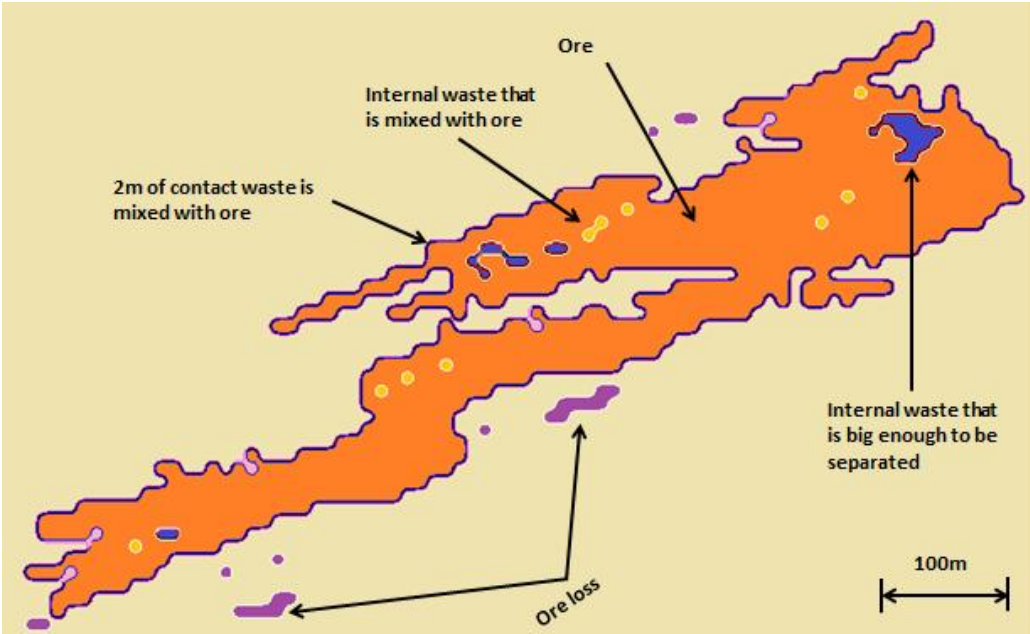

Figure 3 – The -250m plan view of the deposit with ore greater than 0.49g/t (cut-off grade $1,300/oz)

RESULTS

Dilutions for three gold prices ($1,100/oz; $1,300/oz; $1,500/oz) on the-250m bench were calculated. Dilutions are 10.7% for $1,500/oz; 11.6% for $1,300/oz and 14.2% for $1,100/oz. As can be expected for higher gold prices, due to lower cut-off grade, a more unified ore outline is obtained, resulting in less dilution. Figure 4 shows the variation of dilution versus gold price at -250m bench. The figure also shows the equation that relates dilution to the gold price for this bench. This equation can be used to express the variation in dilution instead of using a fixed factor when dealing with price variations.

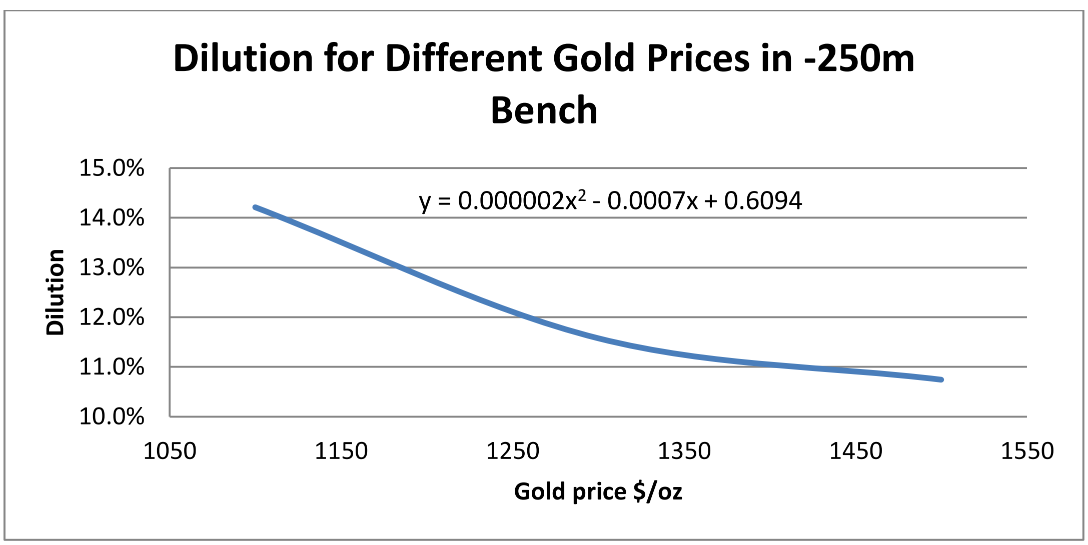

Figure 4 – Dilution for different gold prices at -250m bench

To investigate the variation of dilution in different levels of the deposit, dilution in three different benches (-50m, -250m, -450m) were calculated using $1,300/oz gold price. The dilutions calculated are: 10.2% at 50m, 11.6% at 250m, and 14.8% for 450m depths. Figure 5 shows dilution at different depths of the deposit at a gold price of $1,300/oz. It seems that for this deposit lower dilution occurs at increasing depths. This is beneficial to the project as there will be lower costs and better recoveries in early years of operation.

