A PRELIMINARY DECISION SUPPORT SYSTEM FOR THE SUSTAINABLE DESIGN, OPERATION AND CLOSURE OF METALLIFEROUS MINE RESIDUE DISPOSAL FACILITIES

by

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This report is the first document published on the decision-support system and is part of an ongoing research programme undertaken by the WRC. Comments pertaining to this working draft report are most welcome and can be forwarded to the Director: Water Use and Waste Management at the WRC.

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"The development of a first order decision support system for the sustainable design, operation, and closure of metalliferous tailings disposal facilities"

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EXECUTIVE SUMMARY

Mining of South Africa's gold, platinum and base metal resources has given rise to hundreds of mine residue disposal facilities (MRDFs) of which the footprints cover large areas of land. With a product to residue ratio ranging between 1:60 000 and 1:200 000 for gold and platinum, the metalliferous mines produce a substantial volume of fine-grained waste. It is estimated that approximately 12 000 ha of land is sterilised by 150 gold MRDFs within the Gauteng province alone (refer Figure 1). Mine residue usually contains sulphide minerals, which upon weathering give rise to a range of potential pollutants. Where there is insufficient neutralizing potential in the mine residue, acid mine drainage (AMD) occurs with its associated:

- low pH values,
- high salt loads, and
- high concentrations of metals.

Radionuclides are also found in some drainage associated with MRDFs.

Mine residue disposal facilities are often physically unstable and susceptible to erosion thus giving rise to long term wind and water borne pollution. Seepage to groundwater and discharge to surface water can give rise to water pollution over large tracts of land. The quantitative prediction of these impacts is difficult and is costly to manage and mitigate.

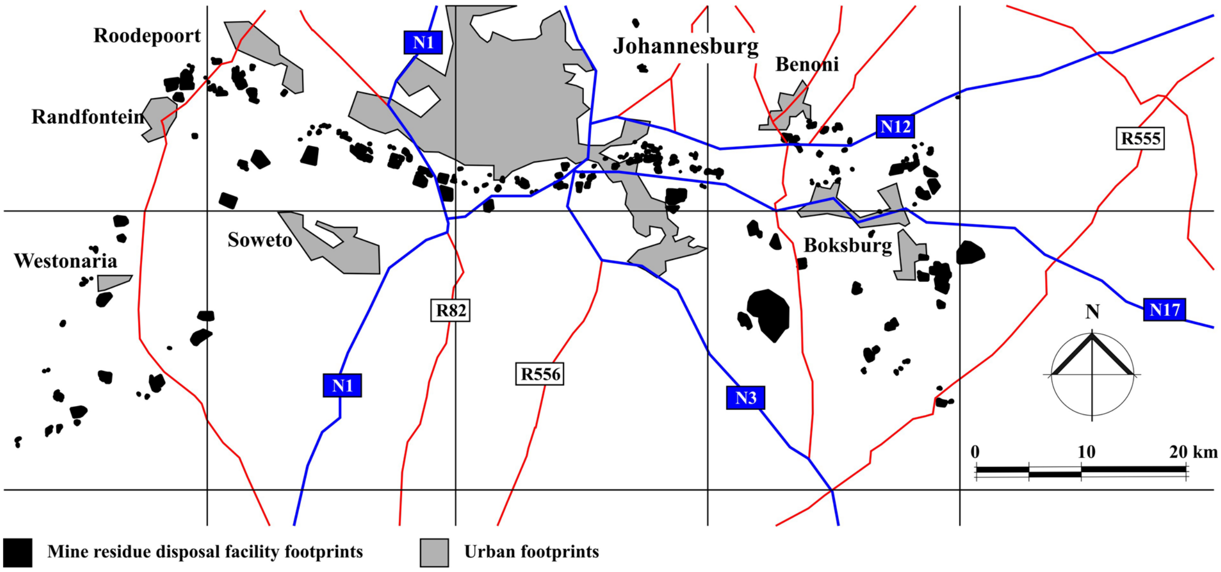

Figure 1: Footprints of mine residue disposal facilities in and around the Gauteng province (Rademeyer and van den Berg, 2005).

The legacy of the impacts associated with MRDFs, particularly in the long term and after closure, has given rise to an increasingly complex regulatory regime. Approvals for upgrading old facilities, for development of new facilities, and for closure plans are difficult to obtain owing to the lack of a suitable framework within which to make decisions. Since efficient development of the South African mining sector is essential, whilst maintaining a balance with an acceptable level of environmental risk, it is necessary to develop a coherent process to facilitate transparent and effective regulatory decision making.

The Water Research Commission (WRC) awarded the research contract referred to in the title of this report to a consortium managed by Golder Associates Africa (Pty) Ltd. This research was intended to be the first of three phases, stretching over a period of five to ten years. The first phase, the preliminary decision-support system (DSS), will be followed by a second phase addressing some of the key knowledge gaps identified during the first phase. The third and last phase will involve the development of a final DSS.

The preliminary DSS comprises three components (illustrated in Figure 2). The central component of the system comprises a top down hierarchy of questions within a rational framework. The two supporting components, decision guidance and decision criteria, direct users through a series of logical steps to identify where the critical issues for each site specific situation lies. Regulators, proponents and consultants can use the system to better understand what questions need to be asked and answered. The DSS can be exited at any of the levels in the hierarchy with either a negative, positive or uncertain outcome. The depth to which the user must progress down the hierarchy of questions is a function of the level of complexity of the environmental setting and the risk associated with the facility. Broad issues are first addressed and dealt with at the top of the hierarchy whereas detailed questions are incorporated further down in the framework.

The decision guidance and decision criteria are aligned to each question in the DSS framework. The decision guidance assists the regulator in making a decision and the decision criteria provide the level and type of information which is required to address the question. The decision criteria can be in the format of guidelines, criteria or standards.

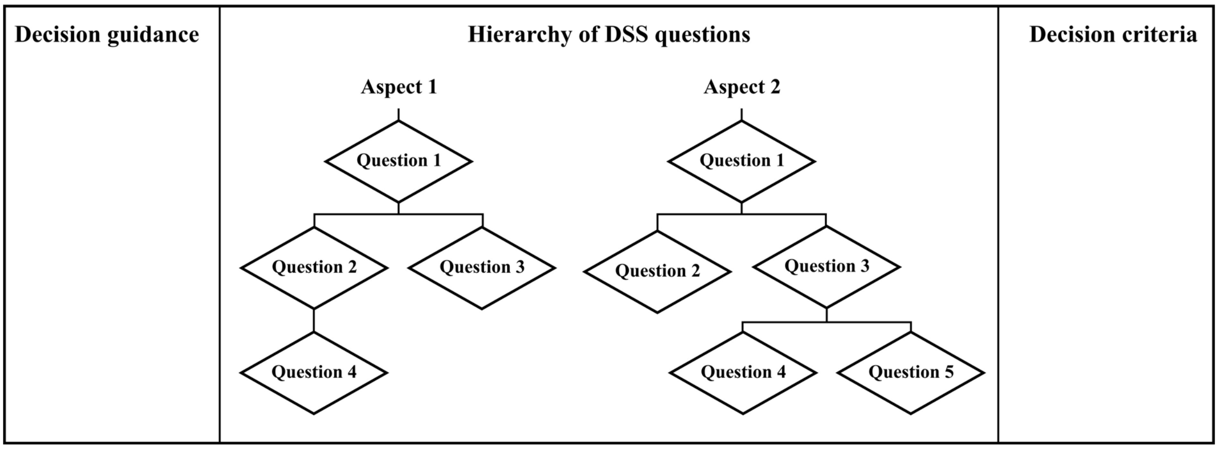

Figure 2: Simplified schematic indicating the three parts of the DSS.

The preliminary DSS was developed:

- using existing knowledge;
- using conservative assumptions; and
- applying the precautionary principle.

Through a process of elimination key issues currently leading to delays in the approval and implementation of new projects, project upgrades and closures, were identified. The two key issues identified in this process are related to water impacts and long term surface stability.

The present knowledge base is insufficient to provide conclusive answers to the questions that are frequently raised around the two key issues. The current state of the art of prediction and mitigation is not yet developed sufficiently to place regulators, in particular, in a position to evaluate and validate proposals mainly as a result of uncertainty relating to water impacts and to surface stability. It was therefore decided to analyse the two areas and identify exactly where the uncertainty lay and to propose a structured way of addressing the uncertainty so that a decision, albeit a conservative one, can be made. Areas where further research would be required to reduce the level of conservatism that would inevitably be associated with the uncertainty were also identified and are described in the section on knowledge gaps in the report.

There will always be cases where an unequivocal answer is not possible with our present knowledge base. New and promising technologies and approaches that could play a role in minimizing water resource degradation are continuously being developed and can provide acceptable solutions in these instances. At present there is no formal way to include such promising technologies in proposals. For these cases it is important to follow a standardised and accepted protocol to demonstrate the suitability of a proposed technology purported to limit the environmental impacts to acceptable levels. This report identifies the need for such a protocol.

The terms of reference for the research described in this report included *inter alia* the development of the framework for a DSS and the development of key parts of the DSS related to the water and surface stability issues, namely the water module and the surface stability module. Only these two modules are presently dealt with in detail in this report. It is envisaged that subsequent versions of the DSS will include further modules on aspects such as air quality and socio-cultural impacts until eventually all relevant modules are included in a final system.

This report covers the following:

- The DSS framework.
- The two major technical components of the DSS:
  - Water module; and
  - Surface stability module.
- Decision trees for the two technical components.
- Knowledge gaps with respect to the water and surface stability modules of the DSS.

The preliminary DSS is useful, provides a starting point for decision makers and should be issued as a working draft even though the final system is not in place. The DSS and in particular the protocol for providing new and promising technology is a new concept for the South African regulatory regime and holds promise for breaking through deadlocks that may arise on projects where current predictive methodologies and mitigation measures have not been proven in practice.

The objectives of the first phase of the project have been achieved and provide a firm basis for the next phase of the research which can now commence.

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LIST OF ABBREVIATIONS AND ACRONYMS

AMD	Acid mine drainage
BDAT	Best Demonstrated Available Technology
CM	Chamber of Mines
DEAT	Department of Environmental Affairs and Tourism
DME	Department of Minerals and Energy
DSS	Decision-support system
DWAF	Department of Water Affairs and Forestry
ECA	Environment Conservation Act No. 73 of 1989
IAPs	Interested and affected parties
ISC	Internal steering committee
ML	Metal Leaching
MPRDA	Minerals and Petroleum Resources Development Act No. 28 of 2002
MRDF	Mine residue disposal facility
NEMA	National Environmental Management Act No. 107 of 1998
OSC	Operational steering committee
PHD	Pulles Howard and de Lange Incorporated
QLD	Queensland
RUSLE	Revised Universal Soil Loss Equation
TDS	Total dissolved solids
UKZN	University of KwaZulu-Natal
UP	University of Pretoria
WRC	Water Research Commission

LIST OF TERMS

decision	A decision is defined as an action that must be taken when there is no more time for gathering facts (Moody, 1983:4).
decision-making	The sequence of steps, actions or procedures that result in decisions, at any stage of a scheme (DEAT, 2002:21).
decision-support system	A decision-support system (DSS) is a system that supports decision making by assisting in the organisation of factors and relations between the latter within a rational framework (Sage, 1991:1).
environment	Environment has a number of definitions depending on the context: • environment means the aggregate of surrounding objects, conditions and influences that influence the life and habits of man or any other organism or collection of organisms (ECA, 1989); • environment means the surroundings within which humans exist and that are made up of:- - the land, water and atmosphere of the earth; - micro organisms, plant and animal life; - any part or combination of the afore-mentioned and the interrelationships among and between them; and - the physical, chemical, aesthetic and cultural properties and conditions of the foregoing that influence human health and well-being (NEMA, 1998); • environment means the associated cultural, social, soil, biotic, atmospheric, surface an ground water aspects associated with landfill that are, or could potentially be, impacted on by the landfill (DWAF, 1998:G-4); • or the environment is defined as those parts of the socio-cultural, biophysical and economic environment affected by the scheme (after DEAT, 2002:20).
environmental impact	An environmental impact is the positive or negative change to the surroundings of a scheme including water, air, land, natural resources, flora, fauna, and their interrelation and which result from aspects associated with a scheme (after DEAT, 2002:20 and SANS 14001, 2005:2).
erosion	Erosion includes a group of processes by which earth materials are entrained and transported across a given surface (Galetovic, 1998:1-1).
fatal flaw	Any problem, issue or conflict (real or perceived) that could result in a scheme being rejected or stopped (DEAT, 2002:21).
hazard	Hazard refers to the capacity of a substance, a structure, an activity or an event to produce an adverse effect on life or property, including health, safety or environment (DME (QLD), 1995).

leaching	Leaching involves removal of minerals from the ground particles by direct contact with solvent, usually a strong acid or alkaline solution depending on the type of ore (Vick, 1883:8).
mine residue	Mine residue includes any debris, discard, tailings, slimes, screenings, slurry, waste rock, foundry sand, beneficiation plant waste, ash and any other waste product derived from or incidental to the operation of a mine or activity and which is stockpiled, stored or accumulated for potential re-use or recycling or which is disposed of (DWAF, 1999:2).
mine residue deposit	Mine residue deposit includes any dump, tailings impoundment, slimes dam, ash dump, waste rock dump, in-pit deposit and any other heap, pile or accumulation of residue remaining at termination, cancellation or expiry of a prospecting right, mining right, mining permit, exploration right or production right (after MPRDA, 2002).
mine residue stockpile	Mine residue stockpile means any debris, discard, tailings, slimes, screening, slurry, waste rock, foundry sand, beneficiation plant waste, ash or any other product derived from or incidental to a mining operation and which is stockpiled, stored or accumulated for potential re-use, or which is disposed of, by the holder of a mining right, mining permit or production right (MPRDA, 2002).
phreatic surface	The phreatic surface is the level of saturation in the impoundment and the embankment – i.e. the surface along which pressure in the fluid equals atmospheric pressure. In natural systems without flow it is often equal to the water table.
risk	Risk refers to a combination of the probability, or frequency, of occurrence of a defined hazard and the magnitude of the consequences of the occurrence. Hazard refers to an attribute or situation that in particular circumstances could lead to harm (DEFRA, 2000).
sediment yield	The sediment yield from a surface is the sum of the soil losses minus deposition in macro-topographic depressions, at the toe of the hill slope, along field boundaries, or in terraces and channels sculpted into the hill slope (Galetovic, 1998:1-1).
significance	Impact magnitude is the measurable change, i.e. intensity, duration and likelihood. Impact significance is the value placed on the change by different affected parties, i.e. level of significance and acceptability. It is an anthropocentric concept, which makes use of value judgements and science-based criteria, i.e. socio-cultural, biophysical and economic. Such judgements reflect the political reality of impact assessment in which significance is translated into public acceptability of impacts (DEAT, 2002:21).

soil loss	Soil loss is that material actually removed from the particular hill slope or hill slope segment. The soil loss may be less than erosion due to on-site deposition in micro-topographic depressions on the hill slope (Galetovic, 1998:1-1).
sphere of influence	Sphere of influence is the term used in this report to describe the three-dimensional mine residue storage or disposal facility zone of influence within which an effect on the environment is anticipated. This zone is the spatial overlay or sum of the different environmental aspect zones of influence and is also representative of a particular configuration at a specific moment in time.
stakeholders	A subgroup of the public whose interest may be positively or negatively affected by a proposal or activity and/or who are concerned with a scheme or activity and its consequences. The term therefore includes the proponent, authorities and all interested and affected parties (IAPs) (DEAT, 2002:23).
sustainable development	Sustainable development means the integration of social, economic and environmental factors into planning, implementation and decision making so as to ensure that mineral and petroleum resources development serves present and future generations (MPRDA, 2002 and NEMA, 1998).
total dissolved solids	Total dissolved solids (TDS) is a term that expresses the quantity of dissolved material in a sample of water.
vadose zone	Vadose zone is the zone containing water under pressure less than that of the atmosphere, including soil water, intermediate vadose water, and capillary water. This zone is that between the land surface and the surface of the zone of saturation, that is, the water table.
water table	Water table is the surface between the vadose zone and the groundwater, that surface of a body of unconfined groundwater at which the pressure is equal to that of the atmosphere.

1 INTRODUCTION

Mining, milling and subsequent disposal of metalliferous mine residue in South Africa is taking place in the context of:

- increasingly stringent legislation;
- the development and adoption of economic policies that requires environmental protection; and
- increasing awareness amongst stakeholders about environmental issues and sustainable development.

The present process is unsatisfactory since it is insufficiently well defined. Essentially it comprises interrogating an application at the design, construction, operation or closure stages in the life of a mine residue disposal facility (MRDF) to ascertain whether it does or will comply with various regulatory criteria intended to prevent adverse environmental impacts.

This process, as with many decision processes, has three distinct elements. These are:

- an acceptable set of environmental standards and criteria;
- an acceptable measurement or prediction of environmental impacts; and
- a complete set of questions linking the criteria and impacts.

For example, the question may be "Will the local groundwater regime be unacceptably polluted by the proposed MRDF?" To answer this it is necessary to have defined an acceptable level of pollution – which may or may not be zero – and also to have appropriate measurement or prediction of possible pollution together with an appreciation of the reliability of the measurement or predictions.

