Geochemical Inputs to Risk Based Environmental Baseline Assessment

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Abstract

Mining can have a wide range of impacts on the physical, social and economic environments and it has become an essential requirement for new projects to fully investigate these prior to commencement of operation. Environmental Baseline Assessments (EBAs) characterise the existing environment in and around the mine site. Traditionally, EBAs have not been risk based. However, the concepts involved can be readily placed within a tiered, risk-based framework, which ensures the correct data is gathered. Using examples from Africa, the Middle East and the UK, the concept of a Risk Based Environmental Baseline Assessment (RBEBA) is introduced.

This approach offers the advantage of enabling benchmark environmental information to be gathered within a framework which allows future changes to be scientifically judged. The approach considers the sources of potential contaminants, how the contaminants will move along pathways, and which receptors are at risk. The methodology described is one which can be adopted at all mine sites, in all geologic settings.

Introduction

The extent and content of environmental investigations develop in parallel with the mining feasibility studies as planning for the mine progresses. At different stages of mine planning, the type of environmental work changes, as summarised in Table 1.

Mine feasibility stage	Environmental work
Exploration	Environmental scoping and developing scopes of work Identifying potential fatal flaws Identifying critical paths
Pre-feasibility	Environmental Baseline Assessments (EBAs) Environmental monitoring
Feasibility	Environmental Impact Assessment (EIA) Continue environmental monitoring Permitting and financing
Final design	Environmental management procedures manual
Construction	Environmental compliance monitoring

Table 1. Environmental work carried out during mine development

The primary objective of the environmental studies is to allow the likely impacts from mine development and operations to be assessed. This is achieved by superimposing the emissions and effects expected from the proposed mine on the existing conditions. However, an equally important objective is to provide a benchmark against which any future changes in environmental conditions can be judged, so that allegations of deterioration in environmental conditions, for example, can be scientifically examined rather than subjectively assessed.

Environmental Baseline Assessments (EBAs) characterise the existing environment in and around the mine site. The extent and nature of the studies required varies with the type of mine proposed and the existing environmental conditions. Traditionally, EBAs have not been risk based and have often been aimed at only characterising the natural environment with little regard to the potential contaminants to be used on site or the ore processing technique. However, the concepts involved can be readily placed within a tiered, risk-based framework. In this way, costs associated with long-term environmental compliance can be optimised. This is because the data gathered as part of the Risk Based EBA (RBEBA) will not only be used to characterise the natural environment but will also reflect any existing environmental impacts and enable better justification and assessment of potential future liabilities. This is the approach taken in the USA, UK, other European countries, New Zealand and Australia for management of contaminated land to ensure justifiable actions. This paper introduces and describes the concept of a RBEBA and highlights the importance of the geochemical environment. The concept of Hazard Management is outlined and case studies are presented from distinct geological environments. The principles involved enable a seamless transition between the various environmental elements summarised in Table 1 and can equally be applied to a Risk Based Environmental Impact Assessment (RBEIA).

The selection of environmental quality standards or guidelines is not discussed in great detail because they are often country specific and in some cases, where it can be demonstrated using a risk-based approach, site specific. However, the identification of appropriate standards should be made at the earliest opportunity as these set the regulatory framework within which the RBEBA is to be developed. Also, as standards vary between countries, analytical techniques and laboratories, it is crucial that analytical techniques are chosen carefully, in terms of analytes and detection limits which are appropriate to the regulatory standards.

Risk Based Approach

The concept of Risk Management has become well established in the field of land and groundwater contamination. Risk Management comprises the two processes of Risk Assessment and Risk Control. Once sites are assessed, control measures can be adopted which manage the risks to an acceptable degree. The Risk Assessment process is tiered, the first tier being the Hazard Identification (also know as the Phase 1 Risk Assessment). This stage involves identifying all plausible Source-Pathway-Receptor linkages. For there to be a risk, all three components are required: the Sources represent the hazards (things with the potential to cause harm); the Receptors are the things which can be harmed (flora, fauna, humans, ecosystems, property, water etc); and the Pathways are the means by which the

Sources get to the Receptors. The second tier in the Risk Assessment is Hazard Assessment, where some judgement is made concerning the likely magnitude of the problems. Subsequent tiers involve Risk Estimation, where detailed assessments of the probability of risks is made by considering the mechanics of contaminant migration, uptake, toxicity etc.