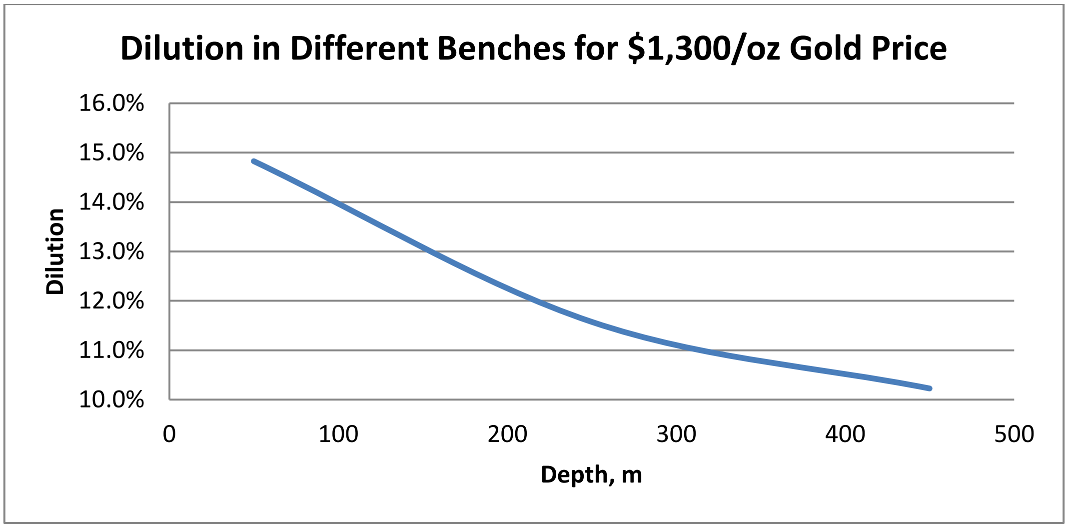

Figure 5 – Dilution at Different Depths for $1,300/oz gold price

DISCUSSION AND RECOMMENDATIONS

NI-43-101 requires the author to provide information about dilution factors that are used in resource and reserve calculation (CSA, 2012). It is generally accepted that dilution is about 5% for base metals such as a copper porphyry deposit and is 10% for precious metals such as a gold deposit. While reviewing mining reports, one may note that dilution factors are sometimes only an assumed number and sometimes an estimated number using different methods which are usually not well explained. Calculating the dilution factor in detail takes time, so for preliminary economic assessment (PEA) studies, where one of the goals is minimizing the cost of the study and completing the work in a short period of time, making an assumption may be reasonable. For higher level studies, such as preliminary feasibility studies (PFS) or feasibility studies (FS), a detailed dilution study should be included. Table3 summarizes the recommended scope for dilution studies that should be included at different levels of mining studies.

Table 3– Recommendation for Minimum Dilution Studies in Mining Projects

Study	Dilution Study	Approximate Hours Required
PEA	Not Required	10 (general investigation)
PFS	Required	40 (minimum three levels in the pit)
FS	Required	80 (minimum every other bench)

The minimum efforts to quantify mining dilution, recommended in this table, are the least amount of time that the author believes to be considered. For complex deposits and for multiple processing methods more time is required.

Given further discussion with experts it may be possible to standardize the calculation and use of dilution factors in mining studies. This can become a recommended task or check list in NI-43-101.

CONCLUSIONS

Using assumed dilution factors may bring unexpected results to mining projects when brought to operation. With all the developments that have occurred in mining software technology today it is time to make sure that every mining study includes enough time and budget to quantify dilution factor. The methodology described in this article provides a methodology that can be utilized in open pit mining studies. It can be modified based on project's specification.

The example in this article also showed that dilution factor in a single mine differs with different depths. It also showed that dilution changes by commodity price. These variations in dilution must be taken into account when designing or evaluating mines.

Author believes that a discussion must be started among experts in mining industry about how to standardize the quantification of dilution factor for mining projects. The results of this discussion can be included in future NI-43-101 amendments.

ACKNOWLEDGMENT

I would like to thank SRK Consulting, for supporting me writing and presenting this paper.

REFERENCES

A. Sinclair, G. Blackwell. (2002), *Applied Mineral Inventory Estimation,* Cambridge University Press

Canadian Securities Administrators (2012), National Instrument 43-101 *Standards of Disclosure for Mineral Projects* (NI 43-101)

Gerald D. Crawford (2004) Pincock Allen and Holt, Pincock perspectives, *Dilution and ore Recovery,* issue NO. 60

Parker H. M. (2012).*Reconciliation principles for the mining industry*.Published by Maney on behalf of the Institute of Materials, Minerals and Metallurgy and the AusIMM, maneypublishing.com

Pakalnis, R., Poulin, R.andHadjieorgiou, J.(1995) .*Quantifying the Cost of Dilution in Underground Mines*, SME Annual Metallurgy and Exploration, Denver.

Scoble, M. J., and A. Moss, (1994).*Dilution in underground bulk mining: implications for production management; in Whateley*, M. K. G., and P. K.