DECISION SUPPORT RELATED TO THE MANAGEMENT AND CLOSURE OF TAILINGS STORAGE FACILITIES-GUIDELINE FOR THE HANDLING OF UNCERTAINTIES IN MODEL PREDICTIONS AND RISK BASED DECISION MAKING

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ABSTRACT

Golder Associates, in conjunction with Fraser Alexander, the University of KwaZulu Natal and the University of Pretoria, developed a preliminary Decision Support System (DSS) for the sustainable design, operation and closure of metalliferous tailings storage facilities (TSF) on behalf of the Water Research Commission of South Africa. During the first phase of the project knowledge gaps were identified and these gaps were investigated further in the second phase. This paper reports on the findings of one of the identified gaps, namely the development of protocols to qualify, quantify and report uncertainty in specialist models.

Regulators (and proponents) find it difficult to make decisions where liability is transferred (or responsibility accepted) and it is often due to lack of knowledge on how to identify uncertainties in impact predictions and assessments, how uncertainties should be quantified and expressed and how to make risk based decisions.

There is a large amount of literature available on the subjects of uncertainty analysis, risk assessment and risk based decision making (RBDM), but there is not much guidance on how to bring all the concepts together when making a decision regarding the acceptability of a particular proposed TSF scheme.

This research developed protocols and guidance to support the decision making processes captured in the DSS, specifically related to the water and surface stability aspects. The research provides a framework to qualify and quantify uncertainties in model simulations (especially predictions) and provides practical decision support guidance on how to make decisions based on predictions that have an element of uncertainty.

1. IMPORTANCE OF UNCERTAINTY

The importance of the concept of uncertainty in the DSS for sustainable design, operation and closure of metalliferous TSFs, relates to the challenge that regulators often find it difficult to make decisions when liability is transferred or accepted based on future predictions of mine water systems.

Although a large amount of literature is available on the subjects of uncertainty analysis, risk assessment and risk based decision making (RBDM), there is not much guidance on how to bring all the concepts together when making the final decision. One example is the uncertainty of impacts of a TSF on water resources long after closure. The decision to accept the transfer of liability from the mine to the regulator is not an easy one. Uncertainties need to be identified, quantified and expressed in ways that the risk of future impact can be understood. These uncertainties may include the water flow (and related quality) predictions after capping, flow through the soil cover, surface stability, the rate of erosion of the cover and the cost of management. In addition there may be uncertainties associated with mitigation measures such as pumping and treatment of the water before a contaminant plume reaches a water body. In order to get closure, the authorities will have to take on responsibility for the TSF and its managed liabilities, and hence there is a need to understand all the processes quantitatively.

Several authors (IWR, 2008, Pappenberger and Beven, 2006) suggest that uncertainty analysis is not widely used in modeling. Although the concept is not new, the use of uncertainty analysis, contrary to risk analysis, seems to be a more recent development in the modeling community (Floodrisknet website, 2009). The lack of use of uncertainty analysis does not reduce its importance, it rather points to the lack of readily available guidance about how to do uncertainty analysis (IWR, 2008). In the same line of thinking, Pappenberger and Beven (2006) suggest that a Code of Practice is needed as a way of formalizing guidance on methods and applications of uncertainty analysis.

This research developed protocols and guidance to support the decision making processes captured in the DSS, specifically related to the water and surface stability aspects. The research provides a framework to qualify and quantify uncertainties in model simulations (especially predictions) and provides practical decision support guidance on how to make decisions based on predictions that have an element of uncertainty.

2. CURRENT UNDERSTANDING OF UNCERTAINTY

The difference between uncertainty and ignorance lies in the awareness of our imperfect knowledge (Brown and Heuvelink, 2005). In water and surface stability analyses there are numerous sources of uncertainty. Although literature is available on many of the individual sources of uncertainty, very limited literature is available on how to handle the combined uncertainty in model assessments and predictions.

