The Application of Quantitative Risk Assessment to Assessing the Impact of Tailings Management Facilities on Groundwater Resources

Gareth Digges La Touche[1], Sofia Nazaruk[2], Thomas Booth[2], Tom Demmer[2], Alireza Nickman[2], Jessica Cammack[2]

[1]*WSP UK Ltd, 7 Lochside View, Edinburgh, EH12 9DH, United Kingdom, garethdiggeslatouche@wsp.com, ORCID 0000-0002-4889-1581*

[2]*WSP UK Ltd, The Mailbox, Wharfside Street, Birmingham, B1 1RQ, United Kingdom*

Abstract

Tailings Management Facilities may pose a risk to water resources. This paper discusses the use of probabilistic simulation within quantitative analytical risk assessment models, especially in scenarios where limited data may undermine confidence in the predictive outcomes.

The application of probabilistic modelling is demonstrated through case studies that evaluate closure and remediation strategies for a tailings management facility, as well as quantifying uncertainty. The impact of different liner and cover systems and the importance of considering facility design holistically is considered, recognising that factors such as landform and cover design are as integral to mitigating risk as liner design.

Keywords: Tailings, risk, closure, water resources, water quality

Introduction

Tailings Management Facilities (TMF), also known as Tailings Storage Facilities (TSF), are engineered structures used for the containment of residues (tailings) from mineral processing. Tailings are often deposited as a slurry, though in recent years as the result of some well publicised facility failures (e.g. Samarco in 2015 and Brumadinho in 2019, both in Brazil (Sliva Rotta *et al*., 2020)) there has been a shift towards the use of filtered tailings (also known as "dry" stack facilities).

Whilst termed a "dry" stack facility, it should be noted that filtered tailings are not dry but are tailings that have been dewatered, often by filter press. Filtered tailings should be compacted after placement to reduce the liquefaction risks and have a water content close to (or drier than) the Standard Proctor Optimum water content (Ulrich (2019)). As such a filtered tailings stack can readily have a water content of 15% (defined as geotechnical moisture content, i.e. mass of water / mass of solids) or more (Crystal *et al*., 2018). The moisture content of filtered tailings can both increase or decrease depending on the environmental setting and facility design.

Historically tailings have been deposited directly on natural ground, contained behind a dam or embankment structure though in recent years, facilities are increasingly engineered with low permeability liners based on an assessment of risk to water resources. For example, the European Directive 2006/22/EC (European Union, 2006) on mine water requires the demonstration of no significant risk of polluting soil, groundwater or surface water as the result of operation of a mine waste facility. This risk assessment may comprise a qualitative assessment of risk based on analogue facilities or more typically an assessment based on the results of a numerical or analytical model of groundwater flow and contaminant transport.

The nature of the hazard, i.e. the concentrations of contaminants in the tailings and resultant leachate arising from percolation of infiltration through the waste mass or in arid settings the drain down of entrained pore water may be determined from geochemical characterisation and modelling to predict leachate quality. Such processes are industry standard (e.g. European Commission 2018) and the Global Acid Rock Drainage (GARD) Guide (International Network for Acid Prevention 2014) outlines a process for predictive modelling as summarised in Fig. 1.

The common approach to environmental risk assessment is to consider the source, pathway and receptor linkages, with the source being, in this instance, a tailings facility and the pathway and receptor both being groundwater, as in the case described in this paper. The assessment methodology should include a robust model that adequately represents the physical system based on the available data, that enables a prediction of water quality and thus risk at the identified receptors. Ideally such a risk assessment should consider both operational and closure phases of the mine operation, taking into consideration for example the evolution of engineering controls over time and in particular the degradation of engineered components such as liners or cover systems.