The normal approach for a mining RBEBA is the Hazard Identification and Hazard Assessment which involves a thorough understanding of the geologic and mining processes. For a mining project an example of this approach is illustrated in Figure 1.

From Figure 1, the source term comprises the chemicals in the tailings facility. The pathway is the dissolution of those contaminants and migration through the vadose zone to the groundwater. One receptor is the groundwater body itself, which can be contaminated.

Figure 1. Source-Pathway-Receptor Model.

Further receptors are the villagers who drink the well water, the pathway being migration of contaminated groundwater into the well abstraction zone. Other plausible source-pathway-receptor linkages can be developed in a similar way.

Relating the scenario depicted in Figure 1 to a RBEBA involves thorough understanding of the numerous inter-related factors. Without knowledge of the groundwater and well water quality prior to mining, the impact of the mining operation on the groundwater cannot be fully evaluated. Therefore, the approach which should be followed in a RBEBA is to consider the data requirements for the level of risk assessment deemed necessary.

In this sense, geochemical and hydrogeological components within a RBEBA should be aimed at identifying the plausible linkages based on present knowledge and an appreciation of potential future changes. This can then be used to design a sampling and monitoring programme to assess baseline conditions within a risk based framework. For this approach to be successful, a complete understanding of the geology of the mineral deposit and the processes to be used for mineral extraction are required so that all potential risks are identified.

Factors Effecting Geochemistry

The geochemical components of an EBA are primarily related to air, soil and water. The natural processes affecting each are numerous and are related to the site specific environment. This is why baseline studies should include assessments of site geology and mineralisation, geomorphology, soils and land capability, meteorology, water resources, vegetation, wildlife, biology, hydrology, hydrogeology and socio-economic factors. Additionally, particularly within a RBEBA, they should also reflect the techniques to be used for mineral extraction. As all of these factors are too varied to be covered here the influence of geology and mineral processing on the water environment are used as examples of the concepts which underlie a RBEBA. The concepts described can easily be transferred to the assessment of air and soil.

Geology

Groundwater and surface water quality are controlled to a large extent by geology. As a result, an understanding of the geology is not only critical to successful mineral extraction, but also how it could impact the environment. For instance, metal leaching and acidic drainage generation are naturally occurring processes and an RBEBA should consider these. However, the mining of certain orebodies, particularly sulphides, can enhance these natural processes leading to the well documented detrimental issues associated with Acid Rock Drainage (ARD). Consequently, if such a deposit is to be exploited, mineralogical and predictive testwork would be essential to establish natural baseline ARD conditions prior to mining (Bowell *et al*, 2000). Conversely, the RBEBA should also consider the baseline potential for the natural attenuation of acid generation by neutralising mineral assemblages and water chemistry i.e. fate-transport mechanism of the pathway. In order to ensure the potential pathways are intercepted, consideration of the geological structure and the influence on hydrogeological characterisation are needed as this will ensure that monitoring is conducted in the correct position.

Mining and Processing

The geochemical parameters selected for monitoring should reflect the plausible risks. For instance, if a gold orebody were to be processed using cyanide (CN), then CN should be included in monitoring. This will then demonstrate background concentrations enabling potential future risk assessments to be made. As mineral processing requires make-up water, the data gathered as part of the EBA should also include assessments of the quality and availability of such water. In this way, the time spent sampling and analysing is optimised.

In summary, the geochemical components selected for a RBEBA monitoring are chosen within a risk-based framework and reflect the geology of the deposit and the mining and mineral processing processes involved. In order to ensure that potential pathways and receptors are included the position of monitoring sites should also be risk driven. This will enable the mine owner to be fully aware of potential liabilities within a risk-based framework.

Case studies

The application of this methodology is now explored using distinctly different examples that illustrate clearly the influence of geology and mining process on the selection of geochemical parameters. The methodology followed can be applied to any mineral deposit provided the source – pathway – receptor model and the factors of influence are understood.

<u>Sedimentary Phosphate Deposit, Middle East</u>

Marine phosphate deposits cover large areas of central and south Jordan, and north west Saudi Arabia (Smith *et al*; 1996). As many of the deposits are close to the surface they are amenable to mining via blasting and stripping with draglines. Much of the surrounding area is sparsely populated and receives sporadic rainfall. As a result, the local population secures water from a small number of groundwater wells. Consequently, one of the main concerns was the protection and characterisation of the water resource. A summary of some of the plausible pollutant linkages considered is summarised in Table 2.