Sources of Uncertainty

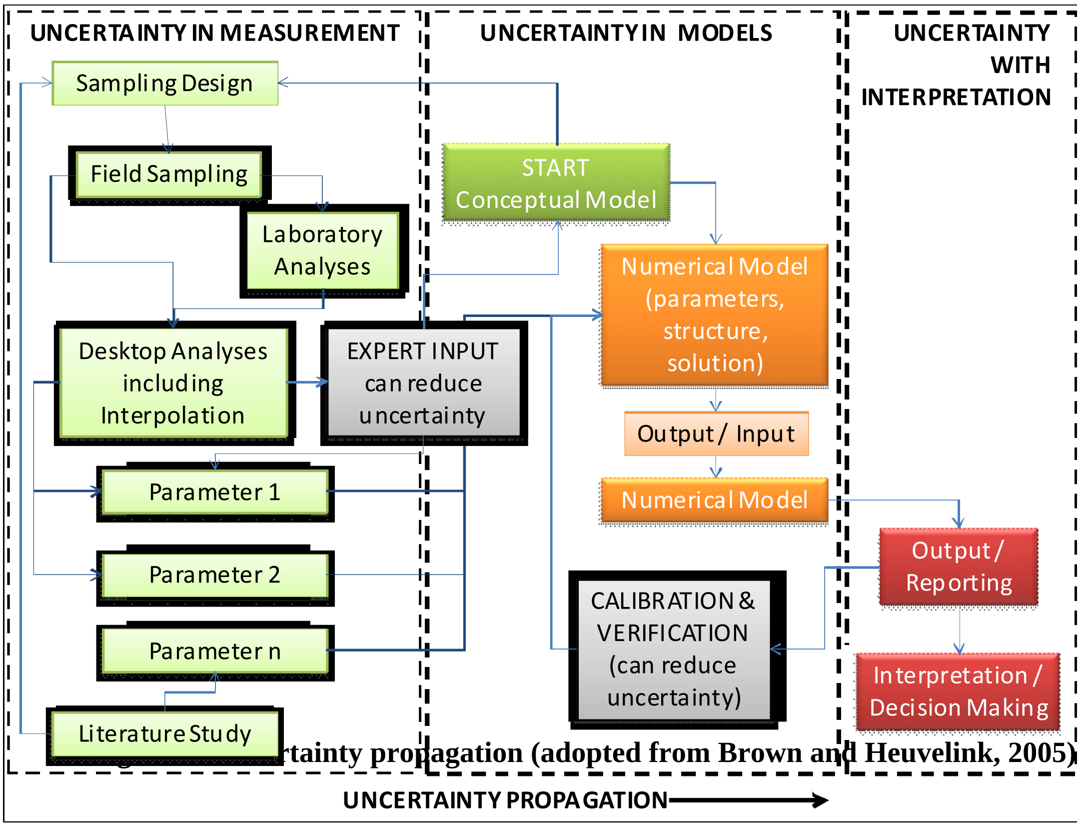
The sources of uncertainty are grouped into uncertain inputs (uncertainty in measurement), uncertainty in models and uncertainty with interpretation. Figure 1 shows the uncertainty propagation.

Uncertainty is associated with every block in Figure 1 and these uncertainties propagate or add up. Input values (with their uncertainties) are transferred to the model and subsequent outputs. These outputs could become input values for another model and eventually results (with the propagated uncertainties) are described. It is important that the uncertainties by quantified or named at every level.

Several authors (Institute for Water Research, 2008; Brown and Heuvelink, 2005; Rademeyer, 2007) mentioned how expert input/opinion is considered as an appropriate way to reduce uncertainty. Other ways of reducing uncertainty are increasing the number of samples, model calibration, and verification (see Table 1). Methods to quantify uncertainty include statistical analysis, sensitivity analysis, and Monte Carlo simulations.