The use of probabilistic (stochastic) calculation approaches using the Monte Carlo simulation method in analytical contaminant transport models to understand the interaction of a TMF with the groundwater environment provides a powerful tool for the assessment of risk and the likelihood of that risk being realised. This can be implemented

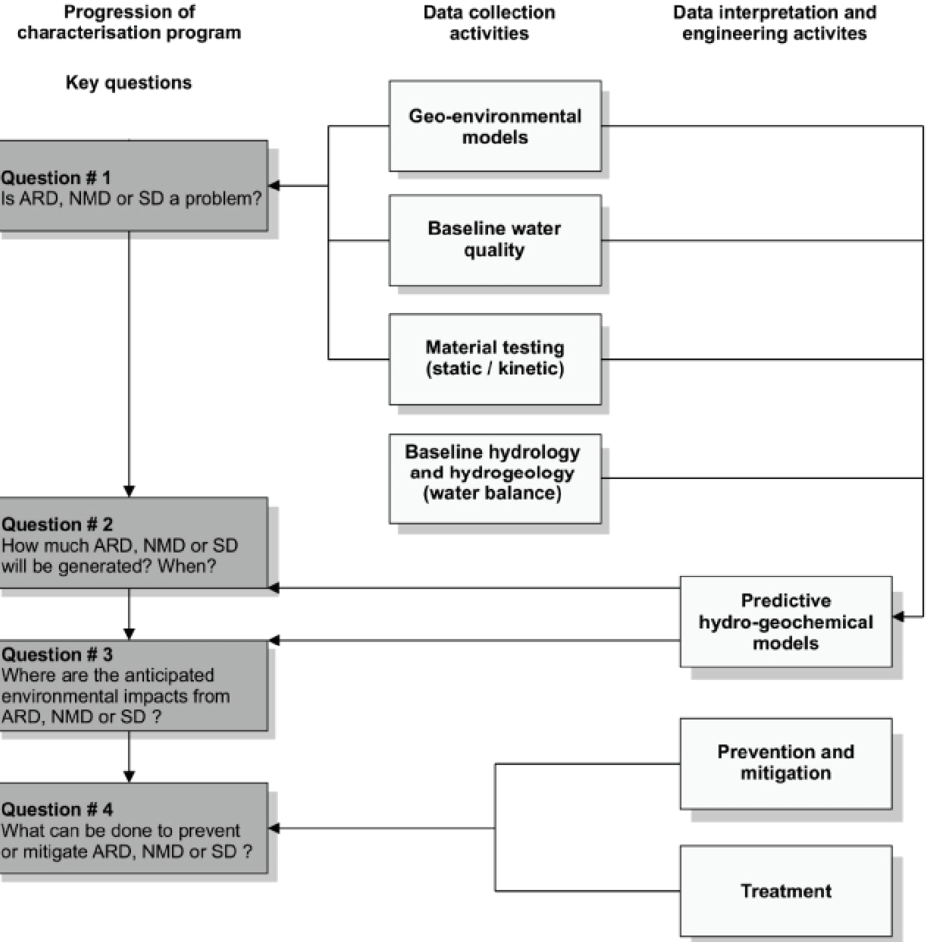

Figure 1 Characterisation process road map (after INAP (2014). ARD – acid rock drainage; NMD – neutral mine drainage; SD – saline drainage.

in both dynamic, i.e. time variant, and steady state models. Both approaches are illustrated in this paper.

Risk assessment and probabilistic models

Probabilistic modelling is employed to manage the inherent uncertainty in most of the input parameters needed for groundwater and impact or risk assessments. This approach allows for the prediction of potential outcomes and their likelihood, providing insight into the risk posed to the water environment by a TMF. Parameters that are not precisely known due to limited sampling or variability (e.g., in geological or hydraulic properties) can be represented through stochastic inputs that capture the estimated value at the relevant scale.

Probabilistic simulation tools use stochastic methods to randomly sample statistical distributions of input parameters and perform model calculations with the selected values. This Monte Carlo analysis process is repeated numerous times, generating a set of output values that can be statistically analyzed to describe the probability of certain outcomes (see Fig. 2).

The range of likely results can be presented based on their probabilities and an understanding of the sensitivity of the model parameters, providing quantitative information to inform decision making. The approach of using probabilistic simulation for groundwater risk assessment has been central to the regulatory approach to groundwater protection in the UK for over 25 years (e.g. Environment Agency, 1999).

As outlined above a groundwater risk assessment comprises three components: the source (in this case, tailings), the pathway or pathways connecting the source to any receptors, and the receptors themselves (such as groundwater and surface water bodies like rivers and streams). If any component of the source-pathway-receptor system is absent from a site, the risk to the groundwater and surface water environment will be negligible.