The present process, although it contains these three elements in some manner is not sufficiently well defined so that it could be described as a complete formal consistent system. The overall result is that neither the regulatory authorities, nor the proponents of a scheme and their designers are satisfied; hence the requirement to develop a decision-support system (DSS).

The aim and deliverables of a solicited research project to address the sustainable configuration of metalliferous MRDFs were discussed at a workshop organised by the WRC during June 2003. A consortium headed by Golder Associates Africa (Pty) Ltd submitted a tender to undertake such research in response to a call for proposals by the WRC. The WRC awarded the project to the consortium in December 2003 and work commenced in April 2004. The preliminary discussions before the invitation to submit a proposal for the undertaking of the project determined to a large degree the extent and nature of the project. The invitation documents defined the overall process to be followed which *inter alia* included the submission of an inception report and at a later stage the conducting of a workshop at which preliminary findings of the project could be discussed with the interested and affected parties consisting of the Water Research Commission (WRC), Department of Minerals and Energy (DME), Department of Water Affairs and Forestry (DWAF), Chamber of Mines (CM), mining houses and consultants. This was followed by refinement of the workshop feedback and finally the submission of this report.

The overall approach of the research team was defined in the inception report. An internal steering committee (ISC) was formed whose task was to set up the framework of the DSS and to define the tasks of the two technical modules, i.e. water and surface stability. The framework or concept evolved through discussion to the three element model comprising a body of questions supported by two legs, namely, decision guidance and decision criteria. This model was to be applied in the first level to a range of more generalised questions regarding the scheme and at the second level to the specific technical modules for which technical teams would develop the elements and define the knowledge gaps.

The overall programme comprises the development of a DSS based on the three elements described in the preceding paragraph. It was recognized at the early discussions that the system would contain a number of technical modules. For example these would include water pollution, slope stability, air pollution, social impacts and aesthetic degradation. The view was taken that initially the system should be developed to include only the first two of these modules with the aim of creating a robust system, demonstrating its efficacy and then extending it to contain all the relevant modules. It was also realized that many of the questions in the system would not be definitively answerable. For example, "What is an acceptable level of groundwater pollution?" This will depend on the proximity of the affected zone to potential users as well as the effect of the pollutant, if this is known, on the user. It can be seen that what may appear to be a relevant simple question regarding criteria can become quite complex and eventually only answerable by applying conservative value judgements.

A similar problem arises with the measurement or prediction element of the system and particularly so with the latter. Measuring systems are not in themselves infallible and it is necessary to ensure that the correct characteristic is being reliably measured in the proper location so that the measured value is representative of the subsystem. This in itself is difficult for an existing facility but it becomes much more difficult, for example, at the design stage or indeed at any stage when the value of the characteristic has to be predicted. Methods of prediction of potential adverse environmental impacts generally have a large degree of unreliability and hence the DSS should take account of this by using a correctly structured risk based approach.

The proposed DSS comprises a body of questions and the supporting legs of sets of guidance on the one side and criteria on the other. The research task is to develop all three parts, initially only for the two technical modules of water and surface stability. As already indicated it was anticipated that some technical questions may be scientifically unanswerable at this stage and therefore a supplementary task was to define and prioritise such questions and knowledge gaps so that they could be investigated and acceptable levels of understanding developed. It is noted that the gaps could be in the measurement, prediction, standards or criteria of the environmental aspect interrogated.

This report describes the DSS framework and two of the technical aspects modules, namely the water and surface stability modules. The modules were selected as they address very important environmental aspects and because it was believed the level of knowledge were such that there was a reasonable possibility that they could readily be incorporated into a system. The primary purpose of the DSS is to aid decision-makers in assessing the environmental acceptability of applications for the development, operation and closure of MRDFs in a consistent and transparent manner. The final DSS will include quantitative and analytical components and integrate biophysical, socio-cultural and economic elements of decision-making in a user friendly system.

The following three milestones highlight the progress during the research to develop the preliminary DSS and are discussed in more detail below:

- Writing and submission of an inception report.
- Hosting a workshop where the concept DSS was presented to decision makers.
- Involving key stakeholders at workshop hosted by the WRC presenting the final DSS and prioritizing the knowledge gaps.

Inception report

An inception report was submitted to the WRC for subsequent circulation to the Reference Group. This report proposed a refined research team structure and communicated the various technical task teams' understanding of the problem and required tasks. The purpose of the inception report was therefore act as an internal document to collate and document pertinent information in order to:

- understand the project's requirements and brief;
- define the objectives, methodologies, tasks, knowledge gaps, deliverables and anticipated outcomes of each technical task team;
- provide background information relevant to the project; and
- consolidate supporting information.

The inception report therefore contributed to:

- focussed discussions between relevant parties; and
- understand the research project brief and requirements.

Workshops to present concept DSS and interim findings

A workshop was held at Golder Associates on 4 May 2005 with 34 participants represented by industry, consultants and regulatory authorities to discuss the concept DSS. The workshop had two main objectives, namely:

- to present and discuss the draft report on the development of a preliminary DSS; and
- for key stakeholders to provide input into the development of the DSS, especially from the perspective of regulators/authorities and the mining industry.

Consensus on the overall approach and methodology was reached regarding the following:

- Top-down approach adopted for the DSS.
- Precautionary approach.
- Risk-based approach.
- Three ‘legs’ of the DSS consisting of the main framework of questions in the middle and guidance on the use of the DSS on the left and criteria on the right.
- Expansion of the DSS in due course to become more comprehensive and complete.
- Knowledge gaps.

Workshop to present outcomes of the research and discuss future research

A workshop was held at the WRC on 31 May 2006 to identify follow-on research aimed at closing the most important knowledge gaps identified in the initial research project. The session was used to introduce the subject and the participants were required to make inputs in order to determine the most important gaps in knowledge which currently exist. This in turn enabled the WRC to formulate the aims, rationale and deliverables for continued solicited research.

2 WORK PROGRAMME

The preliminary decision-support system (DSS) was developed with existing knowledge and information and necessitated following the precautionary principle and use of conservative assumptions to satisfy environmental concerns and compliance with the other two requirements of the sustainable development, namely economic viability and social acceptability.

The report describes the concepts and principles of a DSS with the purpose of providing stakeholders involved in decision making and management associated with the environmental acceptability of mine residue disposal facilities (MRDFs) with a rational framework of questions. The framework can simplistically be described as a tool to facilitate and guide decision making related to biophysical, social and economic components, as well as the connections within and between these components.

2.1 Overall research programme aim

The overall aim of the WRC research programme is to develop a DSS that can be used primarily to aid regulatory authorities in assessing the acceptability of current or proposed MRDFs and can be of equal value to proponents and consultants for the same purpose. The present research project is the first phase of a more extensive research programme stretching over a five to ten year period resulting in a final DSS. The highlighted section below, Phase 1, is the topic of this research initiative.

Phase 1: Develop a preliminary DSS making optimal use of available local and international information and identify knowledge gaps that need to be addressed in order to develop an expanded final DSS.

Phase 2: Research and investigate the gaps identified during Phase 1.

Phase 3: Develop a comprehensive DSS that builds on the experience with the preliminary DSS and the findings of Phase 2.

2.2 Phase I project brief

In developing a consensus understanding of the brief it is useful to interrogate or 'unpack' the project title, "Development of a first order DSS for the sustainable design, operation and closure of metalliferous tailings disposal facilities". It is clear from the documentation that the specific project awarded at this time envisages much more work than will be required to complete a comprehensive DSS. This project may therefore be seen as the first phase of a ten-year programme.

Development in the title therefore implies the beginning of the whole process or the completion of the first part of the process.

First order may perhaps be somewhat misleading in that the meaning could be better described by "preliminary", i.e. the preliminary design of the system. It is not envisaged that there will finally be first order, second order or third order systems since this would imply that a proposed project will be evaluated by subjecting it to a succession of such ordered systems, which is not the intention. It is foreseen that there will be one system albeit this may contain subsystems i.e.

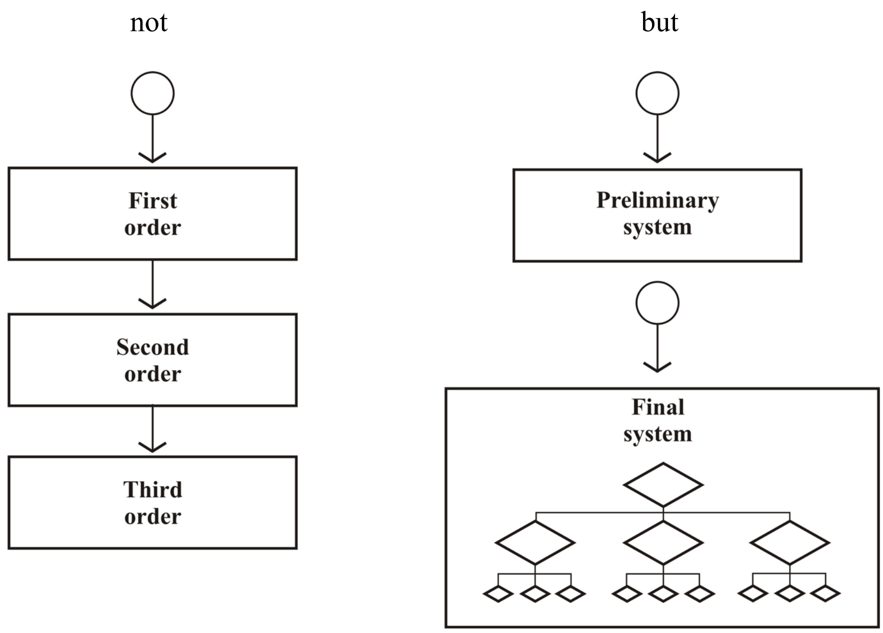

Figure 3: *Concept DSS framework.*

<u>Decision-support system</u>. The DSS supports decision making and does not replace decision makers. This emphasis is important as it stresses the fact that decision making utilises models and tools appropriate for the problem and leaves the rest to the decision maker. The system in this context does not imply a fully automated computer system, but rather a rational framework possibly with access to some form of interaction with computerised models.

Evaluation of proposed or active tailings disposal facilities in terms of environmental impact requires posing numerous questions to determine whether the facility will comply with various criteria or not. The nature of the criteria is typically set in the government regulations although the specific measurable criteria may not be. The evaluation process is in a sense an integration of the responses to questions initiated by regulations. The process must result in a permitting decision which concludes whether the proposed mine residue disposal facility (MRDF) is acceptable, unacceptable or some conditional response where additional information is needed.

It is essential that the questions to be addressed and the evaluation of the responses should be an industry agreed and transparent process. To this end a DSS was developed that is a framework of questions comprising a network in series and parallel (Figure 4). The serial elements concern individual issues which may require a succession of questions to produce a definitive answer while the parallel elements address different issues, or aspects, for example groundwater or slope stability. In general the system questions are of the form, "Does the particular situation comply with a set of predetermined criteria?" The system itself poses these questions within a rational hierarchical framework. Perhaps the emphasis should be on the word support since it is not intended that the system should generate decisions, it must guide the decision maker through the issues which need to be considered and addressed in order to ensure all relevant issues are adequately dealt with.

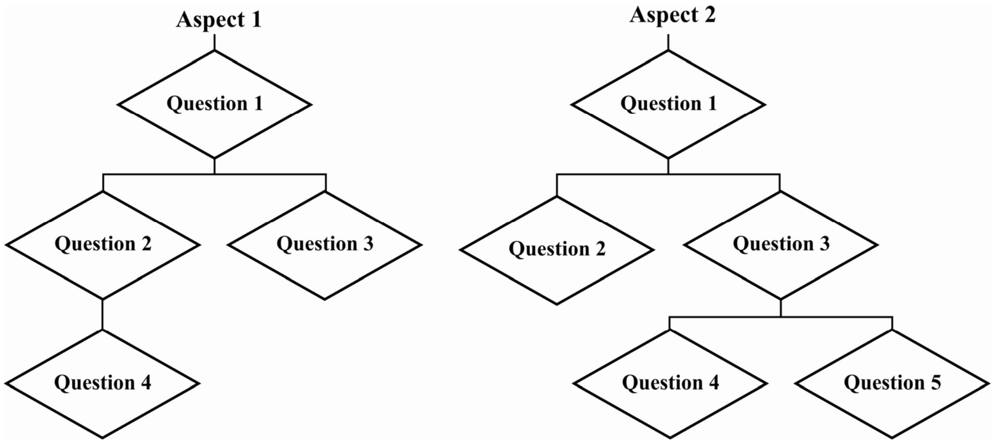

Figure 4: Top down levels questions relating to the different aspects.

It is accepted that the user of the system is knowledgeable on all issues being addressed and could have addressed them outside of the system. The system therefore provides a rational method for addressing all the issues and for recording the outcomes so that transparency is achieved.

<u>Sustainable</u> – this has become laden with so many meanings that it has no universal definition. In this context, however, it was taken to mean that the MRDF should comply with all the environmental requirements. Whether these requirements in themselves result in sustainability may well be a different issue. In this context sustainable is understood to mean, “for ensuring compliance with the relevant standards, criteria and good practice”.

The last phrase emphasizes that the DSS should apply throughout the complete life cycle of the MRDF. This is understood to mean that the system could be applied at the planning phase, at an intermediate operation phase to audit compliance and at pre and post closure phases.

2.3 Phase I project deliverables and outcomes

The deliverable and outcomes for the project included:

- Developing a DSS framework for the sustainable design, operation and closure of metalliferous MRDFs which included:
  - Conceptualisation of the DSS framework.
  - Developing the DSS framework components of the two technical disciplines.
  - Developing the decision/logic trees for the two technical aspects of water and surface stability.
- Review of the state of the knowledge with respect to water, geochemistry and surface stability.
- The hosting of a workshop to solicit input from decision makers and reach consensus on the developed DSS.
- Identification of knowledge gaps.
- Final report.

2.4 Phase I project objectives

The following research objectives were outlined in the WRC proposal:

- to develop a first order DSS for the sustainable design, operation and closure of metalliferous mine residue facilities;
- to define the research gaps and deliverables that need to be provided by follow-on research projects in order to close the knowledge gaps that are identified during the development of the first order DSS; and
- to involve stakeholders in the development and refinement of the DSS and conduct appropriate technology transfer activities.

2.4.1 DSS framework objectives

The following overall DSS framework objectives had been formulated:

- to develop a DSS which will rationally address key issues pertaining to a MRDF resulting in a decision of the type that the scheme is either acceptable or unacceptable.
- to provide decision-makers with sufficient information and guidance when considering MRDFs during the phase under consideration to make consistent and transparent informed decisions.
- to assist with decision-making at the key points in the stages of the life of a MRDF (outlined in Figure 5):
  - conceptualisation, planning and site choice in order to continue with feasibility studies;
  - planning and design in order to consider whether a scheme can continue into the operational phase; and
  - closure planning and design to seek approval of the closure plan.

Although not a stated objective, one of the outcomes of the DSS would be to assist in the auditing and performance assessment at any given time of the above-mentioned phases. Mine residue disposal facilities pass through at least four distinct management phases namely the development, operational, rehabilitation and closure and lastly the post-closure stage. The development stage typically includes aspects such as conceptualisation, preliminary planning, site selection and design whereas the operational stage includes construction and deposition. The final stages include decommissioning, rehabilitation, closure followed by a post-closure stage entailing aftercare, maintenance and monitoring.

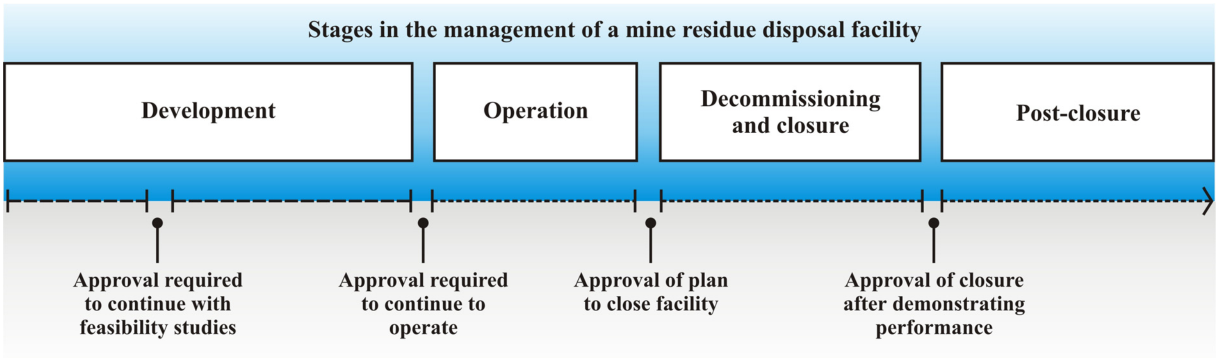

Figure 5: Example of decision-making points during the life cycle of a mine residue disposal facility.

It is postulated that the essence of the system is to pose technical questions at each decision-making point which must be answered favourably for the project to be considered and ultimately approved. These questions consist of a set of basically similar questions with a singular format, which is:

- Will the action result in an environmental impact which is acceptable?

The following steps are required to develop the comprehensive decision-making tree:

- List the activity/activities (the activity causes the impact on aspects of the receiving environment).
- List the environmental aspect under consideration, i.e. develop an aspect register.
- Document what is believed to be the main source(s) of pollution, i.e. the cause of the pollution of the resource.
- Consider methods to be used to estimate the pollution either through prediction or measurement.
- Compare results from the steps above to criteria – i.e. local as well as international limit values in order to evaluate the scheme's impact.
- Determine the acceptability of the scheme's impact on the particular aspect.