Expressing Uncertainty

Although literature is available on many of the individual sources of uncertainty, very limited literature is available on how to record, assess and present the combined uncertainty in model assessments and predictions. This section highlights the findings of relevant papers relating to analysing and reporting of uncertainty in modeling. Since modeling inputs are often from measured data, some background is given to uncertainty in measurement.



tainty propagation (adopted from Brown and Heuvelink, 2005)

Table 1. Sources of uncertainty and recommended ways to reduce uncertainty

Sources of Uncertainty	Group	Uncertainty	Reduce Uncertainty
Uncertainty in measurement (Uncertain inputs)	Sampling design	Sampling uncertainties	Consult experts (geologists & statisticians), use statistical sample layout, communicate shortcomings (e.g. fewer samples due to budget constrains)
	Field sampling	Uncertain categorical distribution	Report similar material classes with which sample could be confused.
		Sampling technique	Select sampling points prior to field visit and stick to plan.
		Sample storage and preparation uncertainties	Study the procedures prior to field visit and follow them.
	Laboratory analysis	Analytical uncertainties	Follow standard procedures
		Imported uncertainty	A higher number of repetitions will show the variance which should be reported.
		Mismatch uncertainty	Have random samples retested.
	Desktop analysis / data interpretation	Interpolation uncertainties	Increase number of samples. Present results to experts who know the area and get their input.
		Hydrological uncertainties	Consult experts (meteorologists)
		Interpretation of Laboratory data	Do basic statistical analysis and report mean and standard deviation.
		Interpretation of Climate data	Do basic statistical analysis and report mean and standard deviation.
Uncertainty in models	Inaccurate model design / Logical errors	Misrepresenting the conceptual model	Consult experts. Document what is known, justify the model, and if possible, rank model components in terms of uncertainty.
		Assumption and estimate uncertainties	Consult experts.
	Model uncertainties	Mathematical model uncertainties	Report the reasons for selecting a specific model.
			Sensitivity analysis and/or likely, best and worst case scenarios.
			Monte Carlo Simulations.
		Model coupling uncertainties	Report uncertainties at all levels.
Uncertainty with interpretation	Reporting errors	Resolution uncertainty	It is recommended that rounding only be done when reporting and not before.

Sources of Uncertainty	Group	Uncertainty	Reduce Uncertainty
		Scale uncertainty	Mention the scale at which the study was conducted and to use the correct model at the correct scale e.g. a catchment scale model will not accurately predict field scale processes.
		Extrapolation uncertainties	Use a calibration period, when measured data are available to verify the model.
	Interpretation errors		

Expressing Uncertainty in Measurements

The guide to the expression of Uncertainty in Measurement (better known as GUM, BIPM *et al.*, 1993) establishes general rules for evaluating and expressing uncertainty in measurement.

Apart from laboratory analysis, that is mostly guided by international standards there is also the statistical analysis of data. GUM mentions two types of evaluation standards:

- Type A - evaluation is the basic statistical analysis of a series of observations that includes arithmetic mean or average and standard deviation (of samples or whole population).
- Type B - evaluation accounts for errors that remain constant while the measurement is made (systematic components of uncertainty).

When it comes to reporting of measurement uncertainty, United Kingdom Accreditation Service (UKAS, 2007) recommends *inter alia*:

- After calculating the probability value (for the desired confidence limit e.g. 95 % probability) of the measurand, the uncertainty should be reported as value ± uncertainty ($y \pm U$).
- The word "approximately" should only be used if the value is sufficiently close that any difference may be considered insignificant.
- The number of figures in a reported uncertainty should always reflect practical measurement capability.
- Rounding should always be carried out at the end of the process in order to avoid the effects of cumulative rounding errors.

Expressing Uncertainty When Modelling

Uncertainty in models originates from different sources, starting with the conceptual model. A valid and complete conceptual model is essential for accurate predictions. The most important sources of uncertainty in a risk assessment stems from an inaccurate conceptual model (U.S. Environmental Protection Agency, 1998; Anderson and Woessner, 1992). The sources of uncertainty in a conceptual model, may originate from the simplification of reality, a lack of knowledge about how the system functions or failure to identify parameters correctly. It is good practice to revisit the conceptual model after results from sampling have been analysed and before the numerical model is developed.

