

**GUIDANCE FOR THE REHABILITATION OF CONTAMINATED
GOLD TAILINGS DAM FOOTPRINTS**

RP Hattingh

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Water Research Commission



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**Report to the
WATER RESEARCH COMMISSION**

by

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FINAL REPORT

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September 2001



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EXECUTIVE SUMMARY

The mining industry is involved in a major initiative to reclaim defunct tailings facilities containing recoverable quantities of gold. Once the tailings material has been removed, the land has a certain potential for land development. The extent of contamination contained in the unsaturated and saturated zone beneath these deposits formed the topic of an investigation completed in 1998. It was concluded from this investigation that the soils underneath reclaimed tailings dams are in general contaminated with pollutants that typically originate from acid mine drainage (AMD) seeping from tailings dams. This investigation also showed that some of the metals are highly mobile, particularly in the surface soil units. Limited groundwater data were available, but it was evident that groundwater in close proximity to tailings dams was being affected by salt loads.

The follow-on investigation conducted over the period 1999 to 2001 had as its primary objective the development of guidance for the rehabilitation of the footprint of these reclaimed gold mine tailings facilities. In general, the outcome of this investigation recommends a change in the technical approach to evaluating and remediating contaminated land. The introduction of a risk assessment approach, a phased and chemically orientated approach to site investigation, and the selection of remediating strategies from a number of technologies are all intrinsic components in the rehabilitation of these areas. Furthermore, the complexity of evaluating the degree and extent of contamination became evident, demonstrating that a simplistic approach is inadequate. Identifying the most appropriate rehabilitation method for a given site is a difficult process and requires consideration of a number of factors, including process applicability, effectiveness, cost, process development status and availability and operational requirements. Additional factors to be considered are process limitations, monitoring needs, potential environmental impact, health and safety needs and post-management requirements. The amount of information required for an effective appraisal of available options is considerable and may not be available. During the rehabilitation process, adequate quality control measures are needed to ensure that the methodology conforms to specification or that treatment targets have been achieved. By implication, this requires environmental monitoring while rehabilitation is in progress. In addition, on completion of the rehabilitation, additional monitoring and management activities may be necessary if contamination sources remain on the site.

Radionuclides were not specifically focused on during this investigation. Given their long radiological half-lives, the relevant uranium and lead isotopes can be treated as heavy metals with known toxicities for the purposes of assessing their potential environmental/health impacts. Further work on the mobility and transport pathways of uranium and lead-210 in the footprint environment, as with any other heavy metals, would most likely need to be site-specific. Because of its low mobility, radium-226 may however remain on site where it may potentially give rise to increased radon exposure in homes built on the site.

The generic case studies on the Witwatersrand Supergroup and Karoo Supergroup has shown that there is adequate reason to believe that the underlying geology plays a major role in the behaviour of contaminants in the vadose zone, and that sites overlying the same geological environment may show significant differences. Further generic research in this regard may therefore not yield additional information. It is therefore recommended that any additional work should be on a site-specific basis, for the specific purpose of identifying the most appropriate rehabilitation option for the individual sites. The basic methodology to do so is outlined in this document.

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1 INTRODUCTION

1.1 BACKGROUND

The mining industry is involved in a major initiative to reclaim defunct tailings facilities containing recoverable quantities of gold. Once the tailings material has been removed, the land has a certain potential for land development. The extent of contamination contained in the unsaturated and saturated zone beneath these deposits formed the topic of an investigation completed in 1998 (Rösner et al, 1998; WRC Report K5/797/0/1). During the course of the study, the pollution sources (tailings dams), the barrier zones (vadose zones) and the receiving groundwater systems were investigated at several sites in order to assess the migration pathways of various elements and compounds. It was concluded from this investigation that the soils underneath reclaimed tailings dams are in general contaminated with pollutants that typically originate from acid mine drainage (AMD) seeping from tailings dams. This investigation also showed that some of the metals are highly mobile, particularly in the surface soil units. Limited groundwater data were available, but it was evident that groundwater in close proximity to tailings dams was being affected by salt loads. Groundwater quality improved with increasing distance down gradient from the pollution source, mainly because of dilution and solid speciation.

The primary aim of this follow-on investigation (Hattingh et al, 2001) is to develop guidance for the rehabilitation of the footprint of these reclaimed gold mine tailings facilities. In order to meet this objective, the following five secondary objectives needed to be satisfied:

- Evaluate and define the existing state of knowledge with regard to reclamation and rehabilitation methods and their water quality impacts.
- Site-specific assessments of the potential of contaminants released from gold mine tailings facilities and soil underlying reclaimed tailings facilities to pollute the aquatic pathways (surface and groundwater), with regards to heavy metals, salts and radionuclides.
- Develop rehabilitation management strategies based on site-specific conditions to minimise the environmental impact on the aquatic pathway.
- Provide guidance for future land use after complete reclamation.
- Provide guidance for site selection criteria for future mine tailings facilities.