The environment can be described as the surroundings in which a scheme is proposed including air, water, soil and landform, i.e. that which provides suitable habitats for humans, animals and plants (receptors) and their interaction (Figure 6). The National Environmental Management Act No. 107 of 1998 (NEMA) defines the environment as the surroundings within which humans exist and that are made up of:

- The soil and landform, water and atmosphere of the earth;
- Micro-organisms, plant and animal life;
- Any part or combination of the above and the interrelationships among and between them; and
- The physical, chemical, aesthetic and cultural properties and conditions of the foregoing that influence human health and well-being.

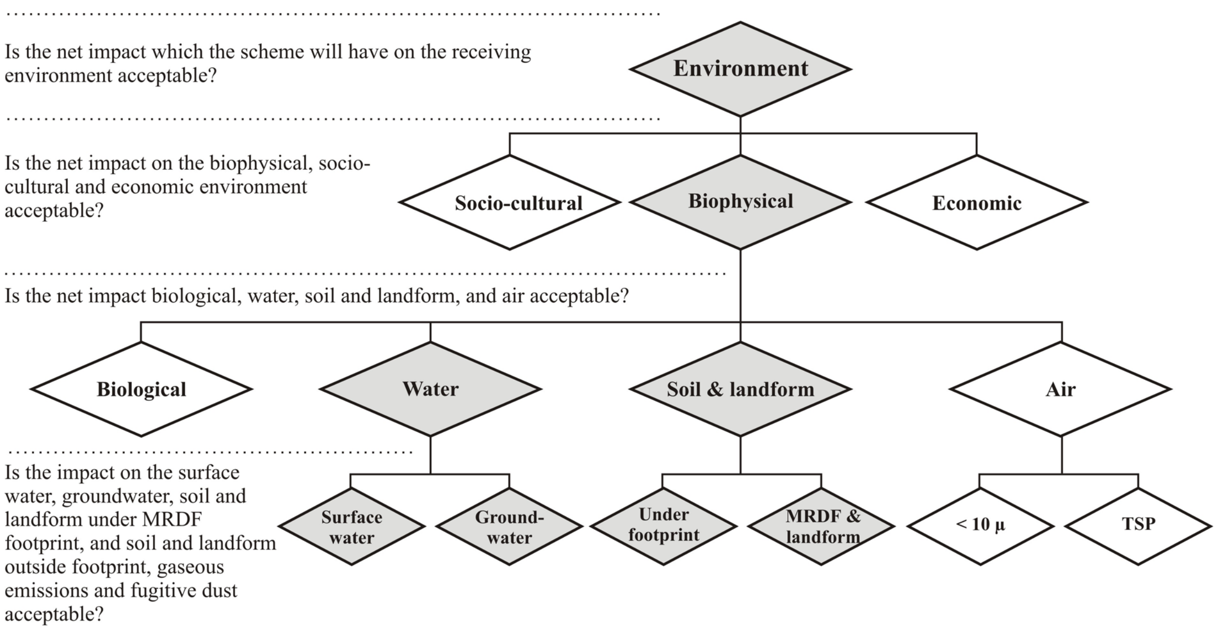

Figure 6: Hierarchy of questions developed for the DSS.

Although the three receiving environment can therefore simplistically be categorised as the:
- Biophysical environment (air, water, soil and landform, fauna and flora);
- Socio-cultural environment (people, visual, heritage and land-use); and
- Economic environment.

The first phase of the research only deals with two biophysical aspects namely that related to the water and soil and landform components (the parts highlighted in Figure 6).

It is therefore important to understand the potential impacts of a scheme on the environment. It is understood that a scheme could cause changes in the environment which in turn will impact either on the health or comfort of people, plants or animals. This however does not tell how these impacts occur or how they are measured but are simplistic descriptions only, but albeit sufficient to begin the process. It is therefore necessary define the mechanics of the process of how for example the impact on air quality takes place, i.e. fugitive dust generated from exposed surface areas and how this causes the adverse impacts on the receiving environment. The DSS considers the contaminants associated with the scheme, the contaminant source release, environmental transport mechanisms and transformation, human exposure and dose, and the potential risk of each contaminant. Depending on the type of source zone (impoundment, vadose zone or aquifer for example) it can be assumed that the environmental transport pathway could be by means of leaching (groundwater pathway), wind suspension and volatization (atmospheric pathway) and lastly water erosion and overland flow (surface water pathway). In addition, with gold mine residue, contaminants could be lost from the zone by radioactive decay or degeneration from the zone (MEPAS, 1996).

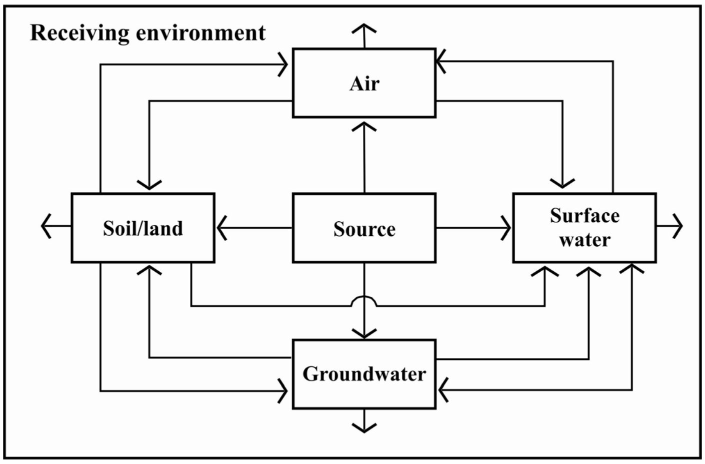

Figure 7: Schematic relationship of the building blocks of the receiving environment.

2.4.2 Water module objectives

The objectives of the water module task team were:
- to develop and contribute to the groundwater and surface water decision matrix to be integrated into the first order DSS;
- define research gaps in understanding seepage volume and quality and how this seepage may impact on the receiving ground and surface water resources; and
- participate in stakeholder involvement in the development and refinement of the first order DSS.

2.4.3 Surface stability module objectives

The objectives of the surface stability module task team were:

- to develop and contribute the surface stability decision matrix to be integrated into the first order DSS;
- define research gaps in the surface stability aspects of erosion and surface runoff quantity and quality which will need to be addressed in follow-on research projects in order to close the knowledge gaps that are identified during the development of the first order DSS; and
- participate in stakeholder involvement in the development and refinement of the first order DSS and contribute to technology transfer activities.

2.5 Project team structure

This WRC research project is based on two inputs from:

- An internal steering committee (ISC) comprising experienced academics, consultants and operators who ensured that the DSS is delivered in a practical and usable format; and
- An external group of stakeholders to obtain information and to solicit ideas during the formative stages of the project and to obtain buy-in to the final result, towards the end of the project.

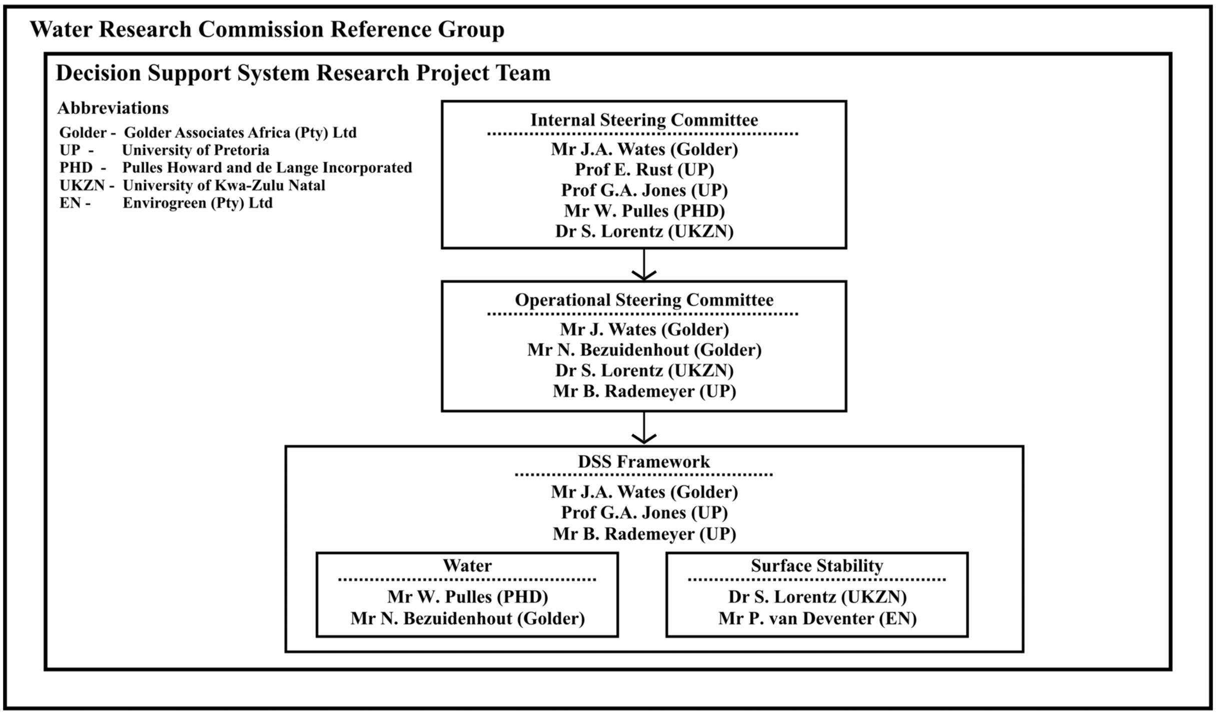

Figure 8: The DSS project team structure.

The research team structure includes the following three disciplines (Figure 8):

- DSS framework task team;
- Water module task team; and
- Surface stability module task team.

At an early stage each specialist technical task team determined which aspects they could deal with rationally with present knowledge and which impacts they could not deal with, and why not. The technical task teams defined the current state of knowledge as well as established the criteria required to support the precautionary route of the DSS. Each expert group provided technical input relating to their specialist field. Integration between the various technical disciplines was facilitated by the operational steering committee (OSC) and the internal steering committee (ISC) ensured that the tasks were completed on time and within budget.

3 DECISION-MAKING THEORY

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3.1 Introduction

The proposed decision-support system (DSS) is an example of the application of how the concept of decision making can be applied to the judgement of the environmental acceptability of mine residue disposal facilities (MRDFs). This section provides a general commentary on making decisions, and the systems and frameworks used to support the process. Hence the term DSS to describe a framework comprising questions in support of the decision making process.

3.2 Decision-making theory

Decisions, ranging from elementary to complex, are continually made by everyone. A DSS supports decision making by assisting with organizing the relevant aspects within a rational framework (Sage, 1991:1). The framework provides support to decision makers through increasing the effectiveness of the decision-making process. The rational choice process allows for:

- The formulation of a number of different alternatives;
- Cause and effect analysis of each alternative, as each alternative will have a set of consequences; and
- Interpretation and selection of the preferred outcome for the scheme by ranking the consequences according to a system of preference.

A key question to developing a DSS is:

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Decision techniques range between the simple selection between two alternatives proceeding to a more complex multi-alternative decision-making process where each alternative has a number of factors influencing the final selection. As a decision becomes more complex, so does the process involved in making a selection.

Using a DSS should support a number of abilities, namely:

- support decision makers in the formulation, or framing, or assessment of the decision situation in the sense of recognising needs and identifying appropriate objectives by which to measure acceptable resolution of issues;
- provide decision makers with the ability to understand the impacts of different courses of action; and
- provide guidance to determine the environmental acceptability of alternatives leading to choosing a preferred configuration.

The purpose of a DSS is to support people in the processing of primarily cognitive tasks that involve decisions, judgements and choices (Sage, 1991:4). Associated with these three steps of decision making must be the ability to acquire, represent, and utilize information or knowledge and the ability to implement the chosen alternative course of action. This must be accomplished with a rational perspective of the decision making process used. Fundamental to the notion of a DSS is assistance provided in:

- Assessing the situation;
- Identifying alternatives;
- Formulating the decision problem; and
- Structuring the decision

in such a rational way that using the system will result in an outcome relating to the acceptability of an alternative.

The following key ingredients are required for effective decision making:

- Availability of quality, factual and defendable data;
- Knowledgeable and experienced decision makers understanding the scope of the problem;
- Best practice methods to analyse problems; and
- Expert judgement to combine facts, knowledge, experience and analysis.

3.2.1 Variability in information relative to decision making

Keen (1978:83) discusses the variables that influence the information that should be obtained relative to any given decision making situation. Although the variables are task dependent it is important that the available information deals with the following:

- <u>Inherent accuracy</u>- Information for strategic planning situations is often uncertain, imprecise, and incomplete.
- <u>Level of detail</u> - Aggregated information is often sufficient for strategic planning situations whereas more detailed information is required to answer specific operational questions.
- <u>Time frame for information requirements</u> - Strategic decisions are often founded on information and predictions based on long time frames where the nature of control is infrequent.
- <u>Frequency of decision making</u> – Although strategic decisions are usually made less frequently than operational decisions, it could be required to refine strategic decisions more often.
- <u>Information source</u> – Strategic decision making makes use of information from many external sources.
- <u>Scope of information</u> - Strategic decisions are based on information with a broad scope. It is also possible that a wide range of factors cannot be fully anticipated or quantified prior to the need for a decision.

- Ability to quantify information - Information required for strategic planning decisions is initially likely to be qualitative with quantitative information only becoming available as the planning process progresses.
- Recentness of information - It is often difficult to obtain recent and current information necessary to make strategic planning decisions.

3.2.2 Decision loop

Decision makers, such as environmental managers, are often required to follow some sort of rational planning process to arrive at objectives, policies or strategies. While there is no single set of rules, they all relate to decisions of different sorts. Although decision making ranges between being simplistic and complex and may even relate to different fields of management such decisions can be guided by the simplistic closed loop decision-making process illustrated in Figure 9. The closed loop decision-making process comprises typical steps common to most decision-making circumstances.

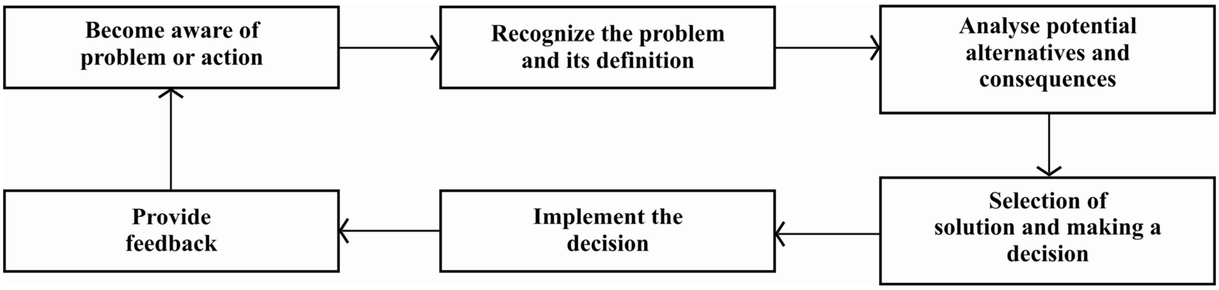


Figure 9: Closed loop decision-making process comprising typical steps common to most decision-making circumstances (after Moody, 1983:1).

3.2.3 Time, cost and benefit, and uncertainty of decisions

It is important to be able to decide when enough facts have been gathered to make an informed and rational decision. Gathering facts takes time and costs money. Moody (1983:4) provides useful graphs indicating the conceptual relationship between cost and benefit over time (Figure 10). The more time spent gathering information and facts to make a decision the greater the total related cost would be. There is a point in time when the cost of gathering information outweighs the derived benefit. In addition, facts are gathered to limit uncertainty in decision making. Although uncertainty decreases as time passes and the amount of data increases it will never reach zero. At a certain point the cost of collecting data does not increase the effectiveness of the final decision and further delays would pass the optimum decision-making point and increase the total cost of the process.

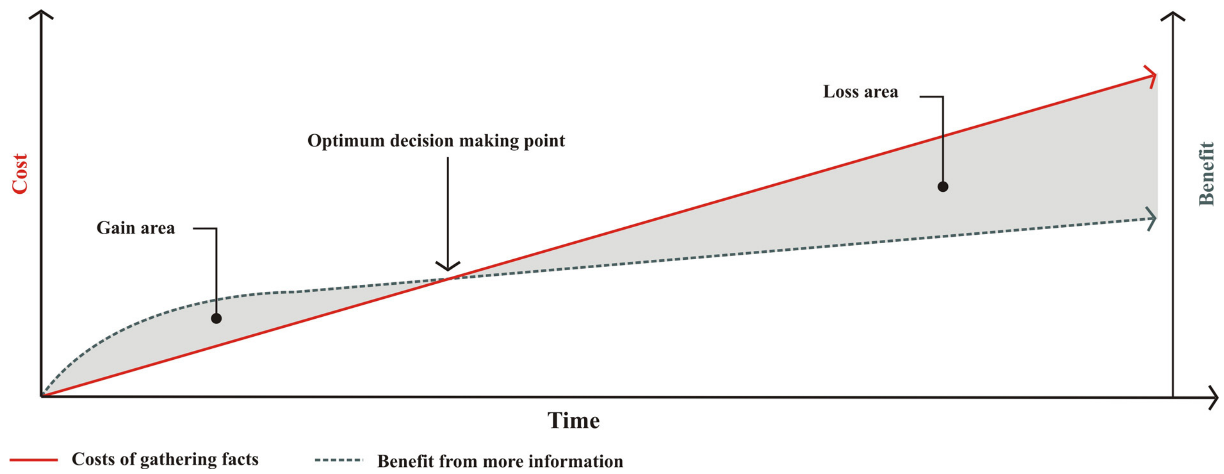


Figure 10: The theoretical optimum decision-making point lies at the cross over point of cost, benefit and uncertainty (after Moody, 1983:5).