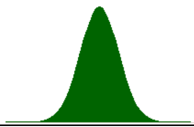
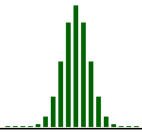
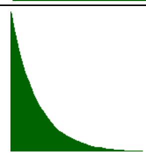
Uncertainty in deterministic models can be reduced by calibration, verification and by conducting a sensitivity analysis. Anderson and Woessner (1992) recommend that calibration and verification of the model should be done prior to sensitivity analysis. During the calibration process a pre-determined calibration target is matched by trial-and-error or by using a stand-alone computer program or an automatic calibration routine within the model. A model is verified when it predicts, within acceptable limits, that a calibrated parameter set will generate acceptable results when applied to different period of input data. A sensitivity analysis is conducted by changing one parameter at a time and reporting the effect of the parameter change on the average measure of error. The purpose of the sensitivity analysis is to quantify the uncertainty in the calibrated model (Anderson and Woessner, 1992).

Stochastic models require input as one or more probabilistic distribution function(s) or PDF(s). A number of distributions are given in Table 2.

Interpretation of Uncertainty

Uncertainty is often expressed as a probability that represents the chance of an event occurring. A 100 % probability implies that you have absolute confidence that the event will happen. Part of the decision making process it to decide what level of confidence is acceptable. In order to determine what level of confidence is acceptable, the risk that the event poses to the environment should be considered. When an event will result in human death, the confidence level that the event will not happen needs to be above 99 %. In terms of water pollution, the risk is compared to compliance to standard water quality guidelines which made allowance for human and environmental safety. Therefore a lower level of confidence is required and a 95 % confidence that an event will comply to water quality guidelines can be acceptable.

Table 2. Probability distributions that can be used in a stochastic model

Distribution	Shape	Distribution	Shape
Single value		Uniform Log Uniform	
Normal Log Normal		Triangular Log Triangular	
Binomial Poisson		Exponential	

When results are not available as a probabilistic distribution function case scenarios provide a means to determine a range of possible answers. Best case, worst case and likely case scenarios can be modelled by modifying the most sensitive parameter(s). By presenting these case scenarios, the maximum distribution (wide range) is given. Information about the parameter that was modified should be given to guide decision makers about the likelihood of the best and worst case scenarios.

It is good practice to document everything that is known and unknown about the system under investigation (U.S. Environmental Protection Agency, 1998). Communicating uncertainties leads to insight and understanding of the system and to better decision making.

Decision Making

A decision making methodology is required to avoid indecision, inconsistency and dissatisfaction (Decision Research, 1980). Risk Based Decision Making (RBDM) is well described in the literature and consist of many steps that include *inter alia* risk assessment, risk management and impact assessment.

This paper will not discuss the steps of a RBDM, but rather suggests a less complicated decision making methodology in the next section. However, the concept of risk and risk assessment is briefly discussed here.

Risk can be defined as the product of chance and outcome. The chance is often presented as probability of occuring and the outcome may be seen as the impact on the environment. The impact can be defined in terms of magnitude, duration and scale. A TSF may have a moderate magnitude that will have a long-term effect on a local scale.

As part of the decision making methodology, all the chances and outcomes should be considered. Cost of mitigation or remediation actions should also be considered. As an example, consider two hazards. The first has a small chance of occurrence (1%), but the outcome has a large value in terms of remediation cost. The second has a significant chance of occurrence (70%), but the remediation cost is relatively small. The risk (chance x cost) for each of these cases may be very similar. Examining the chances and outcomes forms the risk assessment part of RBDM. The purpose of the risk assessment is to transform scientific data into meaningful information about the risk of any system to the environment and to help make defensible decisions.

When a risk assessment cannot be performed and consequences are damaging the environment, the precautionary principle should be applied. The United Nations (1992) stated that: *"Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation"*

Apart from the risk assessment, the decision making methodology should also include:

- Identification the problem;
- Creating alternatives to deal with the problem; and
  Selecting the best alternative.