The extent and type of contamination in the unsaturated zone determines the type and extent of rehabilitation that would be required for safe future land use and the prevention of groundwater contamination. In the case of reclaimed tailings dams, once contaminants have migrated through the unsaturated zone, into the groundwater zone, their rate of lateral movement increases by orders of magnitude. The implication of this is that although there is a dilution effect because of contact with groundwater, the potential impact on the environment is extended in a spatial and temporal sense. Furthermore, once the contaminants have entered the groundwater zone, there is very little that can be done to remediate the aquifer, or contain the movement of these contaminants. Active groundwater remediation is relatively expensive, and does not have a high success rate.

The philosophy adopted for this project is therefore that the generic rehabilitation investigations should focus on processes occurring in the vadose zone with the intent of developing strategies as to how these contaminants can be contained in or removed from the

vadose zone. It was envisaged that the final product emerging from the project would include not only this technical report, but also a preliminary guideline or guidance detailing steps and processes that need to be considered during the design of a reclamation programme. It should be noted that the term "guideline" may imply a certain legal standing or may convey the perception that the regulatory authorities fully subscribe to the contents of the document. Although consultation with the regulatory authorities was a key component in the development process, the Project Steering Committee decided to adopt the term "guidance" instead of "guideline" in order to avoid confusion.

The issue of radioactivity and these tailings dams have received much emphasis over the past few years, and the regulatory control instruments are well established. The inherent risk in diluting available resources to encompass the full spectrum of radioactivity was that the non-radioactive contamination component might have been de-emphasized. It was therefore decided to focus the financial resources on the chemical component, rather than the radioactive component.

During the course of the investigation it became clear that site location is an overriding factor in the decision as to future land use. The emphasis was therefore changed from guidance for future land use after rehabilitation to highlighting the appropriate rehabilitation methods for different land uses.

This document also provides a set of ideas to the interested and affected parties involved in gold mine tailings rehabilitation, which may assist with the effective rehabilitation of these reclaimed mine residue deposits.

1.2 LIMITATIONS OF THIS PROJECT

In a project of this nature, the limitations, exclusions and conditions must be clearly spelled out. The authors would therefore appreciate the following to be considered in the context of this report:

It was decided early on in the project not to focus on radioactivity. The result is therefore that the regulatory requirements in terms of the radioactivity aspects would also need to be satisfied, and that the two aspects would need to be considered in an integrated manner.

There are numerous gold tailings dams in South Africa. The research could obviously not be carried out on each of these deposits, with the result that the representativity of the results may be an issue. However, motivations are supplied for the study site selection criteria, and the validity of the extrapolation of the research findings are spelled out in the report.

The development of the preliminary guideline ideally required a legal instrument, such as a standard promulgated under a specific Act of Parliament. The preliminary guideline derived from this work is not enforceable, nor did the regulatory authorities issue it. However, the preliminary guideline establishes a scientific approach to the rehabilitation of these footprints. As such deviations from this approach should arguably be motivated.

It was found that contamination of the unsaturated zone beneath the footprints of reclaimed gold tailings dams is extensive, however, this statement must be seen in the context of the potential rehabilitation issues at defunct gold mines. Financially it is therefore sensible to

address rehabilitation and site closure in a holistic manner and allocate rehabilitation funds on the basis of potential risk to the environment. The rehabilitation of contaminated footprints may therefore be a low priority in terms of closure expenditure.

In both unsaturated and saturated soils water flow is driven by a potential gradient and is affected by the geometric properties of the pore channels through which flow occurs. In a saturated soil the moving force is the gradient of a positive pressure potential while in an unsaturated soil, suction gradient is the driving force of water flow. Saturated water movement in soils is well understood, with the result that flow in the investigated soils was described using saturated flow methodology. This can be seen as a conservative approach as saturated hydraulic conductivity is usually higher than unsaturated hydraulic conductivity.

1.3 SPECIALIST LITERATURE REVIEWS

Literature reviews were conducted on:

- Risk assessment procedure
- Geohydrological processes in the vadose zone
- Potential remediation strategies related to land surface

The main objective of the literature survey relating to risk assessment procedure was to determine whether the calculation of current pollution impact based on the ratio of extractable to total element concentrations, as well as the calculation of potential future pollution impact from geochemical load indices would yield sufficient information on which a risk assessment can be based. The survey also addressed the question of how geochemical modelling may be used to predict the behaviour of contaminants under changing land use and climatic conditions and how this information can be included in a geochemical risk assessment.