The starting point for any TMF risk assessment is the development of a conceptual model that describes the hydrological and hydrogeological setting and identifies the source-pathway-receptor linkages. A probabilistic analytical model may then be created for the risk assessment process, using site characterisation data to parameterise the model. For groundwater assessments, the model typically includes a one-dimensional contaminant transport model representing advection and attenuation processes such as dilution, dispersion, sorption, precipitation, and biodegradation along a specific migration pathway. It is possible to build complex models that combine multiple models each representing different components of the system such as changes in infiltration through cover systems and evolution in source term chemistry, this can include coupling

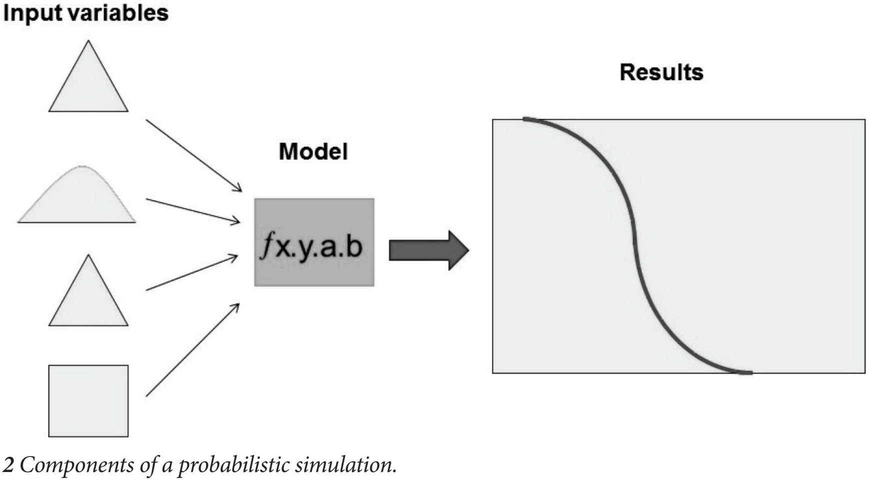

Figure 2 Components of a probabilistic simulation.

to geochemical modelling codes such as PHREEQC.

Probabilistic risk assessment using a steady state contaminant transport model

To understand the potential risks to the wider groundwater and surface water environment from an existing TMF, located in northern Europe, and to provide a rational basis for risk management (including further characterisation studies) a simple spreadsheet based contaminant transport model was developed. Contaminant transport for a number of potential contaminants of concern (PCOC) was simulated using the Domenico (1987) equation simulating advection, dispersion, diffusion and retardation. As many variables were not well constrained, such as hydraulic conductivity, hydraulic gradient, aquifer thickness and chemical properties (such as the soil water partition coefficient) the model was set up to consider these based on the most likely value and an estimate of the standard deviation from that value, assuming a normal distribution. The resulting model was run for 1000 iterations to allow adequate sampling of the probability functions.

Based on the calculations it was identified that at the 95% confidence level the chloride concentration 100 m downgradient of the TMF would be less than 115 mg/L (Fig. 3a) and the nickel concentration 0.023 mg/L (Fig. 3b), compared to initial concentrations at source of 300 mg/L and 0.06 mg/L respectively. The calculated 50%ile or most-likely concentrations were 106 mg/L and 0.021 mg/L for chloride (Fig. 3a) and nickel (Fig. 3b) respectively. Calculated travel times for breakthrough of the plume were approximately 50 years and approximately 27,400 years for chloride (Fig. 3c) and nickel (Fig. 3d) respectively at the 95% confidence level and 38 years and 19,600 years at the 50%ile (Fig. 3c and d).