Source	Pathway	Receptor
Secondary Uranium (U) salts formed through oxidation	Leaching of U and radionuclide daughter products to groundwater following rainfall events.	Groundwater
	Transport of contaminants in groundwater flow	Users of surrounding wells
	Transport of contaminants in groundwater flow	Source of make-up water for mineral processing

Table 2. Examples of plausible pollutant linkages identified at the Sedimentary Phosphate deposit

One particular concern was the occurrence of yellow secondary uranium salts such as metayayamunite and autunite formed through oxidation of U contained in the phosphate minerals (Smith *et al*;1996). These potentially could be leached during periods of rainfall and also concentrated during mining and processing. In order to assess these risks, representative samples of ore from drill core were subjected to leach tests to assess natural leaching characteristics prior to mining. Also, within the wells used by locals, U was monitored in order to establish pre-mining conditions. Because of the presence of U, the well waters were also sampled for radionuclide decay products (^{226}Ra, ^{232}Th, ^{230}Th, ^{228}Th,) which could adversely effect human health if ingested. As a result of these risks identified from the geology and mineralogy the full analytical suite included pH, redox potential (Eh), dissolved oxygen (DO), temperature (T), Electrical Conductivity (EC), Alkalinity, Na, Mg, Cl, F, SO_4, NO_3, NH_3, PO_4, Al, K, Ca, Mn, Fe, Cr, Co, Ni, Ca, Zn, As, Se, Mo, Ag, Cd, Sn, Sb, U, Pb, ^{226}Ra, ^{232}Th, ^{230}Th, and ^{228}Th.

Monitoring was conducted quarterly for twelve months. The study indicated that prior to mining the concentration levels of most constituents, including the radionuclides, were below the host countries' standard values. A small number of determinands however exceeded the environmental standards, particularly those constituents effected by evapoconcentration within the arid environment. Therefore, baseline conditions prior to mining were on some occasions and in some areas in exceedance of standard values. Consequently, the assessment of the impact of any future mining activity would need to consider these naturally elevated levels.

<u>Sulfide-Gold Deposit, Africa</u>

In sulfide-gold replacement deposits, natural sulphide oxidation occurs as a result of seasonal wetting and drying. This can lead to the formation of secondary salts such as jarosite which act as a store for SO_4, Fe and acidity following pyrite oxidation (Bowell *et al*, 2000):

$$3FeS_2 + \frac{9}{2}O_2 + \frac{15}{2}H_2O + K^+ \leftrightarrow KFe^{3+}{}_3(SO_4)_2.(OH)_6 + 4SO_4{}^{2-} + 9H^+$$

As such secondary salts are highly soluble, they can be mobilised during periods of rainfall, potentially releasing SO_4, Fe and proton acidity (H^+) to the water environment:

$$KFe^{3+}{}_3(SO_4)_2.(OH)_6 + \frac{3}{2}O_2 \leftrightarrow 3FeO.OH + K^+ + 2SO_4{}^{2-} + 3H^+ + \frac{3}{2}H_2O$$

Consequently, the potential for natural and mining induced ARD generation was considered significant. Therefore, field mapping and sampling was undertaken with the samples collected being used for predictive geochemical testwork in order to establish baseline conditions. Leach tests confirmed that many trace constituents including Cu, Zn, Fe, Mn and Sb were mobile. This would be in addition to those elements mobilised under natural conditions within the lateritic terrain. A further complication was that there were numerous artisan miners and associated workings, all using mercury as amalgam. In addition to these geologic and artisan influences, the method chosen to process the ore involves cyanide. All of these factors were considered potential sources.

Therefore, potential pollutant pathways and receptors were identified, some of which are and summarised in Table 3. In response, a RBEBA monitoring programme was developed which included measurement of pH, Eh, DO, EC, T, Alkalinity, Acidity, Total Dissolved solids (TDS), Total Suspended Solids (TSS), Cl, SO_4, Ca, F, Mg, Na, K, No, PO_4, Al, Cu, Ni, Fe, Zn, As, Cd, Cr, Pb, Mn, Mo, Sb, V, Ag, Sn, Se, Hg, and speciated CN (measured in-situ). In order to ensure adequate assessment of baseline conditions, these parameters were measured at dedicated sediment, groundwater and surface water monitoring sites, at domestic well supplies used by local villagers and around artisan workings.