3.2.4 Rational decision making

Rational decision making involves:

- growing awareness and identification of the problem,
- determining who and what the stakeholders are,
- whether a solution is possible,
- identification of alternatives,
- considering of consequences,
- selection of the most acceptable solution,
- implementation of the decision, and
- providing feedback from monitoring

in order to close the dynamic decision making loop (Moody, 1983:60).

Political decision making, on the other hand, can be seen as a personalised bargaining process between organisational units and it is argued that power of influence determines the outcome of any given decision (Keen, 1978:63).

3.3 Conclusions

The development of a decision framework comprising questions supported by decision guidance and decision criteria to examine key questions such as whether or not seepage from a proposed MRDF exceeds water quality criteria. Although various factors influence the ultimate decision as to the acceptability of a scheme, it is believed that the overall framework and modelled environmental aspects provide sufficient structure to answer the relevant questions. The preliminary framework is robust enough to allow the addition of information and knowledge if and when it becomes available. It can also be said that as more information becomes available the risk of uncertainty will decrease.

Therefore, the overall objectives of the decision framework are:

- to represent some sort of real-world situation of MRDFs that is simplistic and understandable;
- to assist decision making with regard to the acceptability of the proposed scheme's impact on the environment;
- to provide decision makers with a framework for the decisions related to the former point that involve decisions, judgements and choice; and
- to contextualise some of the factors which influence such decisions.

Because decision making regarding the acceptability of the sustainable configuration of MRDFs is a complex task it is important that the DSS has to be developed and expanded in order to facilitate transparent decision making amongst the relevant stakeholders. The DSS also needs to keep a holistic perspective of sustainability during the key stages of development and must provide a rational framework for biophysical, socio-cultural and economic aspects as well as specific related criteria to facilitate "holistic" judgment.

4 DECISION-SUPPORT SYSTEM

The decision-support system (DSS) is a rules-based decision-making system following a tiered approach (Figure 11) which evaluates the mine residue disposal facility (MRDF) with a checklist guiding the user through a series of choices that would have to be answered in the affirmative. It is intended that questions must be answered in the affirmative at each point or node, before being able to move on to the next question or decision-making node. Specialists will develop and expand the checklists in time by referring to minimum standards, regulations and best practice. The overall objective is to compile a list of questions for all of the environmental aspects in order to ultimately answer the question as to whether the proposed scheme's net impact on the environment is acceptable or not? Decision guidance and decision criteria are provided at each decision-making level in the DSS. Essentially there is a question: 'Is this or that characteristic satisfactory?' This can only be answered if there is a set of decision criteria against which to measure. An important component of the decision criteria will be to provide decision makers with a list of all the relevant regulatory approvals as well as to describe their purpose, compliance and reporting requirements, and respective periods of applicability. For example, typical water quality discharge standards and receiving water quality objectives are provided in the South African Water Quality Standards published by DWAF. There are also licence requirement levels for radioactivity and guidance as to the protection of fauna and flora.

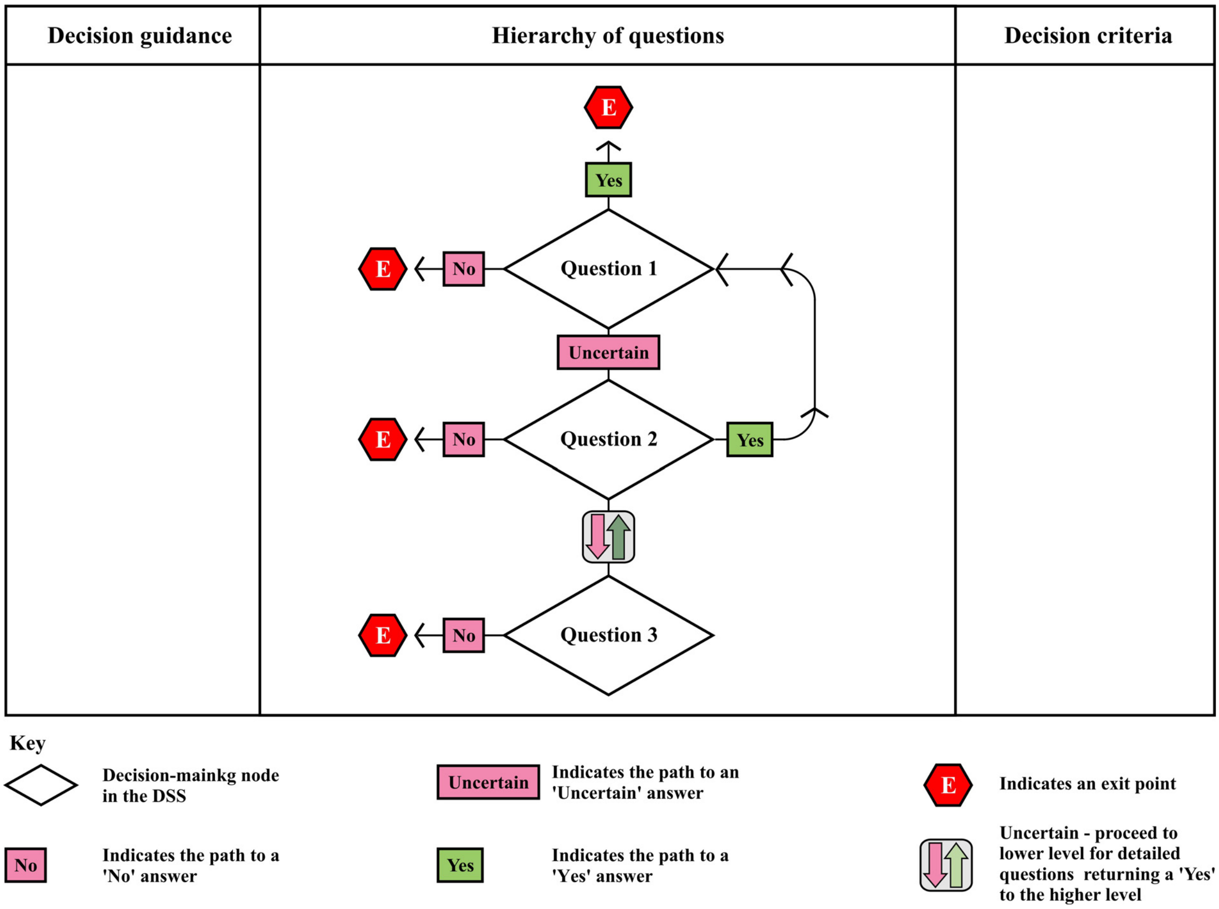


Figure 11: Concept DSS framework.

Since very simple YES/NO answers are unlikely, i.e. the measurement or prediction of a characteristic is not that simple, the questioner is provided with help, i.e. decision guidance. Criteria are immutable, in theory at any one time, and are built into regulations. Guidance on the other hand is a description of how judgment can be applied which leads to a decision. The decision guidance is a set of judgement rules and is not expected to always be hard and fast but deals with the situation where a characteristic exceeds the normal criteria (NO answer) but could still be allowable if this or that condition could be met. Guidance could also apply if a criterion is only marginally applied.

4.1 Principles

The development of the DSS was guided by a number of key principles that were applied throughout and has been demonstrated in Figure 13. These key principles are as follows:

- A tiered approach was developed, in a flowchart format, with key questions being asked at the bottom level with decisions rolled up to the top level to provide answers to strategic questions;
- The questions have been phrased in a manner that there is a consistent application of YES, NO and UNCERTAIN answers to questions where YES is always a positive outcome;
- The first level makes provision for project APPROVAL and consequent avoidance of further investigation;
- The decision guidance and criteria varies in approach / level of detail depending on project life cycle phase;
- Guidance will also be given at the different levels of the DSS;
- It is necessary that the DSS provide specific technical guidance on investigation methodologies deemed acceptable to provide a confident answer, although appropriately motivated deviation from these methodologies could be accepted;
- A risk-based approach is incorporated into the methodology and into the guidance; and
- Uncertainty will be captured in the guidance level and will be explicitly accommodated.

4.2 The DSS framework

In order to gain a better understanding of the MRDF scheme's impact on the receiving environment, the following information is required:

- Material characteristics (chemical and physical properties);
- Chemical properties (radiation, potential to leach and toxicity);
- Physical properties (particle size, moisture content, degree of compaction and colour);
- Size and dimensions of the scheme (height, size and footprint);
- Receiving environment; and
- Locality.

An initial environmental risk profiling, by applying a first-order assessment of the above-listed information, would provide the decision-maker with sufficient information to decide what level of risk might be imposed and which route ought to be followed when evaluating the scheme. On the basis of the information provided and the decisions that will be made in this assessment, one of the following paths will be chosen:

- Unacceptable hazard with a No-Go and immediate exit of DSS;

- Route where sufficient level of information is available and the scheme under consideration poses no or a low hazard - immediately come to an informed decision and not request additional information and assessments; and
- Follow and apply the precautionary path by making choices where the scheme poses an unacceptable hazard – detail of DSS contained in this path.

Figure 13 includes a series of typical questions that would have to be answered, with the level of detail and amount as well as complexity of questions increasing downwards. Essentially the DSS comprises an upper preliminary level of general questions which are independent of the lower level and must be answered positively before entry to the lower level. There can therefore be no political, technical or environmental aspects causing the scheme to be unacceptable.

Although the prime function of a MRDF is the safe, long term storage or disposal of mine residue with minimal environmental impact it is important and necessary to ensure that there are no strategic initiatives, sensitive landscapes, potential regional conflicting land uses or political reasons why the MRDF will be unacceptable.

Knowledge and information of regional planning issues are required to examine whether the MRDF scheme complies with regional planning policies. If there is any non compliance this will be resolved by getting more information on the MRDF and checking with regional planners and planning authorities as to the appropriate decision-making process.

An important part of the first level of assessment flags any fatal flaws pertaining to the MRDF under consideration. This step has been included to capture issues which otherwise might not have been included in the detailed section of the DSS. The purpose is to establish whether or not there are aspects which could potentially give rise to significant or unacceptable environmental consequences through a process of screening or 'flagging' and should ideally be initiated at the same time as any other pre-feasibility investigations.

It is important that the DSS must provide the decision-maker with sufficient decision-guidance information and decision-making criteria to make informed decision with some level of certainty. This will require demonstration that a rational and transparent process involving stakeholders was followed. A list of protocols is required to measure the stakeholder involvement process against. This can be developed if it is not already available and either included or referred to in the decision criteria column. Guidance, on the other hand, would be given to resolve cases where no clear agreement could be reached.

The overall DSS framework is illustrated in Figure 12 (p. 20) and provides the context of the water and surface stability modules. The lower level, separated by a line from the upper level in Figure 13 (p. 21), comprises the technical section which is divided into three parallel paths namely economic, biophysical and socio-cultural. At this stage of the DSS and for the foreseeable future only the biophysical component will be dealt with. The biophysical component in turn is subdivided into the parallel elements of water, soil and landform, air, and biological/ecological (refer also Figure 6, p. 8). At this initial phase of the DSS only the water and the soil and land elements are considered. The DSS is intended to operate at all the stages of a scheme (refer Figure 5, p. 7) resulting in some questions having a different level of significance at different phases.

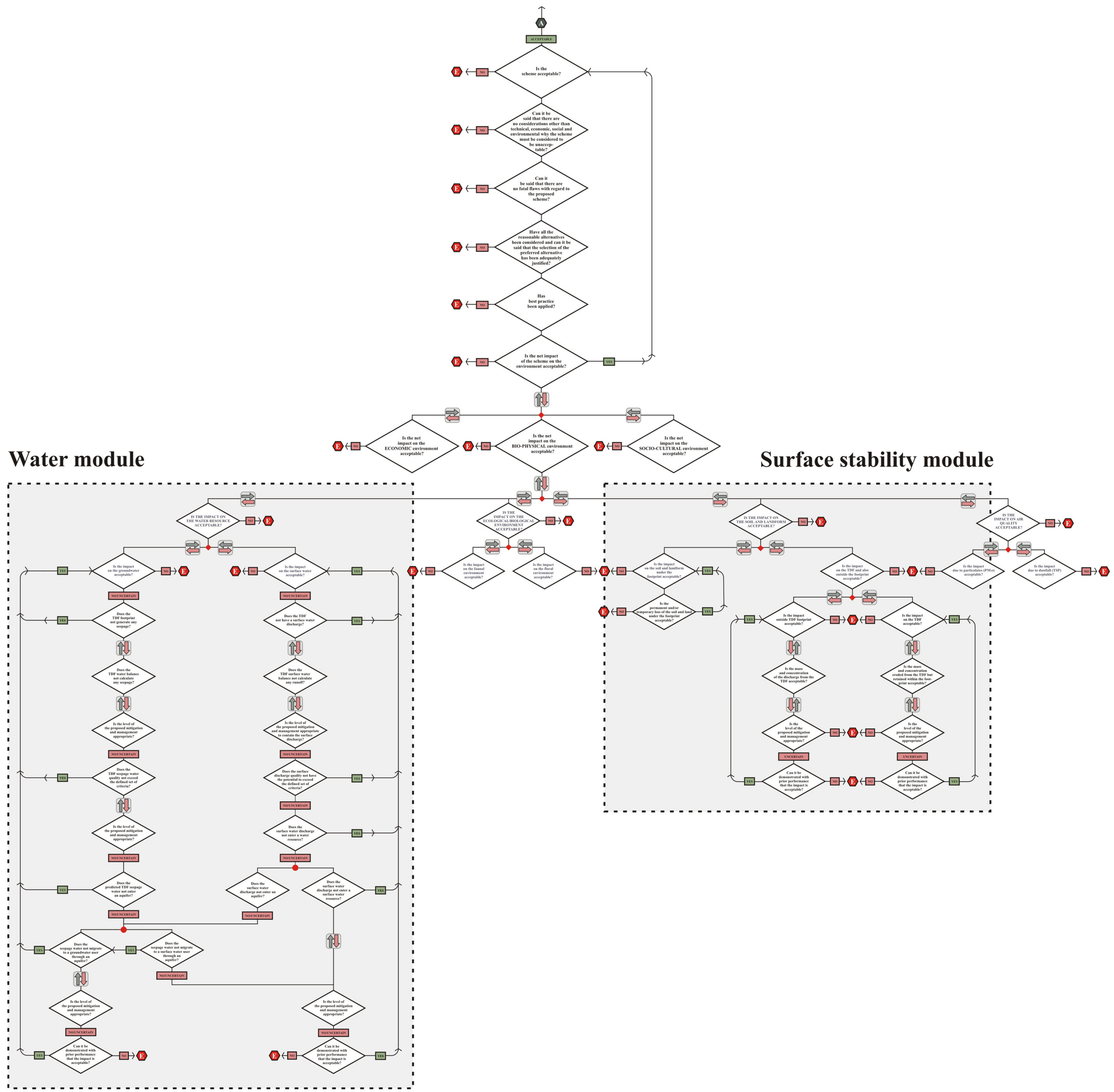


Figure 12: Overall DSS framework providing context to the two technical modules discussed in this report

Decision guidance

Is it clear from the information provided that the scheme is acceptable? The proponent must have demonstrated that the proposed or existing MRDF is acceptable for all of the stages during the life cycle.

Are there strategic initiatives, regional plans or political reasons why the scheme should be rejected? Decision making must include the afore-mentioned and is not limited to technical, social and environmental aspects only.

