Forensic analysis of mine water impacts – a mass balance approach

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Abstract

It is common to find heavy metals in the sediments downstream of mine sites, which can raise questions about the source of the metals and the environmental performance of the mining operation. It is a complex problem to determine the contribution of sediment and heavy metals released from natural erosion processes compared to the mining activities. The study approach described herein uses a mass balance approach that has been successfully applied at a number of sites to address this issue. This approach provides a simple but defendable basis on which to determine the relative contribution from various sources.

Keywords: contamination, water balance model, load assessment, heavy metals, mining, erosion

Introduction

Mine operations are often the subject of community concerns in relation to downstream potential contamination. When heavy metals are found in the sediments downstream of mine sites, questions are often raised about the source of the metals and the environmental performance of the mining operation. Heavy metals can be deposited in these sediments either through natural erosion processes operating over geological timescales, or through enhanced release from mining activity. It is important to determine the contribution from these two mechanisms in order to understand the cause of the problem and develop management strategies.

An investigation methodology centered on a mass balance approach has been developed to investigate circumstances such as this, which has proven to be effective at a number of sites.

The approach focuses on several key areas: determining the distribution of heavy metals in the environment (laterally and vertically); quantifying the mass of heavy metals in the area of concern (e.g. floodplain sediments); modelling the releases from the mine site (using a water balance model) and assessing the movement of heavy metals through river systems within the study area. A hypothetical example is presented in this paper to illustrate the study approach.

Investigation Approach

An investigation approach that can be used to assess the relative contribution of mining activities compared to other erosion processes is as follows:

- Assess the distribution of heavy metals in the environment, both in the source area (e.g. upper catchment areas hosting the ore body) and receiving environment (e.g. foothills and floodplain, being the area of concern)

- Calculate the amount of heavy metals in the floodplain based on a mass analysis using field sampling data
- Develop a water balance model of the mine site to estimate the amount of heavy metals that could have been released to the environment from the mine over its operating life
- Analyse the available long term stream monitoring data to estimate the load of heavy metals carried through the river system over the period the mine was in operation
- Compare the mass of heavy metals released from the mine, carried in the river systems and present in the floodplain sediments to assess the relative contribution from the mine.

Environmental Setting

A hypothetical example is presented in this paper to illustrate the study approach. The example developed involves the circumstance where elevated concentrations of a heavy metal such as cadmium are identified in floodplain sediments below an active mining area. The method is applicable to other heavy metals but for the purposes of this paper and the example, discussion will hereafter refer to cadmium only. Floodplains are usually used extensively for agriculture, and can have extensive networks of irrigation infrastructure developed to redirect water from the major waterways on the floodplain to cropped areas. For this example, it is assumed that the concentrations of cadmium in the near surface floodplain sediments are elevated and a cause of concern.

The study area would therefore include the mine site, the surrounding upper catchment area hosting the ore body, and the floodplain downstream of the mine site. If the mine site is located in the centre of a watershed draining a mountainous portion of the study area (say as in Figure 1), it is likely that a large portion of the watershed would be within a "Mineralised Zone", which is a term used to describe locations where the outcropping rock has naturally occurring enrichment of metals.

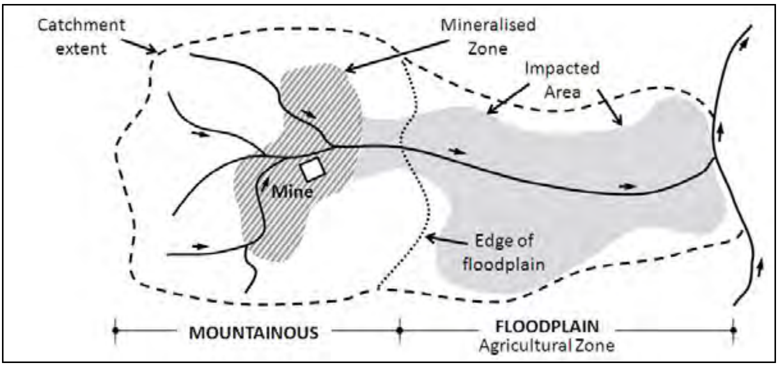

Figure 1 *Schematic diagram of an example study area.*

It is assumed for the example that the heavy metal (cadmium in this instance) occurs with the target metal being mined, so would be abundant in the ore and also present in the mine wastes (waste rock and tailings).

Understanding Potential Causes of Metal Accumulation in Floodplain Sediments

In the example contemplated in this paper, the only mechanism through which mining could have released cadmium is through releases of mineralised sediment via the surface water system, as it is not contained in any chemicals used for processing or mining.

An alternative explanation for high cadmium concentrations downstream is that the surrounding mountains (containing the ore body being mined) have been eroding over geological time (millions of years), providing the source of the sediments now present in the floodplain. In this scenario, the elevated concentration of cadmium would have been present prior to mining, and indeed prior to agricultural development of the area.

Several other mechanisms may also exist, such as use of fertilisers containing heavy metal traces, and other development in the catchment such as land clearing for agriculture and infrastructure (roads, irrigation channels etc).

The investigation approach therefore needs to discriminate between the heavy metals released by mining activities compared to natural erosion processes and other activities in the catchment.

Distribution of Heavy Metals in the Environment

The investigation approach and the amount of data required to support it can be adjusted to suit the seriousness of the circumstances and the level of certainty required for the findings.