The literature survey dealing with hydrogeological processes in the vadose zone was aimed at ensuring that current knowledge relating to these processes was included in this investigation.

The potential remediation strategies can be divided into treatment technologies or utilising on-site management. Treatment technologies refer to soil physically removed and processed in a certain way in an attempt to reduce the concentration of trace elements or to reduce the extractable concentrations to an acceptable level. On-site management usually involves either isolating the soils from interacting with the surrounding environment or it involves the implementation of a strategy that reduces the bioavailability of the existing contaminants.

1.4 METHODOLOGY

The selection of the appropriate sites was a critical step in this investigation. Site selection criteria were developed, and included aspects such as representativity, accessibility, safety, security and recently exposed footprint soils. Three sites were selected, of which two areas overlie the Witwatersrand Supergroup, and the third site overlies the Karoo Supergroup.

Each of the three study sites was characterised in terms of the following aspects:

- *General site characterisation*, comprising the locality and site history, fieldwork conducted on site, topography and drainage, vegetation and geological conditions underneath the site.
- *General soil profile and geotechnical characteristics*, describing important soil parameters such as saturated hydraulic conductivity and soil pH.
- *Geohydrological characterisation of the unsaturated zone*, giving an indication of flow characteristics and mechanisms (e.g. preferential flow).
- *Geohydrological characterisation of the saturated zone* (if data were available), comprising the aquifer type and geology and aquifer parameters (e.g. hydraulic conductivities, borehole yield).
- *Contaminant assessment of the subsurface*, comprising a hydrogeochemical characterisation of the unsaturated and saturated zone with respect to the current contamination situation and the potential future contamination impact.

Detailed fieldwork undertaken on the three sites included trenching, drilling of boreholes and sampling for geochemical and geotechnical investigations. Prior to undertaking the fieldwork shallow test pits were excavated to demarcate the site into areas of similar soils. This zonation was based on the pedological characteristics of the soils as well as the pH and EC determined on saturated pastes made from the samples collected from each trench. After zone demarcation, deep trenches were located and excavated using a track-mounted backactor, allowing soil to a depth of 5 m to be removed. Detailed soil profiling and soil sampling was undertaken in each trench.

Samples collected during the fieldwork were submitted for the following analyses and determinations:

- Determination of the dry density.
- Determination of specific gravity.
- Determination of saturated hydraulic conductivity.
- Grain size distributions.
- Soil water content.
- X-ray fluorescence analysis (in order to determine the major and minor elemental compositions).
- X-ray diffraction analysis (in order to determine the dominant minerals).
- EC and pH were determined on saturated pastes made from the samples.

A number of *in situ*, large diameter double-ring infiltrometer tests and tension infiltrometer tests were conducted at selected depths in or in close proximity to the deep test pits.

Based on the zonation inferred from the shallow trenches, boreholes were located in order to obtain information on the strata below that which the excavator could reach. Chippings obtained at 0.5 m intervals were logged and samples obtained for geochemical analyses. A number of the boreholes were equipped and established as monitoring boreholes. An electrical conductivity profile was conducted in each borehole to identify zones in the aquifer with higher relative electrical conductivity.

1.5 CONCEPTUAL MODELS

The following alternative rehabilitation strategies were considered:

- Base case. The current situation (no intervention) is modelled and the results are used as a reference for alternative scenarios listed below.
- Removal of the source term. This scenario consists of the removal of a topsoil layer of approximately 30 to 50 cm.
- Minimization of infiltration. The flow of water into the underlying soils would be limited by effective covering of the surface. Such covers may vary in terms of efficiency, and could include the construction of parking lots, building of factories or urban development. The source of contamination in the soils in the footprint would not be removed.
- Paddockling. A scenario comprising a system of paddocks used to contain contaminated storm water.
- *In Situ* treatment. This scenario consists of an array of *in situ* rehabilitation techniques, which all result in the reduction of contaminant concentrations in the pollution source.

A general steady state flow regime was assumed for the modelling of the various rehabilitation strategies. With regard to the treatment of chemical species, minerals such as the carbonates, ferrihydrate, silica and sulphate-bearing minerals were considered under equilibrium conditions, due to the fact that they are relatively readily soluble in the natural environment. Furthermore, these minerals have relatively large reaction rate constants that enhance the rate at which reactions proceed. However, equilibrium treatment of chemical systems does not allow for the introduction of time as a variable. In order to introduce time as a variable in chemical reactions, kinetically based interactions were introduced for the sulphides, feldspars, micas and clay minerals. By considering the reaction dynamics in a kinetic manner, provision could now be made for changing environmental and chemical conditions. By implication, the kinetic treatment of minerals allowed for predictive geochemical modelling of pollution migration within the framework specified in the above-mentioned conceptual geochemical models.

