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Ecological risk assessment of acid rock drainage under uncertainty: The fugacity approach

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HIGHLIGHTS

- A methodology for ARD risk assessment during a pre-mining stage was developed.
- A model that accounts uncertainties was developed to simulate metals at mine sites.
- Uncertainty in effect characterization was estimated based on probability bounds.
- Risk characterization methods using p-boxes was presented.
- The methodology demonstrated at a mine site where data are limited.

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ABSTRACT

Acid rock drainage (ARD) is a major environmental problem that poses serious ecological risks during and after mining activities. To minimize the ecological risks and to lower remediation costs in the mining industry, ecological risk assessment is highly important in various phases of mining. In this study, a methodology for ecological risk assessment using probability bounds is presented. The methodology is demonstrated with a case study at a mine site. A fugacity-based model was employed to conduct the exposure characterization. Median lethal concentrations from toxicity studies were used to derive predicted no-effect concentrations (PNEC) and to characterize the effect of copper and zinc on the receptors. Probabilistic risk-quotient and overlaps between distributions of exposure and effect were employed to characterize risk. Data and parameter uncertainties in exposure, effect, and risk characterizations were propagated and quantified using a probability bounds approach. The exposure modeling results showed that the predicted concentrations of copper and zinc slightly exceeded the observed concentrations. The results of the effect characterization showed that the derived effect concentrations for copper and zinc are acceptable compared with guideline values. The risk characterization result indicated that a high probability of ecological risk may exist due to metals that are transported into a nearby lake. Moreover, the results showed that the methodology handles uncertainties due to imprecision and randomness in an integrated manner.

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1. Introduction

Acid rock drainage (ARD) is a major environmental problem in Canada and other parts of the world (Gray, 1997; Verburg et al., 2009). ARD is generated when sulfide-bearing material reacts with oxygen and water during and after mining activities (Morin and Hutt, 2001; Price, 2009). This reaction changes relatively insoluble chemical species within sulfide minerals into more easily dissolved free ionic species (e.g., Cu, As and Zn) or secondary minerals (e.g., sulfates, carbonates and hydroxides). Moreover, the oxidation of some sulfide minerals produces acidity that may lower the drainage pH. A lower drainage pH can increase the rate of sulfide oxidation, the solubility of many products of sulfide oxidation and the rate of weathering for other minerals.

ARD poses environmental risks such as elimination of biological species, significant reduction in ecological stability, and bioaccumulation of metals in the flora and fauna (Gray, 1997, 1998). In Canada, the remediation costs of these damages were estimated 7 billion dollars in 1995 (Feasby and Tremblay, 1995). To minimize environmental risks and to lower remediation costs, ecological risk assessments are highly important in various phases of mining. Ecological risk assessments evaluate the likelihood that adverse ecological effects may occur or are occurring as a result of exposure to one or more contaminants (US EPA, 1992).

Guidelines for ARD management have been developed in Canada and internationally (e.g., Price and Errington, 1998 and Verburg et al., 2009). Risk assessment in the guidelines is conducted following characterization, prediction and mitigation steps. In the characterization step, sources, pathways, and receptors are characterized. The drainage chemistry of ARD is predicted using laboratory or modeling techniques in the prediction step. The predicted chemistry for each contaminant is compared with regulatory values to estimate risk and mitigation measures are implemented in the mitigation step. The guidelines recommend uncertainty analysis at pre-mining, operational, and post-mining phases, but a methodology has not been presented. This paper presents a new methodology to conduct risk assessment under uncertainty during a pre-mining phase, where hydrogeological information that characterizes a mine site is limited.

The remainder of this paper is organized as follows: Sections 2 and 3 present an uncertainty analysis and ecological risk analysis, respectively. Section 4 presents and discusses the results of this study. Finally, Section 5 summarizes and concludes the findings of this study.

2. Uncertainty analysis

Data and parameter uncertainties may originate from randomness due to natural variability and from imprecision due to systematic measurement errors or expert opinions (Walker et al., 2003; Baudrit et al., 2006). Various methods exist to quantify parameters and input data uncertainties. These approaches include Monte Carlo analysis, probability bounds (p-boxes), random set theory, and possibilistic analysis (Ayyub and Klir, 2010). In cases where data and parameters are represented by random and imprecise variables, separate methods must be used to propagate these uncertainties (Hoffman and Hammonds, 1994; Ferson and Ginzburg, 1996). In this study, the probability bounds approach is used to quantify and propagate data and parameter uncertainties.

A p-box is an approach used to represent imprecise probability. Imprecise probability is a generalization of probability when one is not able to define a precise probability function P for an event x (Walley, 1991). An imprecise probability function $P(x)$ is characterized by its lower probability $\underline{P}(x)$ and upper probability $\overline{P}(x)$. Lower probability and upper probability functions map an event $x \in X$ into interval values between zero and one (Ferson et al., 2003). The lower and upper bounds of a p-box associated with a random variable X give the possible range of probabilities that X exceeds any particular value. These bounds are close together when the imprecision is small but may be far apart when it is large. In this study, the concept of a p-box was implemented in the risk assessment using Risk Cal 4.0 software (Ferson, 2000).

3. Ecological risk analysis

Ecological risk assessments evaluate the likelihood that adverse ecological effects may occur or are occurring as a result of exposure to one or more stressors (US EPA, 1992). An assessment comprises problem formulation, exposure characterization, effect characterization, and risk characterization (USEPA, 1998).

3.1. Problem formulation

Problem formulation defines assessment endpoints, a conceptual model, and an analysis plan. The assessment endpoints express the environmental value that is to be protected. They are defined based on the mine's management goals in this study, which are to protect at least 90% of the fish species 90% of the time from stressor exposure in a nearby lake. The conceptual model for the risk assessment consists of the source of the stressors, media, exposure pathways, and receptors. The stressors are elevated copper and zinc released from waste rock. The media that could be contaminated are groundwater and surface water. The potential exposure pathways are ingestion, contact, and consumption of lower-trophic-level organisms. The receptors are fish species that inhabit the lake, which are *Oncorhynchus kisutch, Cottus asper, Gasterosteus aculeatus, Oncorhynchus clarki* and *Salvelinus malma*. In the analysis plan, a risk hypothesis of the study is evaluated that was copper and zinc may cause a permanent reduction in the fish species in the lake.