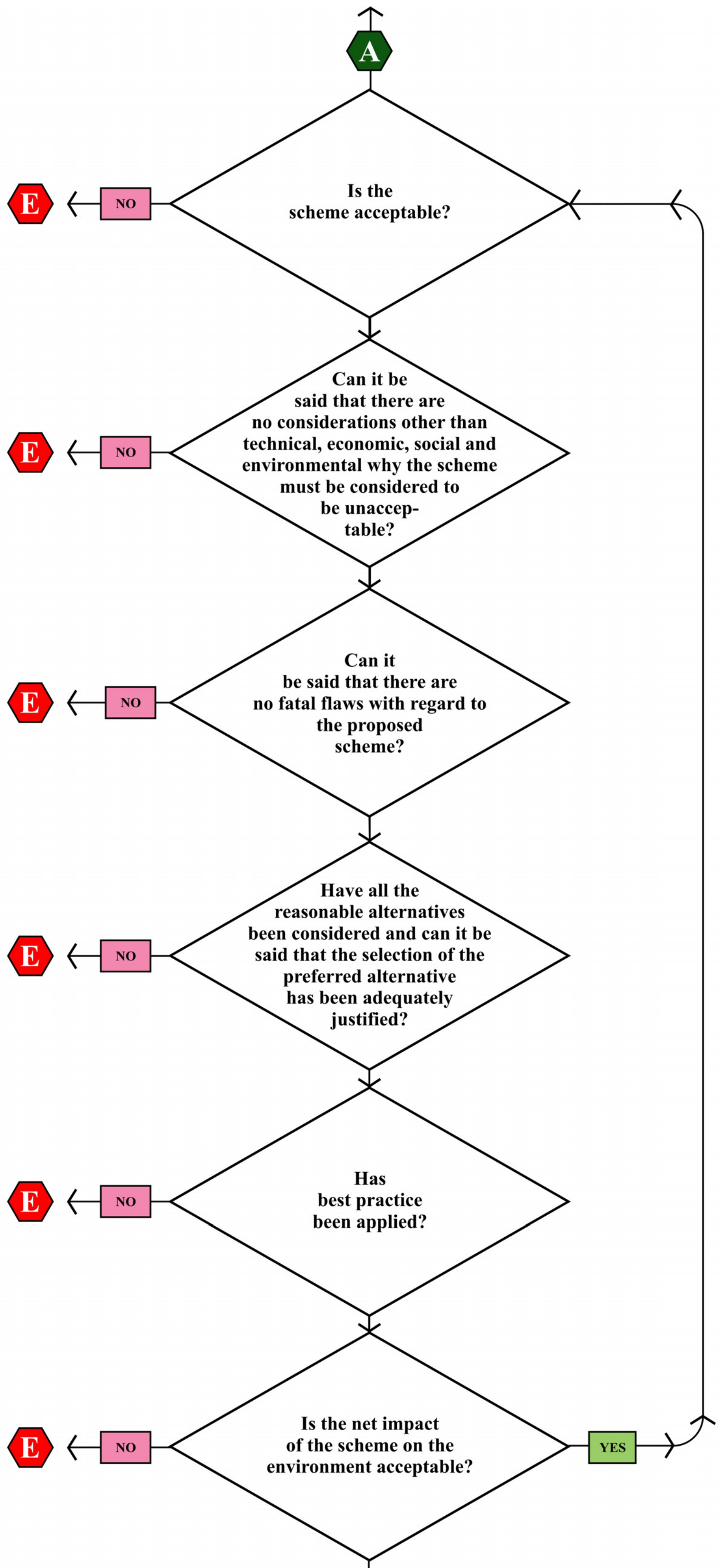
Has it been demonstrated that there are no fatal flaws pertaining to any stage of the scheme?

Have stakeholders been adequately involved and consulted regarding alternatives? Has the proponent looked at all feasible as well as alternatives proposed by stakeholders? Is it possible that stakeholders may subsequently identify alternatives which should have been considered and was not?

Has best practice been followed as a minimum? If not, has the alternative been justified?

Will the net impact of the scheme at the decision-making stages on the environment be acceptable?

Hierarchy of questions



Decision criteria

If there is any uncertainty in answering this question proceed to the lower level questions in the DSS

Present an explicit understanding of regional planning frameworks, policies, plans and initiatives and describe how these may impact on the decision. Motivate why there are no regional planning considerations which would be an obstacle to approval.

Demonstrate that there are no fatal flaws with regard to the stage of the scheme which is being considered.

Deliver a document which contains:

a) the process followed to identify and consult with stakeholders, and the issues raised

b) the process of evaluation of the alternatives in an even-handed and transparent manner on the basis of rational criteria

c) justification of the preferred alternative

Demonstrate that best practice has been followed by reference to the requirements, or alternatively present a thoroughly justified case why an alternative has been proposed.

Demonstrate that the net impact of the scheme on the environment at the stage under consideration is acceptable.

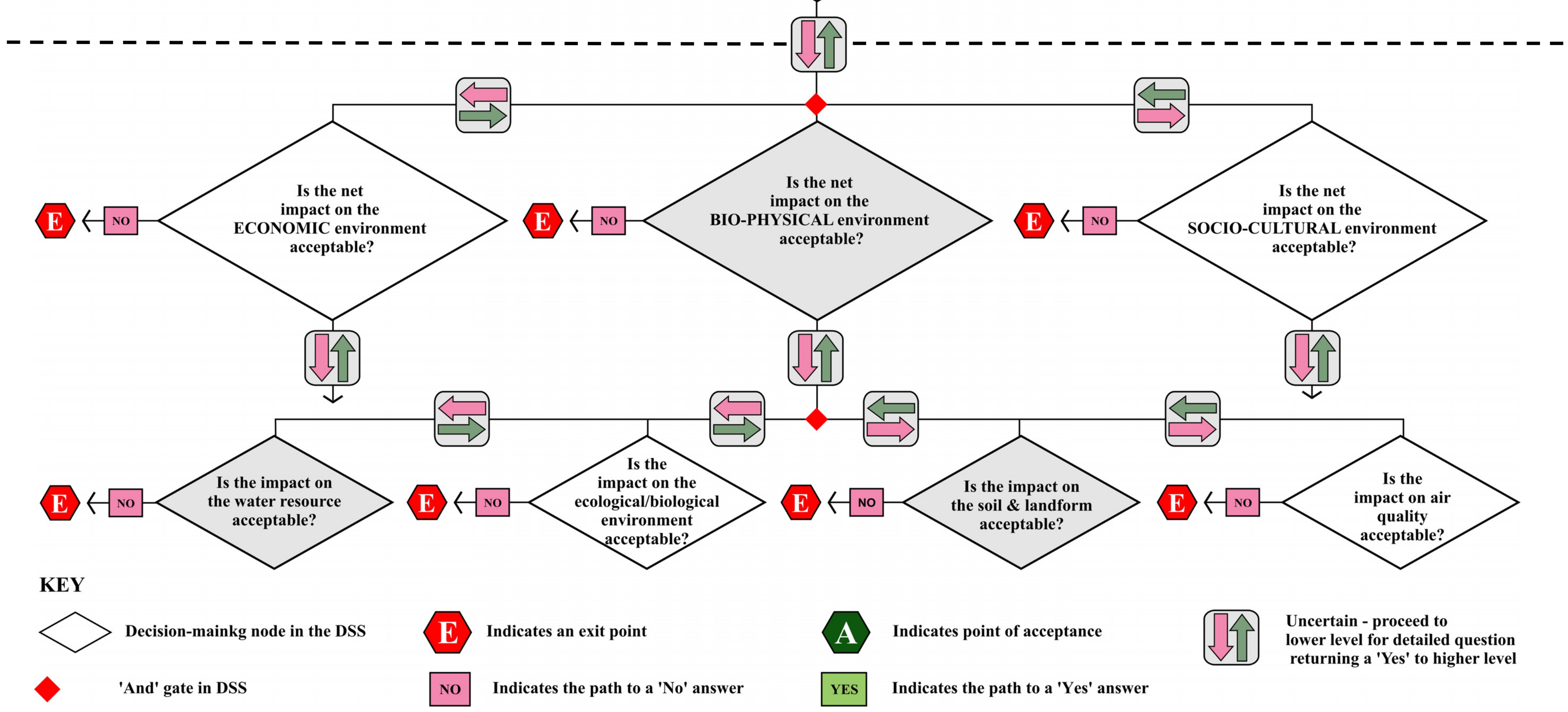


Figure 13: Demonstration of the decision guidance and criteria to the DSS components

5 TECHNICAL MODULES

Developing a decision-support system for the sustainable design, operation and closure of metalliferous mine residue disposal facilities (MRDFs). Many decisions are made about the manner in which mine residue is produced in metallurgical plants, about the way in which it is transported, and the location and manner in which it is disposed of. All of which have a significant bearing on the impact of MRDFs on the environment. For example, the decisions that are made when a metallurgical process is selected at pre-feasibility stage can have a significant impact on the environmental risks that eventually materialise many years later after decommissioning or closure. The regulators, the industry and stakeholders appreciate the existence of the relationships between the decisions that are made and the related consequences but do not yet have a formalised system to define this relationship in such a way as to inform the decisions that must be made. The preliminary DSS deals with only two of the technical modules namely water and surface stability.

5.1 Water module

Water quality impacts from mine residue disposal facilities (MRDFs) are arguably the most critical aspects that need to be considered in the life cycle of a MRDF. The water quality impacts typically relate to contaminated seepage emanating from the base of the MRDFs entering the downstream receiving groundwater and potentially surface water resources. The contaminated seepage typically contains elevated salinity and metal concentration levels.

Metalliferous mine residue could have an acid mine drainage (AMD) and/or metal leaching (ML) potential that, once set in, is very difficult to control and will prevail long after closure resulting in potentially significant downstream water (salinity and metal) water quality impacts.

Although protocols and guidelines exist today to characterise the AMD and ML potential of metalliferous mine residues, very few protocols and standardised modelling methodology are in place to predict the AMD and ML from metalliferous mine residue under site conditions. This results in designers finding it difficult to incorporate AMD and ML issues. Protocols for the handling of uncertainty in model predictions are not well developed making it difficult for regulators and decision makers to interpret modelled impacts.

Significant uncertainty still exists in the prediction of pore water quality evolution in a MRDF, especially during the decommissioning and closure phase. These uncertainties make it difficult to accurately predict impacts and propose/motivate mitigation measures further making it difficult to assess the viability of a particular MRDF.

5.1.1 Approach and principles

The development of the water module of the decision-support system (DSS) was guided by a number of key principles that were applied throughout.

These key principles are as follows:

- A tiered approach was developed with key questions asked at the bottom level and decision rolling up to the top level to provide answers to strategic questions. This approach can facilitate later conversion of the DSS into a computerised system.
- The questions are phrased in a manner such that there is a consistent application of YES/NO answers to questions where YES is always a positive response.
- The first level makes provision for project APPROVAL and consequent avoidance of further investigation.
- Decision guidance and decision criteria are given and vary in approach/level of detail depending on project life cycle stage.
- It was considered necessary that specific technical guidance on investigation methodologies deemed acceptable to provide a confident answer ought to be provided, although appropriately motivated deviation from these methodologies could be accepted.
- The risk-based approach is incorporated into the methodology and into the guidance.
- Uncertainty will be captured in the guidance level and will be explicitly accommodated.

The structure of the DSS also mirrors the traditional environmental risk assessment methodology insofar as it evaluates the impact of the particular mine residue disposal facility (MRDF), first as a source term, then in terms of pathways by which contaminants might migrate away from the source term, followed by assessment of impact at the receptor or downstream water user. This progression is shown clearly in the first-tier questions.

5.1.2 *First tier water module questions*

The first-tier questions of the water module (Figure 14) are logical and ordered in the risk assessment methodology sequence and also in a manner that allows early demonstration that the MRDF is acceptable without enforcing the need for unnecessary investigations, i.e. a correct answer at the first questions "Does the MRDF not generate any seepage?" could lead to early approval of the project from a water management perspective.

5.1.3 *Second tier water module questions*

The second-tier water management questions of the water module are differentiated into two branches on the basis of the water resource potentially being impacted upon (Figure 15 and Figure 16), these are groundwater, and surface water.

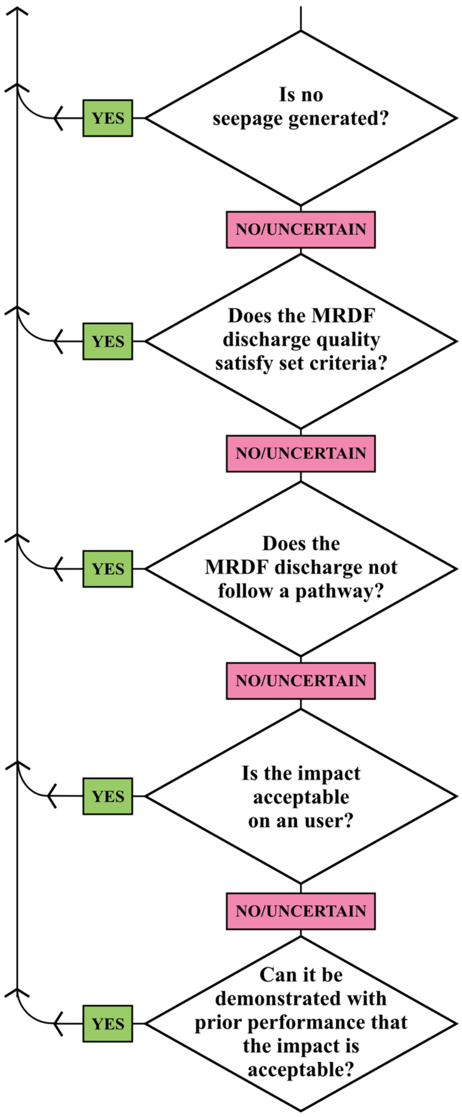


Figure 14: First tier water module questions

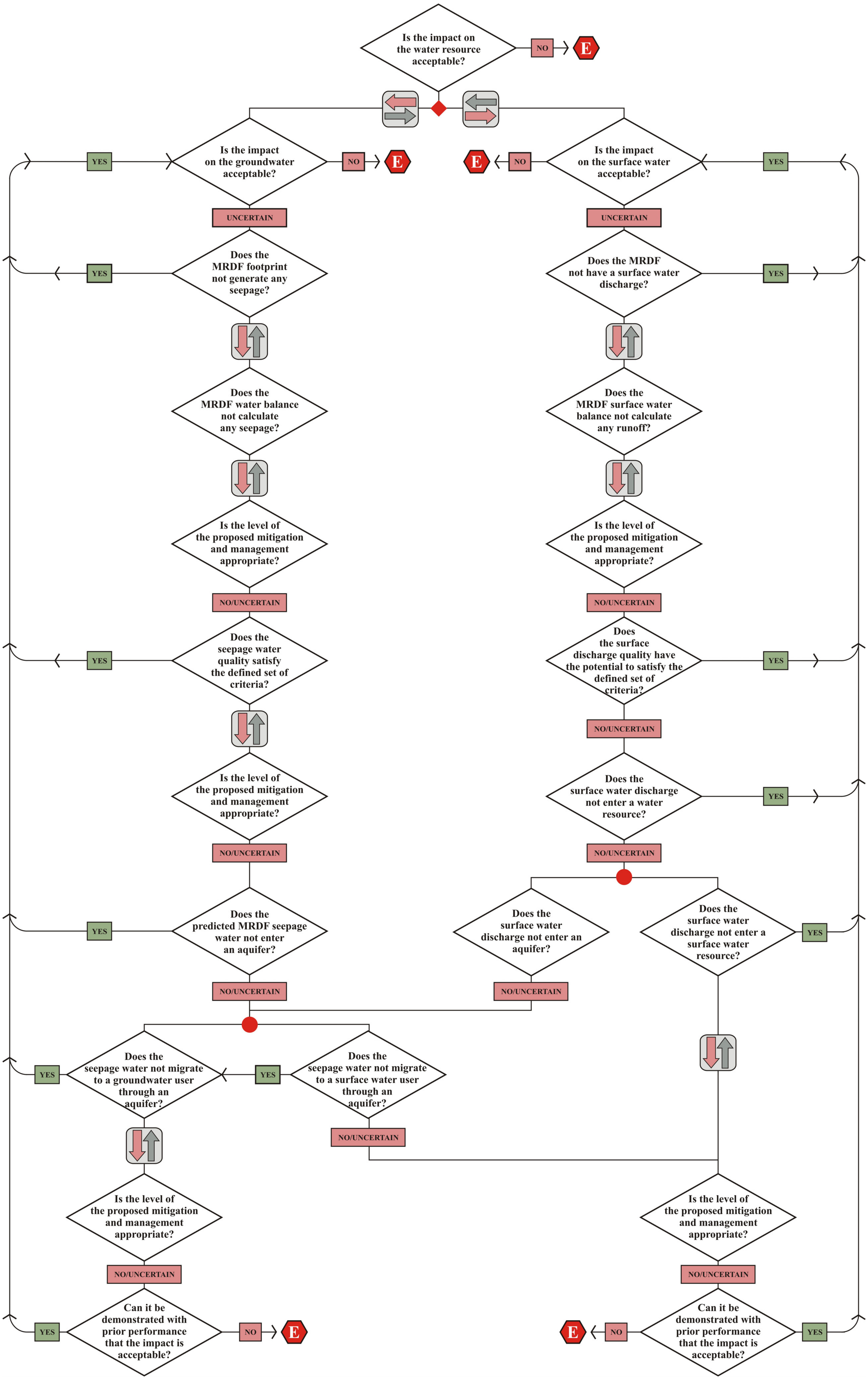


Figure 15: Water module.

The water module questions, shown in Figure 15, can either be incorporated into a manual flowchart or can serve as the basis for a rules-based computerised system. The water module also makes provision to deal with the physical and hydrological interactions between the surface and ground water resource. As is the case with first-tier questions, the answers to the second-tier questions are provided by answers given to detailed questions posed at the third-tier level.

5.1.4 Third tier water module questions

Each of the second-tier questions must be expanded into a set of third-tier questions with a similar structure. The third-tier questions have a standard structure and they seek to obtain answers to the following generic questions:

- Has the issue of concern (e.g. seepage volume; runoff volume and seepage quality) been adequately addressed for the design, construction and operational phase of the MRDF and is the result acceptable?
- Has the issue of concern (e.g. seepage volume; runoff volume and seepage quality) been adequately addressed for the closure and post-closure phase of the MRDF and is the result acceptable?
- Has the technical assessment into the issue of concern been undertaken in accordance with the guidance methodology that has been proposed?
- If the technical assessment into the issue of concern is not in accordance with the guidance methodology proposed, is there adequate technical motivation to ensure that the alternative methodology that has been used is acceptable?