Predictive geochemical modelling of the soil underlying mine residue deposits involves an array of physical and chemical processes. In terms of the physical processes, the flow of water through the system poses the most complex problems. The chemical processes that have been addressed include the following:

- Calculation of the species distribution in aqueous solution.
- Tracing reaction paths involving fluids and minerals.
- Consideration of the sorption of species onto mineral surfaces.
- Calculation of the solubility of mineral species in solution (dissolution / precipitation).
- Projection of the traces of reaction paths.

The study required the use of a detailed conceptual model that provides a general account of the geochemical processes involved in the migration of pollution underneath surface mine residue deposits. The model must incorporate geological, soil (geotechnical) and geohydrological parameters to enable an indication of ground and soil water flow mechanisms, directions and volumes. The conceptual approach involved a simple steady-state flow of water through the exposed affected and contaminated soil. The soil profiles have

been sub-divided into three zones, each displaying characteristic soil properties. Based on field observations, it was assumed that the soils were mainly unsaturated, suggesting that prevailing atmospheric partial pressures were applicable for gaseous species.

Important characteristics of the geohydrological conditions of the vadose zone developed on the Turffontein Subgroup can be summarised as follows:

- Three major soil units are identified, comprising transported units of colluvial origin occurring at surface, a pebble marker unit, and sandy residual quartzite underlain at depth by hard rock quartzite.
- Ferruginisation in soil is usually accompanied by an increase in clay content due to an increase in Fe-oxide precipitation which blocks soil pores.
- Preferential horizontal flow paths occur on the surface of some ferruginous units where groundwater seepage was observed.
- The colluvium and the residual quartzite are in some instances voided. This open structured soil structure can accommodate macro-flow.
- The residual quartzite is usually relic jointed. These joints are remnants of the unweathered nature of the bedrock, which may act as preferential flow pathways.
- The shallow depth to bedrock is favourable for the development of perched water tables as evident from perched groundwater zones observed on soft rock – hard rock interfaces. These zones are areas of potential preferential horizontal flow.
- Preferential horizontal micro-pore flow paths may occur in residual quartzite, which shows relict bedding planes.
- All the soils are inactive and will not swell and shrink due to seasonal changes in water content.

A generic model of the geohydrological conditions expected in the vadose zone of the study area was developed based on the field and laboratory characteristics of the soils as noted above.

1.6 GEOCHEMICAL MODELLING OF THE BASE CASE

A group of interactive software programs were employed to model the various scenarios that formed part of this research project. The programs RXN, ACT2, TACT, REACT and GTPLOT are collectively known as "The Geochemist's Workbench®". A detailed mineralogical assessment of the system to be modelled forms the basis of any thorough geochemical model. The mineralogical database for the current investigation included bulk mineral identification, using the powder pellet based X-ray diffraction technique, as well as detail Debye-Scherrer and Gandolfi camera diffraction work. A complete set of major and trace element data was generated using bulk X-ray fluorescence analyses. In addition, paste pH and EC was determined on samples.

The conceptual modelling approach that was followed in this investigation was a flush model, which tracks the evolution of a system through which the fluid migrates. At each step of the reaction progress, an increment of unreacted fluid is added to the system, displacing the existing pore fluid. This approach is analogous to a mixed-flow reactor. The individual flush model calculations were configured in such a manner as to simulate a continuum, which include a combination of local equilibrium and kinetic models. The advantage of such a conceptual configuration is the fact that the distribution of chemical species could be

predicted in time and space, *i.e.* along a groundwater flow path. Important chemical features such as precipitation and dissolution, as well as surface adsorption reactions are readily simulated within this conceptual context. Furthermore, the advantage of such continuum models is that they predict how the positions of reaction fronts migrate through time, if reliable input data are available about flow rates, the permeability and dispersivity of the medium, and the reaction rate constants.