The results of the calculations, illustrated in Fig. 3, indicate that it is unlikely that the chloride concentrations will exceed the regulatory criteria of 120 mg/L downgradient of the facility, whereas the nickel concentrations will exceed the regulatory limit of 0.01 mg/L, although not for many (thousands) years. The relative travel times are significant in that while based on the chloride travel time, as a conservative tracer, breakthrough is most likely to occur in approximately 38 years, it is unlikely that there will be an impact from nickel for a much longer period. This allowed risk

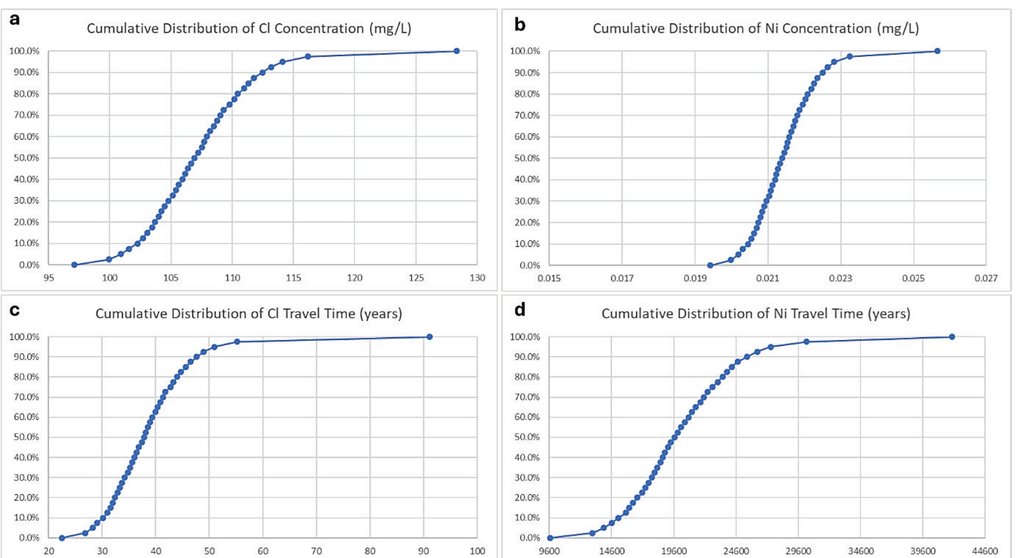

Figure 3 *Selected output from a probabilistic simulation of steady state contaminant transport, showing the cumulative distribution of Chloride and Nickel Concentrations (a and b respectively) and Travel Times (c and d respectively).*

management actions, such as source control, to be prioritised on the basis there was not an immediate risk from nickel contamination in groundwater arising from the TMF.

The use of dynamic probabilistic risk assessment

As discussed in Digges La Touche and Garrick (2011) a dynamic probabilistic model of contaminant transport was used to model the risks arising from an unlined TMF in South America and the residual risks following remediation of the facility by removal of the tailings to a new contained facility. The conceptual model is illustrated in Fig. 4. It was considered that following the removal of the tailings that a residual long-term risk would remain due to contamination of the underlying weathered bedrock. The evolution of concentrations at the monitoring point downgradient of the facility was simulated, using a dynamic probabilistic simulation model, and used as the basis for calibration against 7 years of existing monitoring data. It was found necessary to reduce the assumed partition coefficients for a number of PCOC to achieve a reasonable calibration.

The benefit of using a dynamic probabilistic model is that it allows the simulation of time variant problems. As can be seen from Fig. 5, without removal of the tailings it is predicted that concentrations of lead would continue to increase over time. Simulations of concentrations at the surface water receptor approximately 1 km from the TMF showed consistent results although it was noted that the travel times varied by an order of magnitude between the 95%ile and the 50%ile, most-likely, simulations. On this basis it was possible to demonstrate to the regulator that the remedial action was proportionate.