The third-tier questions therefore ensure that each of the life-cycle phases of the MRDF is taken into account in the assessment and that the impact is differentiated for each of these phases. The third-tier questions also specifically evaluate the methodology that was used in deriving the answers to the impact questions, in order to ensure that all parties can have confidence in the results of the technical assessment. This focus on methodology is particularly important in areas where there are technical knowledge gaps.

The final DSS would also provide technical guidance to the regulator (who is asking the questions) and to the proponent (who is providing the information) at the third-tier level. An example of this decision guidance and decision criteria is provided in Figure 16, page 26 for the questions in the water module that relates to MRDF seepage generation potential.

The figure also indicates that the technical guidance that is provided in terms of the methodology that should be followed in undertaking the technical assessments will vary, depending on the life-cycle phase for which the assessment applies. In particular, the following levels have been defined:

- Investigations for the operational phase of the MRDF will either be undertaken as part of the project pre-feasibility and/or feasibility stage or in the detailed design phase. Pre-feasibility and feasibility investigations will be undertaken in accordance with a first-order (screening level) methodology. The investigations that accompany the detailed design should be in accordance with a third-order (full detailed investigation) methodology.
- Investigations for the closure/post-closure phase of the MRDF will be undertaken many times during the project life cycle. At the pre-feasibility/feasibility phase, the investigations relating to

post closure impact and management will be in accordance with a first-order (screening level) methodology. During the detailed design phase, the post-closure investigations will be enhanced to a second-level methodology, to reflect the uncertainties that will still be associated with the fact that the precise post-closure impact and management investigations can only be undertaken once the MRDF has been built and the as-built configuration can be used. In accordance with the MPRDA regulations, the proponent will be required to re-evaluate the post-closure impacts, management and financial provisions on an annual basis, with such investigations also being of the second-order type. At a point 5 years prior to final MRDF closure, the technical investigations on post-closure impact and management will be enhanced to a third-order (detailed) investigation that becomes the final plan. After closure, there will still be monitoring, predictive model validation and calibration and MRDF maintenance activities to be undertaken and guidance will also be provided in the DSS on these issues.

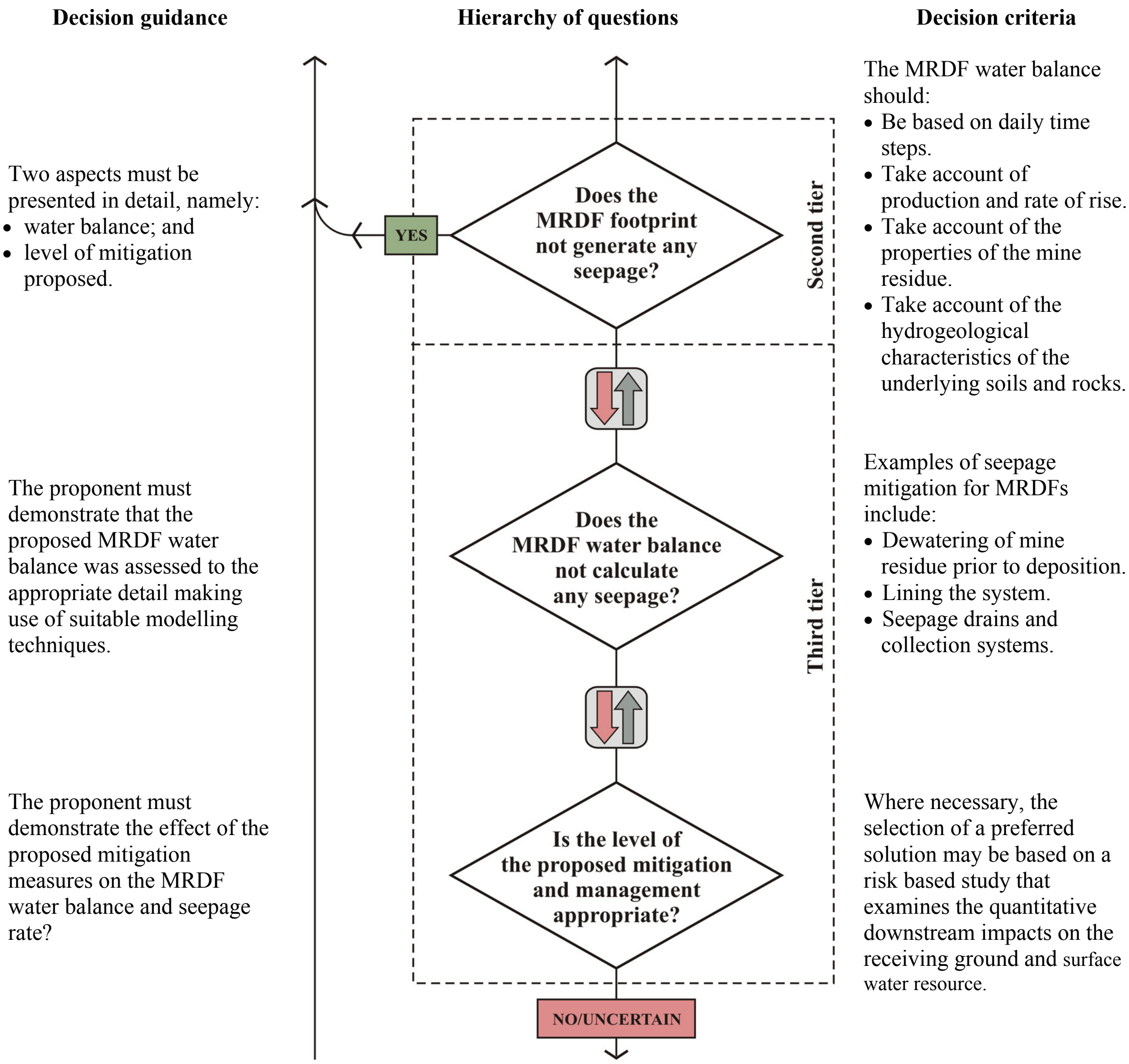


Figure 16: Water module decision guidance and criteria.

5.2 Surface stability module

Surface stability in the context of this project refers to the stability of the outer surface or over of a MRDF against erosion caused by wind and water. It is not the overall large scale geotechnical slope stability. The problem arises primarily because mine residues are usually fine grained non cohesive silts and sands. For both water and wind erosion the transported materials may be deposited both in and outside the footprint. The surface stability of the MRDF affects both the off-site impact on receiving environment as well as the integrity of the facility itself. The surface stability of the outer top surface and side slopes of MRDFs is one of the key considerations in assessing the impact of these facilities on the environment. Models exist for determining the quantity and distribution of particles eroded by wind. Similarly models such as the Revised Universal Soil Loss Equation (RUSLE) also exist to calculate surface runoff and erosion due to water. However, these models are not yet well defined and calibrated nor has acceptable criteria been defined. Nevertheless, sufficient information exists to develop a workable water erosion surface stability module. The wind erosion surface stability sub module and which will be linked to the water erosion surface stability module will be developed at a later stage. This phase comprises evaluating the state of the art of key processes affecting surface stability. A primary decision tree structure has been developed to assess the impact of a proposed MRDF during the various stages of its life. Key aspects to be addressed are the impact of the MRDF on the sediment load within and outside the footprint. It is important how the impact is quantified and also demonstration that remedial measures are sufficient.

The Universal Soil Loss Equation (USLE) was originally developed to quantify soil erosion agricultural land. The RUSLE was adapted for mining conditions. Its use on MRDF side slopes is still being researched empirically. Although this is a limitation, the equation and approach used for the RUSLE are considered adequate to be used in developing the water related surface stability module. RUSLE is used for estimating soil loss from mostly undisturbed lands experiencing overland flow, from lands undergoing disturbance, and from newly or established rehabilitated lands.

The equation is:

$$A = R.K.LS.C.P \tag{1}$$

Where:
A = Average annual soil loss in tons per acre per year (tons/ha/annum)
R = Rainfall/runoff erosivity (MJ.mm/ha/h/annum)
K = Soil erodibility (tons.h/MJ/mm)
LS = Hill slope length and steepness (dimensionless)
C = Cover-management (dimensionless)
P = Support practice (dimensionless)

The RUSLE was developed by a group of recognised scientists and soil conservationists who had considerable experience with erosional processes. Because agricultural fields invariably have flat slopes, it is generally very difficult if not impossible to extrapolate the results of studies on agricultural erosion to the very steep slopes of MRDFs.

5.2.1 Objectives

The objectives of the surface stability module of the DSS are:

- To develop and contribute the surface stability decision matrix to be integrated into the preliminary DSS for the sustainable design, operation and closure of metalliferous MRDFs.
- Define research gaps in the surface stability aspects of erosion and surface runoff quantity and quality which will need to be addressed in follow-on research projects in order to close the knowledge gaps that are identified during the development of the preliminary DSS.
- Participate in stakeholder involvement in the development and refinement of the preliminary DSS and contribute to technology transfer activities.

5.2.2 Primary decision tree

The primary decision tree comprises three tiers in which impacts under the MRDF footprint, outside the footprint and within the footprint are addressed, (Figure 17, page 26). The next tier of questions addresses the impact of the sediment load within and outside the footprint. The final tier addresses the quantification of the impact and demonstration of sufficient remedial measures.

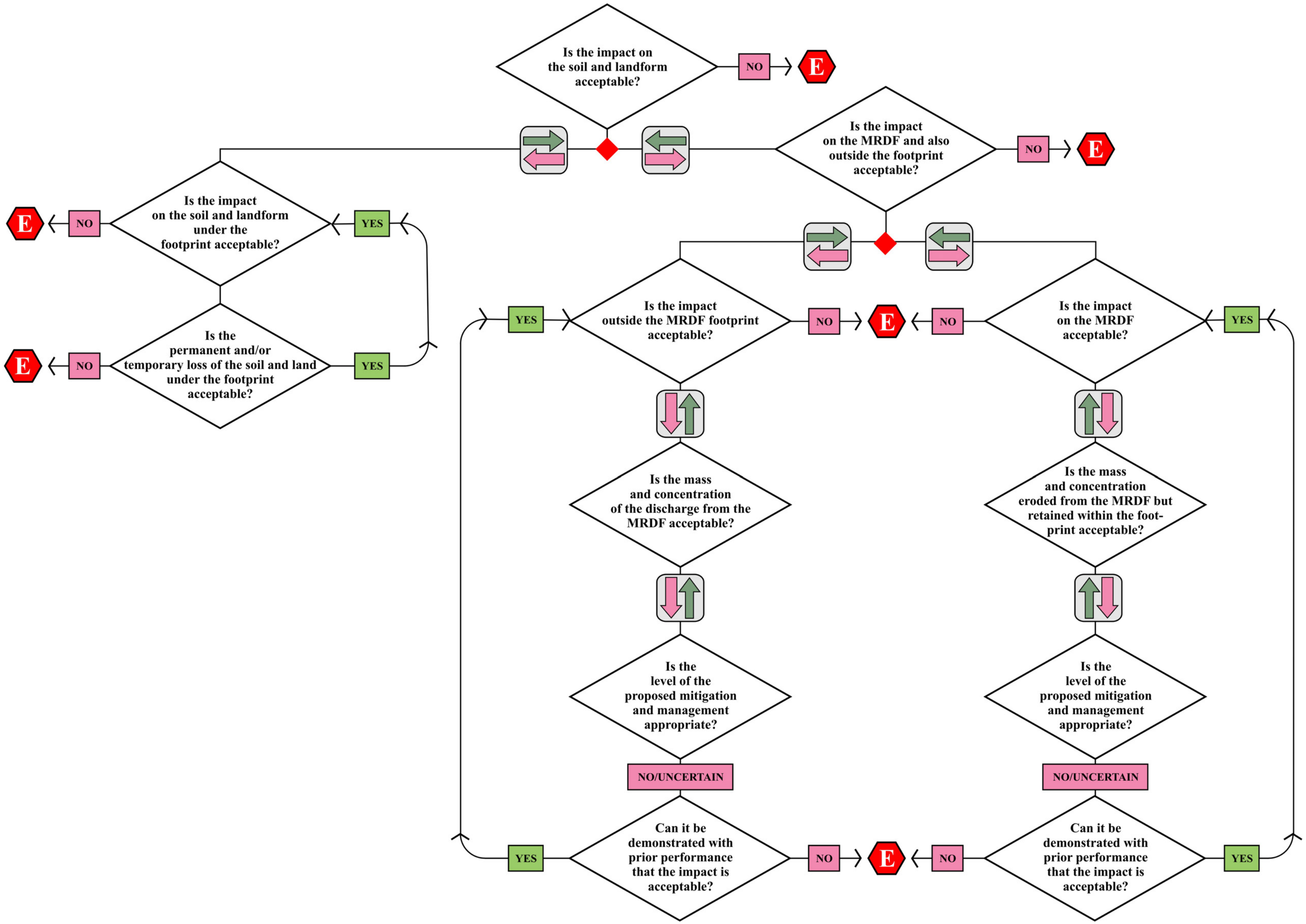


Figure 17: Surface stability module.

6 KNOWLEDGE GAPS

6.1 Water module knowledge gaps

The key technical issues that need to be addressed in evaluating and managing the water-related impacts from a MRDF are shown in Figure 15 and summarised in Table 1 and can be grouped within 11 key questions. Based on the l experience of the project team members who have undertaken numerous investigations of the type addressed by the decision-support system (DSS), the primary technical uncertainties or knowledge gaps lie in questions 3 and 4, with some significant uncertainty also contained in questions 1, 10 and 11. Questions 3 and 4 can be grouped under the heading of "source term geochemistry" and can be dealt with as a single issue in this section of the report. Question 1 relates to source term water balance. Questions 10 and 11 can be grouped under the heading "water quality impact on user".

Table 1: Summary of water module key questions.

	Groundwater questions		Surface water questions
1.	Does the MRDF footprint generate no seepage?	2.	Does the MRDF have no surface water discharge?
3.	Does the MRDF seepage water quality satisfy a defined set of criteria?	4.	Does the surface water discharge quality satisfy a defined set of criteria?
5.	Does the predicted MRDF seepage water not enter an aquifer?	6.	Does the surface water discharge avoid a surface water resource?
7.	Does the seepage water not migrate to a groundwater user through an aquifer?	8.	Does the surface water discharge avoid an aquifer?
9.	Does the seepage water not migrate to a surface water user through an aquifer?		
10.	Can it be demonstrated with prior performance that the impact is acceptable?	11.	Can it be demonstrated with prior performance that the impact is acceptable?

6.1.1 Source term geochemistry

The prediction of the quality of the seepage or runoff from a mine residue disposal facility (MRDF) is a technically complex task that requires access to a variety of specialised tools (predictive models), specialised data inputs and appropriately qualified specialists that have experience in the use of the tools. While any modelling exercise is critically dependant on the development of an appropriate conceptual model as a precursor to mathematical modelling, the particular problem with geochemical modelling is that, despite a sound conceptual model, the available models themselves can be manipulated to give a wide range of results. Where use is made of laboratory simulations as an alternative to modelling, serious problems are still experienced in extrapolating the results to serve as future predictions.

Internationally and locally, there are significant differences of opinion on which assessment methodology to apply. Certain quarters favour huge data gathering and laboratory simulation programmes (e.g. humidity cells) while other quarters favour the application of predictive models. The knowledge gap does not lie in the development of new laboratory assessment techniques or the development of new mathematical codes, although there is room for improvement in both these fields. The real primary knowledge gap lies in the inability to verify the accuracy of the assessment tools and/or models in making future predictions and to objectively assess the accuracy or suitability of any particular tool or assessment technique against the other tools that are available. This knowledge gap can really only be addressed by establishing a test facility or facilities that is/are properly instrumented and characterised and then evaluating the ability of various tools to make the correct future predictions. Only assessment techniques that have been validated through the test facility should then be accepted as appropriate for use in predictive geochemical assessments.

While the ability to verify assessment and prediction techniques will address the primary knowledge gap, there are other technical knowledge gaps that need to be addressed in order that the available tools can be confidently applied. These knowledge gaps include the following:

- Development of detailed oxygen balances for typical MRDFs that provide data on how oxygen profiles develop and change within these MRDFs.
- Development of an understanding of how deep and at what rate the oxidation zone progresses into the MRDF with time.
- Generation of fundamental data inputs, such as kinetic data for key minerals of concern, for use in predictive geochemical models.
- Development of guidelines on sample size and sample numbers in order to comply with defined confidence limits in terms of data representivity.
- Development of protocols for dealing with data and assessment uncertainties and to set guidelines on how such uncertainties should be accommodated, reported and interpreted.

6.1.2 Source term water balance

Literature values on MRDF water balances vary by more than an order of magnitude and this level of uncertainty translates into a similar level of uncertainty in the technical assessment that is based on such a water balance. Accordingly the following knowledge gap is identified:

- Development of detailed MRDF water balances through operational and post-closure phases in order to establish what portion reports to runoff, what portion reports to seepage and how the phreatic surface migrates over time.

6.1.3 Water quality impact on users

The ability to assess and/or predict the impact of a MRDF on a downstream water user, given a value for the seepage/ runoff volume and quality over time, is dependant on the application of a number of mathematical models to track the contaminants from source (MRDF) to receptor (water user). Key knowledge gaps associated with this assessment process are as follows:

- Ability to predict the progression and attenuation of contaminants as they move through the vadose and the saturated zones. While the prediction of water flow is a well-established science, the coupling of water chemistry remains problematic.
- The modelling of water quality changes along a watercourse to a receptor or water user is well developed for conservative contaminants such as sodium, but less so for non-conservative elements typically associated with MRDFs, such as sulphate, acidity/alkalinity and heavy metals.
- The precise requirements of water users are often not known and this lack of knowledge hinders the regulatory approval process and often drives the regulator to an overly conservative stance.