Source	Pathway	Receptor/s
Acid Generating Mineralogy	Flushing of acid generating secondary salts during rainfall through vadose zone	Surface water
		Groundwater
		Sediment
	Transport of contaminants in groundwater flow	Domestic well supplies used by villagers
		Potential supply of make-up water
Use of CN during mineral processing	Spillage or leakage of CN and transport through vadose zone	Surface water
		Groundwater
	Transport of contaminants in groundwater flow	Domestic well supplies used by villagers
		Potential supply of make-up water
Mercury used by artisan workers	Spillage, leakage and leaching of contaminants through vadose zone	Surface water
		Groundwater
	Transport of contaminants in groundwater flow	Domestic well supplies used by villagers
		Potential supply of make-up water

Table 3. Examples of plausible pollutant linkages identified at the gold deposit

Quarterly monitoring was undertaken for 2 years in order to characterise baseline conditions. Following data collation and interpretation, it was recommended to the regulators that until all artisan workers were no longer on site and that their workings were removed, the complete application of regulatory limits be suspended. Also, it was apparent from the data that on a number of occasions, and at a number of monitoring sites, the pre-mining baseline conditions exceeded some of the regulatory standards. Consequently, within a risk-based approach, site specific regulatory limits were proposed based on the available data gathered. This is currently being reviewed by the regulators.

Limestone Quarry, UK

Following identification of additional resources below the water table, a limestone quarry operator working in the Carboniferous Limestone sought to monitor the potential effect of dewatering on the local surroundings. In accordance with planning conditions, a 5 year Scheme of Working was developed with the regulators that was aimed at characterising baseline hydrogeological and geochemical conditions prior to dewatering.

Within the RBEBA approach adopted, two potential Receptors were considered – an abstraction borehole down hydraulic gradient and a wetland classified as a Site of Scientific Special Interest (SSSI), located slightly upgradient of the quarry. The perceived risks were that dewatering would lower the water table in the wetland and limit the capacity of the abstraction borehole.

In order to establish baseline conditions within a risk based framework, a monitoring network of boreholes and piezometers was installed in an around the quarry. A study of the geology indicated the underlying limestone to be overlain by superficial deposits, so borehole and piezometer locations were chosen to ensure that water levels in the limestone and superficial deposits were monitored in order to fully understand the hydrogeology and the potential groundwater pathways.

Source	Pathway	Receptor
Dewatering of quarry sump leading to a lowering in groundwater level	Groundwater migration	Flora within SSSI
		Abstraction borehole

Table 4. Example of some of the plausible linkages identified at the limestone quarry

The geochemical component of monitoring was limited as the principle risk identified was to the groundwater level. However, it was considered that if quarry dewatering lowered the water table then the nutrient status within the SSSI might be affected. Also, based on the geological understanding, it was known that the lower limestone layers were dolomitised and that the waters interacting with this limestone could be differentiated on the basis of mineralisation and Mg/Ca ratio. Therefore, hydrochemical indicators were considered potentially useful in assisting the identification of potential pathways and assessing future impacts. Therefore, their inclusion within the RBEBA was warranted, and the suite of determinands chosen for monitoring was pH, Eh, T, DO, Na, K, Cr, Ca, Fe, Mn, Alkalinity, SO_4, NO_2, NO_3, TDS, TOC, NH_4 and PO_4.

Monitoring was initiated in 1996 and is currently on going under regular review. Chemical monitoring is conducted quarterly and water levels continually automatically logged using down-hole data loggers. The data are stored within a database enabling rapid data interpretation. Baseline conditions were well established prior to the commencement of quarry dewatering in mid 1999. This has enabled the impact of quarry dewatering to be assessed against natural groundwater seasonal variations, allowing the quarry operator and the regulators to fully assess the actual risks and apportion liability.

Summary

Traditionally, EBAs have not been risk based. However, the concepts involved can readily be placed within a risk-based framework. Risk Based Environmental Baseline Assessments (RBEBAs) offer the advantage of enabling benchmark environmental information to be gathered within a framework which allows future changes to be scientifically judged. The approach considers the sources of potential contaminants, how the contaminants will move along pathways, and what processes will naturally attenuate movement and what receptors are at risk. The methodology described is one which can be adopted at all mine sites, in all geologic settings.

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