The following specific assumptions formed part of the input data for the geochemical modelling:

- Redox reactions in the natural environment cannot be assumed to approach thermodynamic equilibrium, thus, redox reactions were calculated in a state of disequilibrium.
- Activity coefficients: Use was made of a virial technique known as the Harvie-Møller-Weare method, which is considerably more accurate than the Debye-Hückel method when predicting saturation states for concentrated solutions. Activities were allowed to slide according to reaction progress, with the exception of CO_2 and O_2 . The initial values for latter two components were initially fixed for calculations in the top layer. Once the seepage emerged from the top layer, the activities and fugacities were allowed to slide. The reason for such an assumption was that both oxygen and carbon dioxide was considered to be initially similar to atmospheric values. However, the deeper soil environment is considered to be deprived of oxygen. Since the level of deprivation is unknown, it was decided to have the reaction progress manipulate these conditions.
- Sorption of species onto mineral surfaces was calculated only when complexation involved hydrous ferric hydroxides.
- The temperature for all reactions was fixed at 25°C. In the case of exothermic and endothermic reactions the heat being produced or lost was not taken into consideration, since it was assumed that the heat being produced would be dissipated in the flushing fluid flow environment.
- Kinetic reactions: In the continuum flush reaction model, reactants are added to or removed from the system at arbitrary rates. The rate law that was used for mineral dissolution and precipitation causes minerals to precipitate when supersaturated and dissolve when undersaturated at a rate that is a function of the rate constant and surface area.
- Catalyzing and inhibiting species: Under low pH conditions, H^+ was considered as a catalyst. The precipitation of species was never inhibited.
- Cross-affinity rate laws: The saturation state of secondary mineral species, for which rate constants were not available from published literature, were calculated by using the Q/K ratio of another mineral involved in the reaction.
- Nucleation: a simple description of nucleation for kinetic minerals was set in order to introduce new minerals, which would otherwise not form because of its surface area being zero.
- Results were calculated using a specific set of controlled input data. These results were then collected and used as input data to simulate the conditions of the following chemical node.
- The available reactive surface area for the various minerals that were treated in a kinetic manner was based on experimental work conducted by various researchers on the topic.
- Porosity was based on the fluid and mineral volumes specified for a particular system, taking into account the value ascribed to the inert portion of the system.

Sensitivity analyses were performed on a number of parameters for the base case scenario. These results clearly indicate that the most important parameter that controls the response of a system to external variables is the modal mineralogical composition of such a system. Parameters such as the flow rate are significant, but do not displace the position of the concentration profiles in such a manner as to infer changes in management strategies. The available reactive surfaces of the various minerals are significant in the sense that the response of a particular mineral is enhanced in terms of reaction time as well as intensity of the response. Variations in the shape of the concentration profile because of changes in the available reactive surface area invariably have a significant influence on the associated management strategies. A similar effect is brought about by the decision whether the reaction should make use of equilibrium or kinetic treatment mechanisms of a specific mineral or suite of minerals in chemical reactions. Both of the latter parameters, i.e. available reaction surface area and equilibrium versus kinetic reaction mechanisms, are very sensitive in terms of the detailed variation of the reaction profiles. It is therefore critically important in terms of making the geochemical model as realistic as possible, to attach realistic values to these parameters.

The modelling results for the base case can be generalised as follows:

- The pH of the effluent will initially be acidic, but will reach neutral or near-neutral values within a period of 5-20 years.
- The major cation concentrations will remain at elevated levels for more than 50 years.
- A continuous flow of salt (SO_4^{2-}) persists for a period of at least 50 years. There are fluctuations in the production rate of salt, but the load remains at elevated levels over the 50 year period modelled.

The modal distribution of minerals in the soils is the most significant parameter that controls the quality of seepage emanating from the soils. The water quality is primarily dependant on the type of water – rock interactions that are taking place, as well as the scale on which these reactions are taking place. Other parameters may displace the profiles by shortening, expanding or smoothing the curve, but the fundamental shape of the curve remains.

The most significant fact emanating from the predictive geochemical modelling of seepage leaching from soils under tailings dam footprints is the understanding that the composition of the seepage is dominated by the mineralogical composition of the soils. The profiles clearly indicate when a specific mineral has ended its role in controlling the pH, or any of the other internal thermodynamic parameters. Furthermore, the time required for the seepage to return to near-neutral conditions is usually less than 35 years. However, the disconcerting observation is the high concentrations of especially sulphate in the seepage. In many instances the sulphate load remained at elevated levels, indicating that the actual cumulative salt loads are high. Apart from the sulphate molecule, no other ionic species seem to pose a serious threat to the environment. In a few instances the sulphate concentration decreases, after which there is a second marked increase. Such seemingly erratic behavioural patterns are directly related to the dissolution and precipitation of mineral species. The only mineral phases that precipitate from solution are the sulphate group of minerals, in particular alunite, gypsum and anhydrite.