- The integration of geochemical, geohydrological and hydrological model datasets is a major knowledge gap and clearer guidance is required on how this problem should be addressed.

6.2 Surface stability module knowledge gaps

The major knowledge gap with respect to surface stability of MRDFs is due to the difference in material properties of normal soils and the "soil like" properties of the mine residue. Although there is a lot of information available on soils *per se*, the equivalent information on mine residue is not that well researched and investigated. A few examples are:

- The influence of clay mineralogy of natural soils on soil erosion is well documented, but in mine residues one very seldom finds natural clay minerals as in natural soils; it is rather a clay size fraction and not natural clay minerals. Therefore direct extrapolations are not that accurate and additional field verifications are required.
- Typical vegetation covers on mine residue are seldom in a stable and balanced condition compared with vegetation on soil slopes which have a certain degree of maturity and comply with some sort of sustainability parameters.
- The nutrient cycles in mine residues are far from ideal compared with soil nutrient cycles and the knowledge about nutrient cycles in mine residues are still in an infant stage.
- Natural soil profiles with rock fragments are normally graded into weathered rock and eventually into solid rock, compared to typical rock armour material which has no rock fragments at the base.
- The great variety of mine residues with respect to particle size distribution, mineralogy, geochemistry, weathering potential, hydraulic properties e.g. water retention, infiltration capacity, water holding capacity make it difficult to group them together with specific soil types with respect to stability behaviour.

These significant differences have to be investigated in field plots as well as in laboratory analyses to distinguish between soil and mine residue with respect to stability parameters and criteria.

Key questions have been divided into the components of the Revised Universal Soil Loss Equation (RUSLE), which describe the surface stability effects of material, slope, cover and practice. The two critical factors in MRDF side slopes are the slope angle and length and the material properties (Blight and Du Preez, 1997; Blight and Amponsah-Da Costa, 1999; Robertson, 2002). Key questions related to these factors (together with other key slope stability attributes that have not been discussed or identified before) are presented together with a summarized state-of-the-art.

6.2.1 Surface stability

Although the RUSLE equation is the basis for the evaluation of the surface stability module, the interaction and integration of other environmental attributes and management systems also contributes to the end product i.e. sustainable surface e.g. surface stability. Keeping in mind that vegetation establishment is currently the major form of surface stabilisation on MRDFs and also the relatively poor quality of these rehabilitation efforts, there seems to be a major knowledge gap or technical flaw with respect to the quality of the end product. A knowledge gap and technical missing link exists in current rehabilitation and closure plans. It is foreseen that a model for land rehabilitation must be developed, providing major factors and their interactions that must be taken in consideration when planning a scheme. Without such a holistic and integrated approach, the rehabilitation will most probably continue to fail as is the case with the majority of impoundment sites. In many cases rehabilitation designs underestimate certain issues, i.e. climate, materials property, geographical, pedological and geological properties, slope geometry, end product, and maintenance and management programs. The envisaged model must be developed to such an extent that it will fit into the main principles of this DSS.

It is anticipated that the definition of acceptable long term sediment loads from a MRDF would be a reliable method of assessing acceptability of long term impact. However, there are very few instances of such criterion being defined for any receiving environment. This is seen as a significant knowledge gap.

6.2.2 Material erodibility

The soil erodibility factor, K, represents the processes of soil detachment by raindrop impact and transport by surface flow and localised deposition due to topography or roughness. The K-factor can be estimated by different means depending on available information. Mc Phee *et al* (1983) have found significant agreement between the K-factors derived from the nomograph and those measured in runoff plots comprising a wide variety of soil types in southern Africa. Reliable/exact K-values can be obtained experimentally from run-off plots on the specific sites where run-off water and sediment transport are measured. Significant exceptions were noted for plots where the soil had a large percentage of stone or rock fragments and for those soils containing predominantly 2:1 swelling clays (Van Deventer *et al*, 2002). The major erodibility factors are soil physical characteristics (texture, permeability, moisture content, soil structure), organic content, exchangeable sodium percentage (ESP) and environmental factors e.g. topography (slope angle and slope length) and cover material on the soil.

The required K or LS factor is thus obtained from reliable input parameters and decisions can be made in terms of changing the cover material (from topsoil to rock armouring) or manipulating slope length, slope gradient, or both. This is the only way that the output from landscape modelling will have a high confidence level and the designing of associated mechanical measures are based on good input values. If the cover factor is less than the required cover factor then it is not necessary to alter the cover material or the slope factor LS.

<u>Key questions</u>

- Is the erodibility of the material acceptable?
  In the mining, agriculture or environmental industry there are no well defined norms, standards or parameters for acceptability of soil erosion for different soil types, topographical situations, rainfall regimes, vegetation cover types, mineralogy and geochemical reactions. All the more so if there are a great variety of mine residues. It is anticipated that specific parameters will have to be defined for specific materials in specific environmental conditions i.e. site specific.

- What are the governing criteria for application of cover material?
  The use of cover materials e.g. top soil, vegetation (with or without top soil), rock armour, rock cladding, compacted clay layers and geotextiles is a relatively new technology, especially on hostile mine residues such as gold. Therefore there are not yet well defined standards for the placing of different types of covers on MRDFs which could be guaranteed for a life time. Each mine residue type should be evaluated first before any final decision could be taken with respect to the sustainability of surface covers.

- What are the required characteristics of the cover material?
  The parameters and criteria with respect to the characteristics of the cover material will greatly been influenced by the mine residue physical properties and environmental conditions.

The cover and management factor, C is the most important factor in the RUSLE equation as a result of its considerable range (1 to 0,003), the difficulties in its estimation as well as its variation during the year. The required cover factor is obtained from reliable input parameters. Vegetation parameters such as the density, height, and weight of the aerial parts of grasses, the density, depth and weight of the root systems, and the amount and quality of plant residue from natural grass fields with different cover factors should be measured. Measuring these same plant attributes on the MRDF would then give a good indication of the actual cover factor of the vegetation on the facility

Typical top soil cover material questions are:
- Is there sufficient cover material available?
- Does the material have crusting characteristics?
- Is the material susceptible to subsurface erosion?
- Is the material susceptible to gulley formation? Is it appropriate to make use of current erosion models and erodibility concepts on mine residues, taken into account major differences between real soil and mine residue with respect to the following:
  - actual grain shape (particle shape);
  - clay mineralogy versus clay content;
  - chemical stability and balances of mine residues;
  - extreme physiochemical characteristics e.g. pH, salinity, Eh which are not possible in real soils; and
  - extreme biochemical conditions e.g. microbial activity.

<u>*Knowledge gaps*</u>
- Effects of mineralogy of mine residue on its erodibility
  Mineralogy of mine residue influences to a large extent the geochemical behaviour during the weathering of the primary minerals in the mine residue. If it contains for instance sodium minerals, it could be expected that the weathering product (which is related to soils), will contain some sodium in the cation exchange capacity regime of the newly formed material. If sodium becomes dominant as an exchangeable cation, the material could become dispersive and consequently soil erosion will increase. This is a very common phenomenon in Kimberlite mine residue. If the mine residue contains pyrite e.g. gold mine residue in South Africa, one of the weathering products is first class acidity and salination due to the oxidation processes of the pyrite. Although acidity and salination will not cause erosion, it will have a severe negative influence on vegetation covers and eventually the C factor will reduce.

- Infiltration and surface runoff on slopes
  Existing models make use of soil texture to predict hydraulic properties. Existing hydraulic models (infiltration, water retention etc.) for mine residue depends heavily on soil models with special reference to texture, but it differs vastly between soil and mine residue even if the texture are still the same. The reason for that is that the mine residue clay and silt fraction don't have the same shape and structure as in normal soils and therefore the water flow regime through a mine residue might be complete different to a similar soil with the same soil texture. The clay fraction in mine residue doesn't have a typical plate structure as in normal soils and therefore the total difference in behaviour.

- Crusting characteristics of mine residue
  Surface crusting in specific mine residue where new minerals are formed due to active weathering of the primary minerals are a common phenomena e.g. gold mine residue. One of the weathering by products is hematite which accumulates on the surface in the form of a thin coating which has a low infiltration rate and consequently more surface run-off and eventually more sediment transport to the surface water.

- Applicability of RUSLE
  RUSLE is based on soil material and not on similar textural classes of mine residue but with completely different physiochemical and geochemical characteristics. Although RUSLE was originally based on soil material, the major differences between the soil and mine residue could be investigated and where necessary, the required amendments could be made.

6.2.3 Slope length and steepness

Some research has examined existing natural materials to determine possible steady state equilibrium slope length and angle relationships. However there is very little evidence of these relationships for long term stability of mine residue. It may be that the definition of acceptable long term loads is a more reliable method of assessing acceptability of long term impact and that new definitions should be developed to incorporate mine residues.

<u>*Key questions*</u>
- Are the slope length and angle acceptable?
- Slope geometry (slope angle and length) related to soils (as used in RUSLE) should be re-defined with respect to the following:
  - interaction of length and angle;
  - interaction with other stability attributes e.g. mine residue texture and structure, crusts, hydraulic properties (infiltration vs. run-off); and
  - interaction with soil cover factors e.g. potential to sustain normal plant life (root development, nutrient cycles), water retention, plant available water on slopes with no or minimum organic matter, no or poor structure, no natural rock fragments etc.

These other stability attributes should be incorporated into an integrated model before the equilibrium of slopes (and for that matter also angle of repose) could be quantified.
- Can the slope angle be decreased?
- Is the slope in equilibrium?

All these critical questions could be answered if one knows more about the mineralogy, geochemical behaviour, weathering regime of the primary minerals, detail about the texture e.g. shape and structure of individual particles and many more specific mine residue properties e.g. metallurgical treatments. Unfortunately the influence of these issues still has to be identified before one could predict use full relations with real soil. In many case there are information available, but one must be sure that all other attributes are also the same before application of the relationships.

Knowledge gaps

- Effects of steep slope on erosion processes of mine residue
- It is assumed that the internal constituents and characteristics of natural soil slopes are not the same as for mine residue with the same slope angle and length, e.g.:
  - soil cohesion factors i.e. rock fragment content, root development, soil structure, organic carbon content, microbial activity, and
  - physiochemical characteristics and behaviour e.g. pH, salinity, Eh etc.
- Rill/inter rill flow mechanisms on mine residue
- Scour mechanisms in mine residue
- Applicability of erosion models (RUSLE, SIBERIA, MINErosion) to predict the effects of slope and slope angle on erosion from mine residues.

6.2.4 Cover protection

Cover protection can comprise biological or physical techniques and has the most significant influence in erosion protection of all the factors affecting erosion, given a fixed slope. Biological cover protection consist of managed vegetation cover or constructed vegetation supporting cover systems, while physical covers include constructed soil/clay caps or placed rock cover. However, there is limited evidence of the benefits of this protection on mine residue loss from side slopes and lack of knowledge of the factors affecting sustainability of vegetated covers.

Key questions

Vegetated covers

- What is the total cover functionality?
- Is the cover effective in erosion reduction?
- Is the cover material sustainable?
- What vegetation species or cover materials are available?
- Is there sufficient ground cover to sustain vegetation?
- Is there sufficient buried biomass and roots?
- Does the vegetation affect the water balance of the mine residue adversely?
- What are the effects of anticipated long-term changes of the vegetative or material cover?

The main issue about vegetation covers is the total ecological functionality and sustainability of the vegetation with respect to surface stability over a long period of time. The material (mine residue properties), environmental factors (climate), physical environment (slope geometry), species diversity and management practices are the most important factors which could have an influence on the sustainability and quality (functionality) of the vegetation on stability of the MRDF. Some of the knowledge gaps are strictly speaking just a lack of skills to interpret analytical results of the material properties. It is also important to realise that the most of these material and environmental attributes which contribute to stability, have an interaction amongst them and this interaction could be very dynamic over time. For example if one attribute change due to management practices, many other attributes could change for the worse e.g. if sodium rich irrigation water is applied, the material's cation exchange capacity could be dominated by sodium and eventually the ESP (exchangeable sodium percentage) could become so high that the material could become dispersive and erosion will follow and consequently the surface stability will deteriorate.

The following management knowledge gaps are mainly related to the long term sustainability of the vegetation cover:

Managed vegetated cover knowledge gaps

- Diversity/stability/sustainability/vitality relationships
- Adaptability and sustainability of vegetation in a ever changing physiochemical environment, i.e. the root zone
- Vegetation species/Slimes material interactions
- Fires/moribund/recycling processes
- Utilization of vegetation for end use and interim use
- Applicability of erosion models to predict the effects of managed vegetated covers on mine residue erosion.

Physical covers together with vegetation refer mainly to top soil, rock armour and or a combination of the two. The physical and chemical properties of the material are the most important factors which could have an influence on the final cover factor i.e. vegetation. The following are some of the major issues: pH, salinity, nutrient status, water retention, water holding capacity, dispersiveness, texture, compaction, microbial activity and seed bank. The interpretation of the interaction of these properties together with management practices are the major lack of experience and knowledge gaps.

Constructed vegetated cap knowledge gaps

- Diversity/stability/sustainability/vitality relationships
- Stability of the cover/mine residue interface
- Vegetation species/soil/slimes material interactions
- Fires/moribund/recycling processes
- Utilization of vegetation
- Applicability of erosion models to predict the effects of constructed vegetated covers on mine residue erosion.

Capping of MRDF with non-vegetated materials is not common practice yet in South Africa. However, it should be investigated to ensure long term stability and sustainability of the MRDF. Typical knowledge gaps are:

Non-vegetated constructed cap knowledge gaps

- Stability of cover/mine residue interface
- Optimum profile
- Hydraulics of flow within the layer and into the mine residue as well as infiltration into the sloped cover layer surface
- Applicability of erosion models to predict the affects of constructed covers on mine residue erosion.

6.2.5 Practices reducing erodibility

Specific surfaces preparations are known to reduce erosion in agricultural practices. However there is a knowledge gap in the effect of similar practices on mine residues. The following practices are in use with mixed success:

Reshaping

The main object of reshaping is to produce slopes whose angles, lengths, and shapes are stable, suitable for the proposed final land use, and not prone to an unacceptable rate of erosion. Integrated with this should be a water control system, which is capable of conveying runoff from the newly created catchments without risk of erosion and sedimentation

Erosion control through terraces (benches, banks)

Apart from reshaping (to lower the angle of the slope) re-vegetation and/or rock armouring, considerable control can be exerted over the velocity and depth of flow. One means of controlling surface flow is to construct graded terraces (also called banks or benches) at intervals down the slope. The effect of these is to divide a long slope into a series of short ones with the catchments area commencing at each terrace. This prevents the runoff from reaching a depth of flow or velocity, which could cause erosion. Graded terraces have an advantage of providing erosion protection as well as drainage of runoff to selected points. However, to achieve this function they must be constructed within close tolerances of shape, capacity, and gradient. The gradient is selected according to soil type, channel shape and vegetation cover, to maintain the flow below an erosive velocity.

Rock armouring and cladding

As an alternative means of reducing erosion, the slopes of a MRDF may be clad with a layer of a mixture of rock and soil or just rock. The total material is usually highly pervious and water running down a rock-armoured or cladded slope will tend to run at the interface between the rock and the underlying mine residue. This water will erode the mine residue unless geofabric or a filter layer is provided at the rock-residue interface. Rock armour (gravel materials mixed with fines to reduce the permeability) can overcome the shortcomings of rock cladding and may be a cheaper alternative to protect slopes against erosion, depending on earthwork cost versus geotextile cost.

Water control measures

Specific measures to control storm water are required to ensure minimum damage to slopes and other structures during heavy rain storms. Water control measures are very much applicable in cases where vegetation cover becomes low, areas with high vehicle and human transport e.g. ramps, roads, walk ways etc.

Reseeding

Reseeding is necessary where bare patches occur, but the source of the bare patches should be identified and addressed first. The choice of seed mix should also be investigated to ensure the correct species are used. Additional cover of seed is necessary to ensure proper germination.

Fertiliser application and amelioration

Very often nutrient deficiencies are the major factor which influences poor vegetation cover and it is so simple to rectify the problem. The correct type of fertiliser application could be determined by means of sampling and assaying. In some cases it might be necessary to apply the original ameliorates again e.g. lime or compost and to apply physical amelioration again due to potential hard setting, surface crusts etc.

Change in seed mix - more resistant type of species

More resistant types of vegetation should be established on the areas where severe dye back occurs. Proper monitoring will identify if there are major problems associated with species mix.

Establishment of cluster vegetation populations - nucleus principle

In severe hostile conditions e.g. steep slopes, very dry climatic conditions; it might be necessary to change the normal vegetation establishment practices. Cluster populations are a method where small areas are ameliorated in very much detail and a specific combination of micro-habitat and species mix are used to create a nucleus of supreme vegetation. These nucleuses will act as eco-friendly systems in a hostile environment and eventually new combinations of species will established itself around these clusters. Eventually the complete system will be covered with vegetation. It must be emphasised that this method could take much longer than conventional vegetation establishing methods.

Each additional management practice should be evaluated separately and within the ecosystem boundaries of that specific environment to determine the success and sustainability of it with respect to surface stability (erosion).