3. CONCLUSION - DECISION SUPPORT GUIDANCE

There are several reasons why regulators and proponents find it difficult to make decisions regarding predictions that are expressed in terms of an uncertainty parameter. The reasons include:

- A general lack of guidance on how uncertainties are to be modelled, reported and interpreted.
- Even when uncertainty has been reported, it is not easy to make a decision based on that uncertainty. Risk assessment and risk-based decision making require additional study that often involves stakeholder participation.
- Risk to the environment and human health is influenced by perceptions and not easy to measure.

It is important to be practical and not to spend time determining uncertainties on inputs that do not contribute significantly to model outcomes. Recommended methods should be scientifically sound and practical/feasible.

Guidance for Analysing and Reporting Uncertainty

Comprehensive reporting of information regarding the system under investigation will guide regulators who have to base a decision on this information. The guidelines below are not meant to give a step by step procedure, but rather to list good practice in relation to reducing uncertainty.

- Follow procedures at all levels of uncertainty (refer to Table 1). By following standard or reported procedures, errors will be excluded and uncertainty will be minimized.
- Make use of expert knowledge. The Institute for Water Research (2008) suggests that manual calibration requires an experienced user. Modellers may need additional information from statisticians, geologists or other experts. Even at the point of decision making, expert opinion will provide valuable insight.
- Make sure that the conceptual model represents system behavior (Anderson and Woessner, 1992) and that all the key processes are represented in the conceptual model. Field and analysis data should be used to refine the conceptual model.
- Conduct a sensitivity analysis. The sensitivity analysis will indicate to which parameter the model is most sensitive. The effort should be directed to get the uncertainty reduced for these more sensitive parameters.
- Motivate why a model was selected. This will inform the client about important functions within the model. E.g. for simulating seepage fluxes the finite element model SVFlux, developed by Soilvision Systems Ltd. (Thode and Stiansen, 2006) may be selected because is utilizes a hydraulic conductivity function, which is a continuum of the material’s hydraulic conductivity from saturated to dry conditions, instead of a single hydraulic conductivity value.
- Mention model limitations.
- Reduce uncertainty where possible. Refer to Table 1 for guidelines to reduce uncertainty at the various levels. Report also if these steps could not be taken due to any constraints, e.g. should there be no budget to increase the number of samples, state it in the report.

Specific Guidance for the Decision Support System

Regulators need to ask the following questions before following the guidance on decision making:

- Did the proponent describe the procedure followed?
- Did the proponent express uncertainty, either by confidence limits, probabilities or scenarios of best, worst and likely cases?

If the answer to any of these questions is no, the proponent should be asked to comply.

Authorities should consider if RBDM (not discussed in this paper) is practical, feasible or desired before embarking on decision making. The guidelines presented here are aimed to provide a practical way of taking decisions without conducting a full RBDM process.

Working with uncertainty, defined in a PDF, regulators can follow two approaches to make a decision. However, in both cases the precautionary principle is applied to ensure compliance, either to an acceptable risk level (ARL) or to a set value at the 95 percentile. The two approaches to follow are:

- A risk based approach. Here compliance is based on a risk and will be site specific. This approach takes account of receptor risk adverseness, i.e. measure against ARL’s and compliance required at 95 percentile of PDF. E.g. the Water Quality Guidelines (Department of Water Affairs and Forestry, 1996) could be used as the ARL for sodium. If the sodium levels in a river comply to the Water Quality Guideline for 95 % of the time, the risk is acceptable.

- Regulatory framework (e.g. Water Quality Guidelines) as basis for decision making. Regulators are advised to follow the precautionary principle where compliance is set at the 95 percentile of the predicted concentration, e.i. the 95 percentile of the predicted PDF must comply with set value of the relevant regulatory framework.

The very first step in this guidance would be to select the ARL. The recommendation here is to use the 5 and/or the 95 % as the confidence limit. Although no literature was found to confirm that 95 % should be used as the confidence limit rather than 99 %, the argument below was used to justify the use of the 95 %confidence limit.