1.7 REHABILITATION SCENARIOS

The various rehabilitation scenarios were considered by comparing the predicted concentrations of contaminants in the respective effluents. The quality of effluent was predicted by employing geochemical modelling techniques, similar to those used for the base case scenario. Each of the case study sites was modelled in terms of the different rehabilitation options. Although the hypothetical scenarios contain a degree of simplification, the overall characteristics are contained in the simulations. In general, the following conclusions could be drawn from the predictive geochemical modelling exercises for the various management options:

Minimization of infiltration

The inhibition of infiltrating fluids would bring about an increased precipitation of secondary minerals due to the increased concentration of chemical species per volume water. Furthermore, the pH values would decrease significantly and would take quite a while to recover compared to the other scenarios. The sulphate concentration in the effluent would however remain relatively low, but would have difficulty returning to background levels due to the low flow rates. Although the concentration may be relatively low, the cumulative load for the duration of the modelling period will be similar to the other management scenarios. Relative low concentrations of sulphate emanating from the soils should therefore not be confused with a low salt load being produced.

Paddockging

The term paddocking refers to the containment of precipitation and operational fluids within the confined space of the residue deposit, thereby creating a scenario where maximum infiltration of fluids into the polluted area are being allowed. The behaviour of the sulphate concentration profile show that the peak concentration is reached soon after the start, when values of an order of magnitude greater than those predicted for the minimum infiltration scenario are experienced. The precipitation of secondary mineral phases last for a very short period and the pH levels do not reach acidic values similar to the previously mentioned scenario. The question is however whether it is preferable to leach the pollutant out of the confinements of the system, or whether the chemical species should remain near the concentrated source, *i.e.* at the footprint of the residue deposit. Rehabilitation should be adjusted accordingly.

Source term removal

This scenario entails the removal of the source of pollutants. The effect of such action is clearly demonstrated in the pH profile, which recovers to near neutral conditions within a much shorter period compared to the other rehabilitation options. The sulphate profile appears to be similar in shape, compared to the minimum infiltration profile. The similarity is probably because of the signature of the soil profile being reflected in the concentration profiles, rather than the actual effluent emanating from the residue deposit.

In conclusion, the various modelled scenarios form mainly two opposing alternatives, *i.e.* those that result in the pollutant remaining within the confines of the residue deposit area, and those in which the pollutants are transported to the deeper aquifer, away from the source. The preferred management option would depend on a decision whether containment or dilution and migration of pollutants would be the desired option. Alternative management strategies, such as *in situ* treatment would require similar criteria in order to decide on its feasibility as a rehabilitation option.

1.8 RISK ASSESSMENT

The most effective method of addressing the problems that are associated with reclaimed mine residue deposits would be to follow a path of evaluating the various risks that are associated with the area and to address these risks in order of significance. In terms of contaminated land, risk to the environment can be regarded in terms of the following components:

- Source: contaminated substance with the potential to cause harm.
- Pathway: a route by which a receptor could be exposed to, or affected by the contaminated substances.
- Receptor: a particular entity that is being adversely affected by the contaminated substance.

In the context of this document the remaining tailings material as well as the top 30 to 50 cm of soil that contains the bulk of contaminants that have been leached from the overlying material would represent the pollution source. The vadose zone through which the water migrates and in which additional pollutants are being scavenged during water – rock interactions, would represent the pathway component. The receptor would be represented by the deeper aquifer in which the contaminants are being collected. The lateral distribution of pollution plumes takes place in the groundwater environment, and is a function of geohydrological flow conditions.

In view of the above, the process of risk assessment could be defined as an evaluation of the probability of harm, and in context of contaminated land, is concerned with the gathering and interpreting of information on the characteristics of sources, pathways and receptors at a specific site and understanding the uncertainties inherent to the ensuing risk assessment. The requirements of the risk assessment set the scope of a site investigation and, together, these activities form the scientific part of the contaminated land investigation. In practice, this involves characterization of the environmental chemistry of the contaminants, relevant properties of the soils encountered and the site characteristics that influence contaminant fate and transport.

The methodology that was followed during this investigation for contaminated land risk assessment was quantitative in its approach. During the technical phase of the project an extensive analytical database was compiled which allowed for rigorous data manipulation. This brought about an understanding of the processes involved as well as the sensitive parameters that dictates the behaviour of the system. A qualitative assessment of risk is sufficient to identify the key issues at a contaminated site, providing it includes the full range of contaminants encountered, takes account of the direct and indirect exposure pathways and considers relevant receptors. Where the source – pathway – receptor linkage is established, the qualitative approach can usefully provide an initial ranking of risks as a function of site-specific factors.