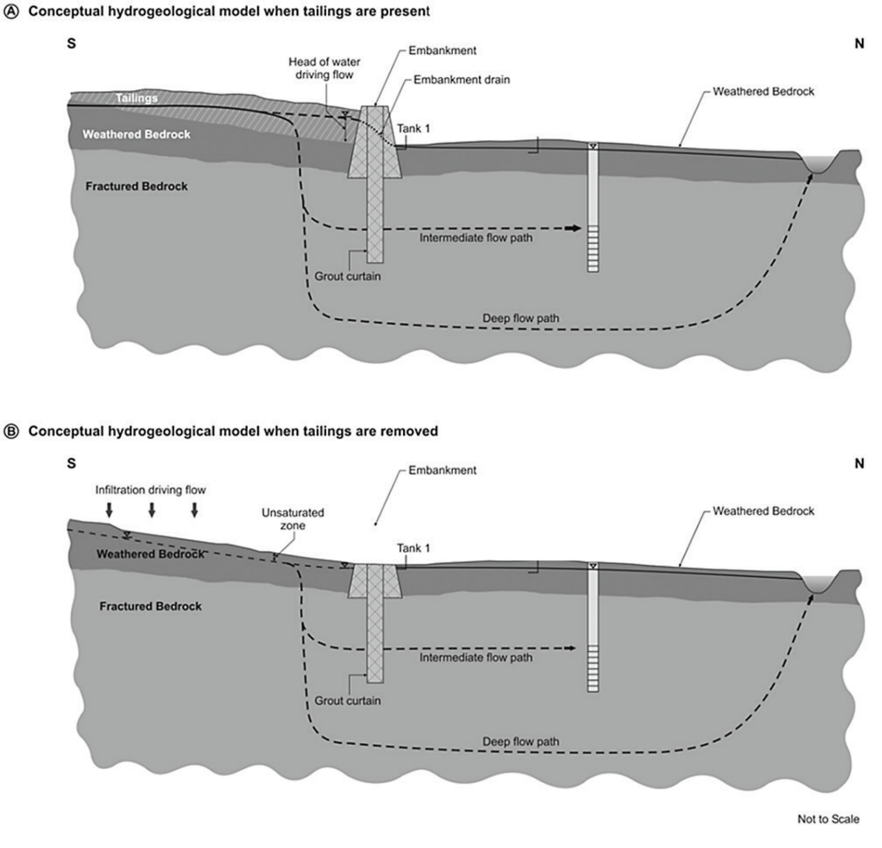

Figure 4 *Tailings Management Facility Conceptual Model during operation and following remediation (after Digges La Touche and Garrick (2011).*

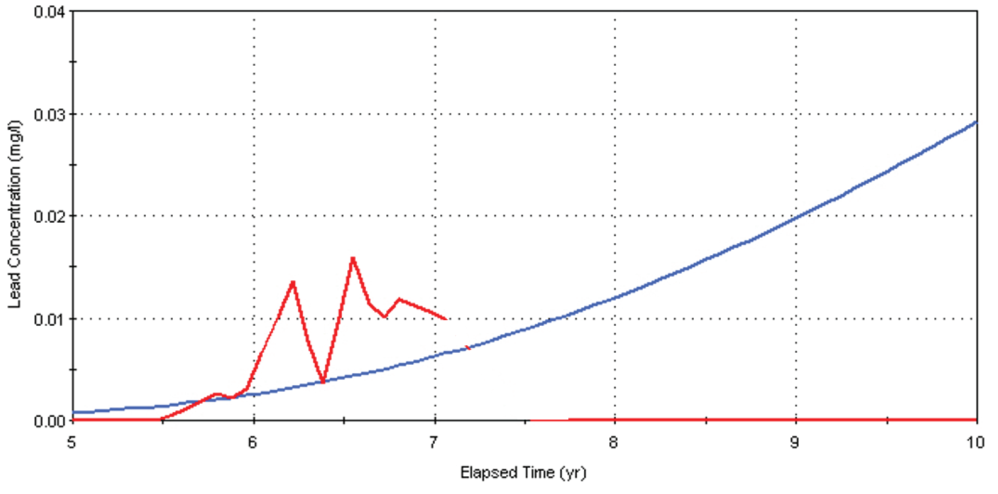

Figure 5 *Modelled 95%ile lead concentrations in groundwater (blue line) compared to measured concentrations (red line).*

Conclusions

The use of probabilistic models for the assessment of the impact of TMFs on, and thus risk to, water resources can be applied using relatively simple and cost-effective tools. The use of probabilistic simulations allow the natural variation in physical and chemical properties of the system to be taken into account and also allows for the quantification of uncertainty in those properties and thus also in the predicted impacts. While in both of the examples presented the models do not consider geochemical reaction pathways, it is considered that as screening models that can be calibrated to a sufficient degree based on simple retardation factors that the models are fit for their intended purpose. That is to inform short term decision making rather than trying to represent the details of the system and its evolution.

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