One of the major concerns with TSF's is that the quality of downstream water resources may be negatively affected due to seepage from the TSF. Regulators need to decide what level of uncertainty is acceptable when they receive predicted water quality values with a probability distribution (uncertainty). Before they decide on the ARL, they will compare the value with the acceptable limits for water resources described in the water quality guidelines (Department of Water Affairs and Forestry, 1996).

A 95 % confidence that an event will comply to water quality guidelines can be acceptable (see "Interpretation of Uncertainty") and is recommended as the ARL.

It is recommended to consider the consequences in terms of magnitude, scale and duration of the impact as part of the decision making process.

Should the predictions within the ARL (of say seepage from a TSF) meet the requirements of the water quality guidelines, no further action is required. If not, steps should be taken to either reduce the level of uncertainty or the magnitude of the impact. This process is outlined in Figure 2. Three options are available:

- Refine the assessment. Some examples are to:
  - Revisit the conceptual model, assumptions and make sure that the processes are understood.
  - Do more measurements in order to reduce the input uncertainty.
  - Conduct a more detailed modeling, e.g. a three-dimensional model instead of a one-dimensional model or make sure all the layers underlying the TSF are included in the model.
- Apply more robust mitigation, e.g. install pumping and treatment action to counteract seepage into a water resource. The regulator may leave the liability of the mitigation action with the mine or accept responsibility.
- Request 'demonstration protocol'. In this case the regulator accepts liability (e.g. partial closure) on condition that the mine will develop and install a monitoring programme to demonstrate that the risk is within the ARL.
- The process of 'demonstration protocol' is very important as a verification process. Consider the example of request for closure of a TSF. The impact prediction has been conducted and the regulator agrees to accept liability in future once it has been demonstrated that the risk is within the ARL. Measurements should be conducted at the source, in the contaminant transport pathway and at the receptor. Surface water flow of nearby rivers and groundwater levels should also be measured seasonally. Measurements are compared to the ARL and if there is non-compliance, the mine should put additional mitigation measures in place.

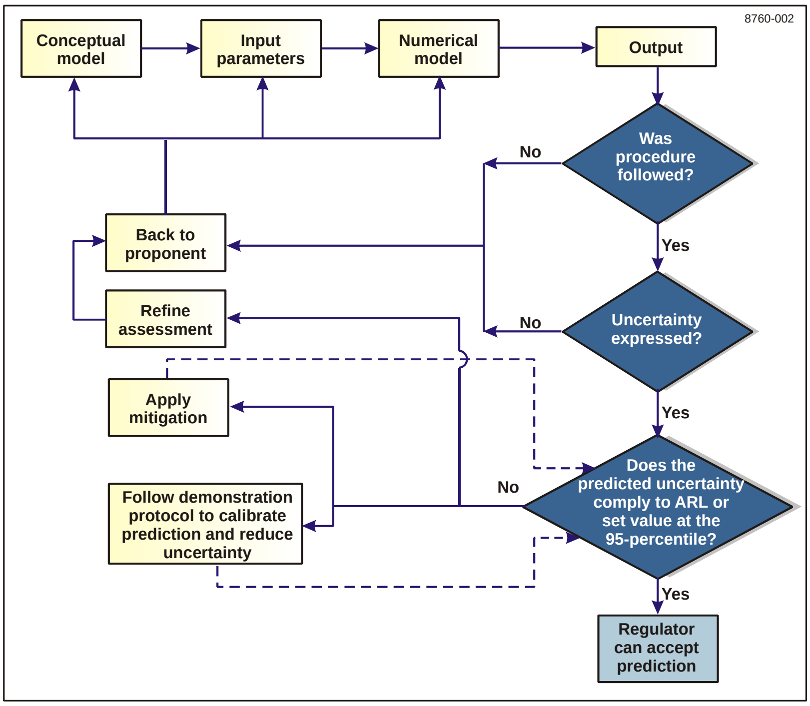


Figure 2. Proposed decision making process

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