The chemical, physical, and geographic characteristics of the various pathways are described in detail in the report. In terms of the risk assessment of these various domains, the definitions of the components can be extended as follows:

- Source - the risk associated with the source of contamination is mainly dependent on the mineralogical composition of the material. The importance of mineralogy and the understanding thereof cannot be overestimated, since it is the core of environmental impact problems.
- Pathway - the impact of the pathway is dependent on the nature of the fluid flow through these pathways. For example, a steady state matrix flow would yield dramatically different results in terms of available reaction time for water – rock interaction compared to vertical fracture flow along the cracks that have developed in clayey soils.
- Receptor – the characteristics of the receptor is the largest unknown in this particular risk assessment process. However, the quantification of environmental impact parameters did not form part of the current investigation.

Risk assessment associated with geochemical modelling traditionally centres around the treatment of various parameters that form an important part of the iterative calculation process. For the purpose of this investigation, it was decided to develop a risk profile that would be unique for the system that is being modelled. Such a profile would provide the reader with knowledge regarding the aspects that should be considered and which are significant risk factors in terms of reclaimed mine residue deposits.

The most important cause for concern in reclaimed residue deposits is incomplete clean-up operations. Any remaining material, in particular sulphide minerals, poses an environmental hazard. Acid mine drainage, which stems from the oxidation of sulphide minerals, is still regarded as the most damaging environmental problem associated with mining. The significance of high modal proportions of sulphide material in the remaining residue material is corroborated by the sensitivity analyses. The chances of encountering unreacted sulphidic material in the centre of residue deposits are good, since oxygen does not enter tailings facilities readily. The latter statement is confirmed by the variation in redox conditions measured across the footprint of a residue deposit, as well as the lack of changing conditions along a vertical profile through the tailings facility.

The underlying geology on which the residue deposit is situated dictates the extent of pollution migration. Two aspects that are both directly related to the geology are the textural nature of the soil and the grain size distribution. The soils that are derived from carbonaceous dolomitic material would be distinctly different compared to the soils that are derived from siliciclastic rocks. However, the soils in the Witwatersrand area do not show a large degree of variation due to their aeolian origin.

An important factor that should be considered in a risk assessment is soil texture, which influences the flow of contaminants into the deeper aquifer and plays an important role in the remediation of contaminated areas.

A second parameter is the significance of grain size distribution in terms of pollution migration. Apart from the fact that grain size distribution has an influence on the flow of water through the matrix, it also dictates the available surface reaction area together with parameters that facilitate chemical interactions.

The intensity of flow through the system is an important parameter that dictates the extent of pollution migration. The conditions that dictate flow, apart from the inherent characteristics of the soils and rocks, are climate as well as the type of rehabilitation option that was selected.

In general, these factors are the most significant considerations in a risk assessment of a particular site. It is important to notice that the common denominator in these risk factors is the dependence of the system on the modal mineralogy. Ideally a detailed mineralogical account should thus be kept from inception until that reclaimed residue deposit has been rehabilitated.

Table 1.8.1 provides a summary of the risk assessment of the various rehabilitation options. It should be stressed that this summary represents a qualitative assessment at a conceptual level. Site-specific variation in physical characteristics could have a marked influence on the resultant risk assigned to individual aspects.

Table 1.8.1 Summary of risk assessment for the various rehabilitation options

Description	Base Case	Removal of the source term	Amelioration of soils	Paddock	Minimization of infiltration	Biological treatment options	Chemical treatment options	In situ treatment options
Legend: resultant risk L = low M = medium H = high								
Selected range of contaminants could be disposed	H	L	L	L	L	H	M	L
Contaminants are not completely removed	H	L	H	H	H	H	H	H
Contaminants are contained in a small area	H	L	M	H	M	M	M	L
Long-term rehabilitation of the site	H	L	L	L	L	M	L	M
Technique does not offers advantages of improving ground conditions	H	L	L	M	H	L	L	L
Surface areas are sterilized in terms of future use	H	L	L	H	H	L	L	L
Need to consider contingency liability and insurance implications	H	L	H	H	H	H	H	H
Possible long-term restrictions on use of site	H	L	L	H	L	L	L	L
Limited understanding of long-term integrity	H	L	M	H	H	H	H	H

1.9 CONCLUSIONS AND RECOMMENDATIONS

In general, the outcome of this investigation recommends a change in the technical approach to evaluating and remediating contaminated land. The introduction of a risk assessment approach, a phased and chemically orientated approach to site investigation, and the selection of remediating strategies from a number of technologies are all intrinsic components in the rehabilitation of these areas. From a technical viewpoint, the complexity of evaluating the

degree and extent of contamination became evident during the current investigation, demonstrating that a simplistic approach is inadequate. The approach presented in this document addresses the key processes that are active underneath mine residue deposits and takes account of the availability and pathways of key contaminants. The link has also been made between the soil and water environments so that contaminated land assessment and remediation should succeed in addressing all potential impacts in one overall risk-based approach. Awareness of the rapidly developing technological base is required, whether in investigation, risk assessment or remediation.