However, the key question will remain if these additional management practices are effective or not. Typical key questions are:

Key questions

Is the practice effective in reducing erosion of mine residues?
How long will these practices be effective?
Should there be ongoing changes or just one effort?
What is the expected long term maintenance going to cost?

The erosion reducing knowledge gaps are based on a lack of experience, missing analytical data, poor interpretation of analytical data, ignorance of specific and important attributes, misunderstanding of the holistic integrated approach to surface stability or a combination of these factors. Sometimes agricultural norms, standards, methods or practices are applicable, but one must be aware of the over estimating the value of these practices in a new environment i.e. a MRDF. The major knowledge gaps are:

Erosion reducing practices knowledge gaps

- Erosion reducing effects of tillage practice
- Erosion reducing effects of ripping- depth and spacing
- Strip planting advantages
- Terracing and mini terracing advantages
- Applicability of models to predict erosion reducing effects of practices on mine residues

All the above mentioned knowledge gaps and uncertainties are not restricted to specific mine residues, but they are common and there are even more of them as the mining industry expands, new legislation becomes effective, or where new materials become available. Nevertheless sufficient experience is available to justify a DSS dealing with the specific topic of surface stability so that a rational series of questions can be asked and pragmatic answers developed to allow acceptance of a scheme.

7 DISCUSSION AND CONCLUSIONS

The decision-support system (DSS) is a framework providing decision makers with a structure for addressing key questions related to the sustainable configuration of mine residue disposal facilities (MRDFs). It was decided at the first WRC workshop held in June 2003 that although a final system is envisaged which will ultimately include and address all environmental aspects it is a priority to address the two key technical aspects of water pollution and surface stability. Although the first phase of the project only deals with these two issues, it is argued that they represent the key technical aspects which decision makers usually have most difficulty in reaching consensus about. Other issues such as aesthetics or dust will be added in subsequent research phases. The WRC's main focus is on water-related issues and it is therefore proposed that the remaining environmental aspects be considered in collaboration with the government departments tasked with regulating such issues.

It is unlikely that a final DSS will ever be developed. Technology is expected to evolve and methods will be found to analyse and to mitigate impacts. New issues are also expected to emerge as time goes by and as stakeholders priorities evolve. Although the DSS should be considered as a work in progress it should not remain in the research domain indefinitely and should be incorporated into the regulatory system as soon as practicable. Once incorporated into the regulatory system, it should be maintained and updated from that position on an ongoing basis.

The approach presented in this report does not replace sound application of knowledge and judgement but is simply a systematic rational application of these. The DSS is and should always remain easy to apply. The framework presented in this report is generic in nature and facilitates reaching consensus. It is a tool intended to help with transparent decision-making between regulatory authorities, proponents and consultants. The system provides a top down perspective during the key stages of impoundment development and provides a rational framework for consideration of biological, physical, socio-cultural and economic aspects. As such the system streamlines decision making and reduces the potential for multiple loops in authorisation processes.

Although decision-making for the sustainable design, operation and closure of metalliferous MRDFs is not an easy task, the decision trees of the preliminary DSS can already be used as an aid by decision-makers. Future project phases will focus on researching the knowledge gaps identified and as such will contribute to further simplification of the decision making process.

The application of the DSS, although simple in concept, will require some experience to ensure its effective use. It is therefore recommended that examples and training materials be developed by the authorities before the system is implemented. Training seminars for industry and government users would also be useful.

The essence of the DSS is that it should always lead to a decision. The key to this outcome has been the introduction of an "end of the line" question which will always provide the regulator and the proponent with a way to address uncertainty. This may be done by demonstrating performance or the reasonable probability thereof. The fallback situation is always that performance can be measured and rectified if required. This is the observational method, advocated by, amongst others the fathers of soil mechanics, Terzaghi and Peck. It is however essential to note that the core of the approach is that plans should be in place to deal with lack of performance before it occurs or in other words the adverse what ifs must be considered and solutions conceptualised before they occur. It should however be noted that it is not the intention that this now becomes the default position since there are many instances where a decision can be made without reverting to demonstration.

The systematic observational approach exemplified by the DSS represents a major opportunity for the South African mining industry together with the regulatory authorities to advance the design, the performance and the closure of mine residue facilities to the satisfaction of all stakeholders.

8 RECOMMENDATIONS

The preliminary decision-support system (DSS) for the sustainable design, operation and closure of metalliferous mine residue disposal facilities (MRDFs) presented in this report has developed to the point where it can be used to guide decision making. It must however be refined further by developing the decision guidance and decision criteria components of the system and to facilitate inclusion of new and promising technologies and approaches for mitigation. To achieve this, it will be necessary to pursue the following three research objectives:

8.1 Protocol to establish new technology

A protocol to demonstrate the suitability and acceptability of a proposed and as yet untested technology purported to limit the environmental impacts on the surface stability and water aspects to acceptable levels is required. This approach can be considered similar to the concept of Best Demonstrated Available Technology (BDAT) applied in the United States. This protocol should be developed by:

- Reviewing and combining procedures and methodologies for demonstration of acceptable environmental performance.
- Developing a protocol/procedure to guide the demonstration of acceptable environmental performance of new technology.
- Testing the applicability of the DSS through case studies involving examples of BDAT.
- Aligning the DSS with present legislation with specific reference to incompatibilities in legislation as it impacts on the DSS.

8.2 Knowledge gaps

The first step towards filling knowledge gaps is to have a thorough understanding of the state of the art. The second phase of the project should therefore focus on desk-top studies to assess the current understanding and remaining knowledge gaps regarding the following water and surface stability issues identified. These should include:

- Mine residue disposal facility water balances for the operational and post-closure phases, with specific reference to the net percolation through MRDFs during the post closure phase as well as the behaviour of the phreatic surface.
- Modelling of pore water quality evolution in a MRDF as a function of geochemical processes, mineralogy, flow processes and climatic variation, during the post closure phase. (This should include an assessment of data requirements, modelling tools and approaches. In particular, the possible linking of mass balance and kinetic models should be addressed.)
- Development of protocols for the handling and reporting of model uncertainties in pore-water quality evolution studies and geochemical modelling in general.
- Depth of the oxidised zone on sulphide containing MRDFs.
- Long term soil loss and erosion rate on MRDFs.
- Establishing standards for acceptable sediment loads on receiving environments.

- Long term effectiveness and success rate of covers and top liners as well as the ideal conditions for applying different types of liners and covers to maximize surface stability on MRDFs.
- Effect of slope geometry (length, steepness and shape) on the surface stability of MRDFs.
- Techniques that can be used to monitor surface stability after rehabilitation and closure of MRDFs.
- Techniques for measuring erosion process and surface infiltration of sloped mine residue and covers.

The desk-top studies will provide the basis for prioritising the research for the next phase of the project since it is unlikely that all of the above topics can be funded at the required level simultaneously.

Since new and promising technologies and approaches that could play a role in minimizing water resource degradation caused by metalliferous MRDFs will inevitably be developed following implementation of the DSS, it is important to start with a basis for selecting demonstration projects. It is therefore recommended that a study of the current state of the art be undertaken in the next phase. This may be used as the basis for further research and development in the next phase or could be used as a reference by industry.

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APPENDIX A: CAPACITY BUILDING

All of the capacity building targets on the project have been met. The project contributed to three University of Pretoria undergraduate civil engineering students' final year research projects by means of a stipend and probably more importantly through focused and dedicated interaction with several specialists on the research team. The students completed their research projects successfully and graduated in 2005.

The three undergraduate BEng students were:

- Sean Lindsay
- Jabulile Sibanyoni
- Wiehan Küsel

Mr B Rademeyer, a PhD student with the University of Pretoria, was also seconded to Golder Associates Africa (Pty) Ltd for the duration of the WRC project.

The undergraduate student's compulsory final year first semester project report work was aligned with this WRC research initiative and grants were made available to the afore-mentioned students assisting them financially during this period. The main purpose for involving the undergraduate students was to provide them with the opportunity to develop the skills necessary to undertake independent research and to gain experience in the methodology for undertaking such research. The undergraduate research was not to make contributions to a particular field, either by experimentation, data collection, literature studies or testing methods.

The reports submitted by the students were:

Küsel, W. *The use of High Resolution Digital Cameras in the modelling of Mine Tailings Impoundments*. Unpublished Report. University of Pretoria, Department of Civil and Biosystems Engineering, Pretoria, RSA.

Lindsay, S. *Evaluation of the Effectiveness of a Simple Model in determining Concentration of Contaminants from Decommissioned Tailings Dams in Groundwater*. University of Pretoria, Department of Civil and Biosystems Engineering, Pretoria, RSA.

Sibanyoni, J. *The use of the Revised Universal Soil Loss Equation when assessing the Surface Stability of Tailings Dams*. University of Pretoria, Department of Civil and Biosystems Engineering, Pretoria, RSA.

APPENDIX B: SURFACE STABILITY KNOWLEDGE GAPS MATRICES

MATERIAL ERODIBILITY

Factors affecting the process	Study, research or case	Status	Rank
Particle size distribution Infiltration rate Structure Mineralogy Clay mineralogy Water content Crusting	The COMET gives anomalous result (Dorren&Blight, 1986)	Complete	L
	Non-vegetative covers are more cost-effective Blight&Smith (1996)	Complete	H
	The coarser the material on a slope the more stable the slope. The longer the slope the higher the erosion. (Blight, Smith, Van Wyk and van Deventer) and (Hattingh, 2002)	Complete	L
	Erosion losses from terraced slopes are relatively small (Blight, 1984).	Complete	H?
	Digital terrain modeling is a useful tool in environmental engineering (Goh *et al*, 1997).	Complete	M
	University of Potchefstroom (J. Swart) COM (COMET), ISCW(P. Nell)	Complete/current	H?
	Erosion plots (G. Blight, M. Smith and Envirogreen)	Complete	M
	Hydraulic characteristics (WRC, project PHD K1460)	Complete	M?
	Australian ref: Functionality	Complete/current	H
	G. Annandale: Scour on mine residue	Complete	M?

Knowledge gap	No go	Further testing	Proceed	
Mineralogy of material	X			
Infiltration on slopes		X		
Crusting characteristics		X		
Applicability of RUSLE		X		

SLOPE LENGTH AND STEEPNESS

Factors affecting the process	Study, research or case	Status	Rank
Slope angle Slope length Rill/inter rill flow	At slopes steeper than 25 degrees erosion will be high even for vegetation with a basal cover in excess of 10%. For slopes not steeper than 15 degrees vegetation is very effective in protecting slopes against erosion.	Complete	M?
	3:1 (33%) slopes stable in many areas. Why?	Complete/current	M?
	Slope length poor correlation, but may be attributed to measurements only in the centre and not throughout the slope. Wind loss from top 1/3rd and is often re-entrained on top surface (G. Blight) Optimum angle and length (A. Brown and P. Swart).	Complete	H?
	Australian studies	Complete	L
	University of Potchefstroom – vegetation and slope trials (van Wyk).	Complete/current	H?
	Runoff plots (G. Blight)	Complete/on going	H?
	Redco Potch (Sishen)	Current ?	L?

Knowledge gap	No go	Further testing	Proceed	
Steep slope effects	X			
Rill/inter rill flow mechanisms on mine residue		X		
Scour mechanisms in mine residue	X			
Applicability of models (RUSLE, SIBERIA, MINErosion)		X		

MANAGED VEGETATION COVER (vegetation cover established on mine residue slope)

Factors affecting the process	Study, research or case	Status	Rank
% canopy cover % basal cover Mass of roots and buried matter Height Surface roughness Nutrients in material Interaction of vegetation with material type, layering and slope (growth, stability, water availability) Nutrient status, recycling and material interaction	• Vegetated - Adv: cost, regenerates, good wind + water, salt migration - disadv: establishment on phytotoxic materials, roots clog drainage layers, gully erosion, increase infiltration, contaminant uptake, functionality	Complete	M
	• Soil - Adv: cheapest layer, reduces infiltration, support vegetation - disadv: cost, erodible unless vegetated, salt migration. - erosion, increase infiltration, contaminant uptake.	Complete	H?
	• Rock - Adv: sheet and gully resistant, inhibits salt migration, drainage - disadv: cost, increases infiltration.	Complete	M?
	WRC *899/1/04* (Hatting& van Deventer 2004)	Complete	H?
	M. Mentis (Stability, diversity)	Complete?	M?
	I. Weiersbye (Wits)	Complete?	H
	ISCW effects on roots (H. Smith)	Complete	?
	H. Kirsten		
	G. Blight		
	J. Cooke (UKZN)		
	WRC *413/1/98* CSIR	Complete	?
	Koffiefontein, Mark Berry: Vertivar(De Beers)	Complete	L

Knowledge gap	No go	Further testing	Proceed	
Diversity/stability/sustainability/vitality relationships		X		
Vegetation species/Slimes material interactions	X	X		
Fires/moribund/recycling processes		X		
Utilization of vegetation				
Applicability of models		X		

CONSTRUCTED VEGETATED CAP (Constructed soil cover with managed vegetation)

Factors affecting the process	Study, research or case	Status	Rank
% canopy	WRC 1002/1/04 (Vermaak *et al*. 2004)	Complete	H
% basal cover	WRC 899/1/04 (Hatting and van Deventer 2004)	Complete	L
Mass of roots and buried matter			
Height	M. Smith: Vegetation Pockets	Complete	L
Surface roughness	J. Dekker, ca 1995: CSIR	Complete	L
Nutrients in material	G. Laker: U. Pretoria	Complete	M
Interaction of vegetation with material type,	F. Van Wyk: U. Potchefstroom	Complete	L
layering and slope (growth, stability, water	I. Weiersbye: U. Wits: additives	Complete	M
availability)	ISCW effects on roots (H. Smith)	Complete	H
Nutrient status, recycling and material	J. Annandale, N. Rethman: U. Pretoria	Complete	H?
interaction	H. Kirsten	Complete	?
Thickness of cap	G. Blight	Complete	H
Drainage of cap	J. Cooke (UKZN)	Complete	?
Rock armoring with vegetation	Daggafontein: Golder, P. Swart	Complete	M
Rip-rap 40-60% cover with vegetation	WRC v Deventer *et al*: Hydr. prop. stony soils,	Complete	M
	Cullinan mine, Envirogreen	Complete	L

Knowledge gap	No go	Further testing	Proceed	
Diversity/stability/sustainability/vitality relationships		X		
Stability of cover/mine residue interface	X			
Vegetation species/soil/slimes material interactions		X		
Fires/moribund/recycling processes		X		
Utilization of vegetation				
Applicability of models		X		

NON-VEGETATED, CONSTRUCTED CAP (Constructed cap of rock or geotextile)

Factors affecting the process	Study, research or case			Status	Rank
Subsurface piping Quality/Stability of material/grading Stability of cap/mine residue interface Drainage	WRC 1002/1/04 (Vermaak *et al*. 2004) M. Smith: Rock cladding COM buttresses G. Botha Council for Geosciences: Subsurface piping AngloGold-Envirogreen: Runoff and subsurface erosion			Complete Complete Complete Complete Complete	H H? M M? M
Knowledge gap	**No go**	**Further testing**	**Proceed**		
Stability of cover/mine residue interface Optimum profile Hydraulics of flow/infiltration Applicability of models		X X X X			

EROSION REDUCING PRACTICES

Factors affecting the process	Study, research or case			Status	Rank
Terracing Contours/deep ripping Roughness and placing materials Drains Strip vegetation	P. Swart: Overflow terraces Industrial Landscaping: Vertivar Bunds Water control measures Envirogreen Reshaping of slopes:Fraser Alexander Tailings Rock armouring and cladding: Golder and Envirogreen Vegetation clusters: Envirogreen			Complete Complete Current Current Complete/ Current Current	H? L L? M? M? M?
Knowledge gap	**No go**	**Further testing**	**Proceed**		
Tillage practice Ripping- depth and spacing Strip planting advantages Terracing and mini terracing Applicability of models		X X X X X			

OTHER PROCESSES/PRACTICES AFFECTING SURFACE STABILITY

Factors affecting the process	Study, research or case	Status	Rank
Maintenance Tailings water regime Subsurface erosion Climate/material/slope/vegetation interactions Impact of sediment load on receiving environment Gulley formation Surface construction/compaction/placing Dispersion of fines Weathering rate of minerals	At slopes steeper than 25 degrees erosion will be high even for vegetation with a basal cover in excess of 10%. For slopes not steeper than 15 degrees vegetation is very effective in protecting slopes against erosion.	Complete	H?
	The coarser the material on a slope the more stable the slope .The longer the slope the higher the erosion. (Blight, Smith, Van Wyk and van Deventer) and Hattingh (2002)	Complete	M
	Wind Erosion losses from terraced slopes are relatively small (Blight, Rea, Caldwell and Davidson) and Blight (1984).	Complete	M?
	Digital terrain modeling is a useful tool in environmental engineering (Goh, White and Swart).	Complete	M
	Van Rensburg and van Wyk – University of Potchefstroom: Impact of sediment load	Complete	M?
	Aucamp and van Schalkwyk. University of Pretoria	Complete	L?
	Wits: salinity impacts from mine residue	Complete	H?
	WRC report SRK late 80's Salinity impact of mine residue	?	?
	WRC report PHD salinity impact	Complete	L?

Knowledge gap	No go	Further testing	Proceed	
Impact of sediment yield on receiving environment	X			
Weathering/dispersion characteristics of materials		X		
Gulley formation		X		
Subsurface erosion		X		