For a scenario such as the one discussed, and if a robust set of findings is required, the data collection effort can be substantial. For example, several thousand floodplain sediment samples and a similar number of upland sediment and rock chip samples may be warranted to determine the spatial distribution of heavy metals in the environment. More specifically, the sampling program would typically involve:

- depth profiles in the floodplain sediments, extending through the full profile of alluvial sediments
- grid based surface samples of floodplain sediments with a grid spacing varying between 10m and 500m, concentrated over areas with the greatest concentration of cadmium
- grid based samples in the mountainous area containing the Mineralised Zone
- stream sediment samples from streams above, within and below the Mineralised Zone.

In circumstances where it is available, long term monitoring data from routine monitoring carried out by mine, including stream sediment sampling at multiple locations over a period of years, along with water quality data from nearby creeks would also be utilised. A large dataset such as this can confirm that heavy metals are abundant in the Mineralised Zone. However while it can confirm that the Mineralised Zone is the obvious source of cadmium, the dataset alone does not explain the mechanism would cause it to accumulate in the floodplain sediments (i.e. mining, natural erosion, other development).

The data from the floodplain area can assist in understanding the mechanism for metals presence. For example, it is important to understand the spatial variability of cadmium concentrations in soil in localised areas or even within particular fields, and whether the locations with the highest concentrations are generally closer to the creeks. The floodplain data set can also confirm whether cadmium is present at high concentrations throughout the whole vertical profile of alluvial sediments (and therefore provide insight to the time scale for deposition). Water quality results can indicate the form in which cadmium is present, for example whether alkaline conditions prevail in the study area which would suggest that metals would not be present in dissolved form, and would be transported attached to soil particles.

Floodplain Mass Analysis

The mass of cadmium in the near surface zone of the floodplain can be calculated by kriging the sampling results and assigning a bulk density to the soils. Various kriging methods and bulk density values can be trialed in a sensitivity analysis. The mass analysis can indicate the mass of cadmium present in the cultivation zone within the study area (for example in tonnes per $km^{2)}$.

Mine Water Balance

A water balance model of the mine site can then be developed to estimate the amount of cadmium that has been released to the environment from the mine site over its operating life. The water balance model can be developed to represent the flows from the mine site as the mine developed. The key inputs to the model are described below:

Catchment areas – these may be determined through review of historical aerial photography, old site survey, mine plans and site personnel recollections. Pond development and operating methods – data can be obtained on the commissioning date, location, capacity and operational regime of sediment ponds in order to model the performance of the ponds over time. Sediment mobilisation – the suspended sediment load can be determined by separating baseflow load (flow x baseflow Total Suspended Solids (TSS) concentration) and stormflow load (flow x stormflow TSS concentration) to produce a total suspended load. Concentration distributions can be determined from monitoring data within the mine, and from review of water quality data from other mines in similar climatic settings. Particle size distribution (PSD) of suspended sediment – it is important to understand the PSD of sediment mobilised in the water column in order to assess its ability to be captured in sediment ponds. PSDs from the source areas can be analysed, as can soil samples from the sediment ponds within the mine site.

Distribution of heavy metals across particle size fractions – the concentration of cadmium in various particle size fractions can be determined by hydraulically separating particle size fractions and analysing each fraction (say <11 µm, 11-15 μm, 15-21 μm, 21-29 μm, 29-42 μm, 42-75 μm, >75 μm). For example if the lowest concentration of cadmium is consistently in the <11 μm fraction, and highest concentration in the 11-15 μm fraction, this provides further insight to the transport and deposition mechanism. Source concentration – concentrations of cadmium in the source areas can be determined by field sampling, as well as reviews of any database of rock geochemistry data which are often held by mine operators. This includes routine grade control of high and low grade ores, exploration sampling and ore reserve sampling and estimation. Pond performance – pond performance needs to be represented in the water balance model by modelling retention time, settling velocity and making allowances for pond inefficiencies and short circuiting. For example from the above, particle size fractions less than 11 μm could be conservatively assumed to not settle, which would not significantly affect the results because cadmium is typically negligible in this size fraction.

The model can then be used to simulate the performance of the mine water management system over the life of the mine using the climatic record observed over that period. The model results would for example estimate the mass (in tonnes) of cadmium which would have been released over the life of mine.

Stream Load Assessment

Typically, virtually all cadmium present in the floodplain would have been transported by streams. A model can be developed that uses the available long term stream monitoring data (desirably covering a period of several years or more) to estimate the load of cadmium carried through the waterways over the operational life of the mine. In the situation described, a stream flow model would be developed and calibrated where possible to gauging data from a nearby location. Various methods can be used to link the observed concentrations (typically based on monthly sampling) to flow events in order to estimate loads. Stormflow and baseflow concentrations need to be identified in the dataset and distributions fitted to the concentration profiles applicable to each flow regime.

The developed stream load assessment model can then identify how the load of cadmium changes through the river system and compare the load upstream and downstream of the mine site. The stream load assessment model can then be used to predict the mass of cadmium transported from the catchment in the creeks over the period that mining has occurred.

Relative Contribution

The output of the modelling effort is an estimate of the amount of cadmium released into the environment from the mine, the amount transported through the river system, and the mass of cadmium present in the floodplain sediments, all of which can then be compared. In a number of cases where this methodology has been used, the mass of heavy metals released from mining operations in typically orders of magnitude less than the mass present in the receiving environment. The results generated through this type of assessment can provide compelling evidence as to whether the elevated cadmium concentrations in the floodplain sediments would have been present without any mining development in the catchment.

Conclusions

This paper describes a relatively simple approach to assessing a difficult problem – assessing the relative contribution of sediment export from mining and other development activities compared to natural erosion processes. It also highlights the importance of collecting baseline environmental data prior to mining operations. Although this is a simple approach, application can require rigour both in the setting of baseline environmental monitoring and in the modelling and analyses associated with the methodology. Applications to date have justified the methodology and demonstrated the value in collecting extensive baseline data.

Disclaimer