Identifying the most appropriate method for rehabilitation of a given site is a difficult process and requires consideration of a number of factors. These include process applicability, effectiveness and costs, process development status and availability and operational requirements. Additional factors to be considered are process limitations, monitoring needs, potential environmental impact, health and safety needs and post-management requirements. The amount of information that is required for an effective appraisal of available options is considerable and may, in many situations, not be available. It is pertinent to note that the details of a site investigation needed to determine that a site is contaminated and requires rehabilitation is generally not sufficient to identify what rehabilitation option would be most effective.

During the rehabilitation process, adequate quality control measures are needed to ensure that the methodology conforms to specification or that treatment targets have been achieved. By implication, this requires environmental monitoring while rehabilitation is in progress. In addition, upon completion of the rehabilitation, additional monitoring and management activities may be necessary, in particular, if contamination remains in any form on the site.

Radionuclides were not specifically focused on during this investigation. Mining industry assessments of the radiological impact of gold mining have already shown that uranium and radium-226 (and, for fish consumption, lead-210) are the only radionuclides likely to have any significant environmental/health impact via water pathways (Pers. Comm. Dr. D Wymer, Chamber of Mines). Given their long radiological half-lives, the relevant uranium and lead isotopes can be treated as heavy metals with known toxicities for the purposes of assessing their potential environmental/health impacts. Further work on the mobility and transport pathways of uranium and lead-210 in the footprint environment, as with any other heavy metals, would most likely need to be site-specific. Radium-226 might however need further consideration. Because of its low mobility, it is likely to remain on site where it may potentially give rise to increased radon exposure in homes built on the site.

The generic case studies on the Witwatersrand Supergroup and Karoo Supergroup has shown that there is adequate reason to believe that the underlying geology plays a major role in the behaviour of contaminants in the vadose zone. It has also been demonstrated that sites overlying the same geological environment may show significant differences, mainly as a function of the soil forms that occur on these sites. Further generic research based on the underlying geology may therefore not yield additional information, due to the site specificity demonstrated here. It is therefore recommended that any additional work should be on a site-specific basis, for the specific purpose of identifying the most appropriate rehabilitation option for the individual sites. The basic methodology is outlined in this document.

2 LEGAL FRAMEWORK

2.1 APPLICABLE LEGISLATION

There are a number of statutory Acts of Parliament that are directly involved in the regulation of mine residues. These include, but are not limited to, the following:

- (i) The Nuclear Energy Act (Act 46 of 1999), or **NEA**.
- (ii) The Minerals Act (Act 50 of 1991), or **MA**.
- (iii) The National Water Act (Act 36 of 1998), or **NWA**.
- (iv) The National Environmental Management Act (Act 107 of 1998), or **NEMA**.
- (v) The Air Pollution Prevention Act (Act 45 of 1965), or **APPA**.

2.2 BRIEF DISCUSSION

The MA applies to residues which are generated at the mine and which consist of either minerals, tailings, waste-rock or slimes. The disposal of such residues is managed via the Environmental Management Programme Report (EMPR). The EMPR requires approval by the Department of Minerals and Energy, in consultation with other relevant departments, including the Department of Water Affairs and Forestry.

In general, mining residues as such are not addressed specifically and explicitly in the NWA or the ECA. Residue is however addressed in the NWA in terms of the potential pollution of water resources (Section 21). The disposal of solid residues strictly speaking requires a licence for a water use, since an activity such as waste disposal, which may lead to the deterioration of a water resource, is considered a water use in terms of the NWA (Section 21(g)). This would apply if deterioration in the quality of the water resource has the potential to occur as a result of the disposal of residues, and is interpreted to include both radioactive and non-radioactive residues.

The Minimum Requirements for Waste Management, administered by the DWAF under the provisions of Section 20 of the ECA use the integrated waste management approach. The minimum standard for integrated waste management is the "best practicable environmental option" or BPEO, which is *the outcome of a systematic consultative and decision-making procedure that emphasises the protection of the environment across land, air and water. It establishes the option that provides the most benefit or least damage to the environment as a whole at acceptable cost in the long term as well as the short term.*

While the ECA is currently not applicable to mining residues, the principles embodied in the BPEO approach is considered to be appropriate for this guideline in terms of providing a framework.

In accordance with these principles, the management of waste should be such that:

- The reduction of pollution in one medium (e.g. air) must not take place at the expense of another (e.g. groundwater).
- There is no bad legacy. In other words, a long-term solution to waste management is emphasised.

- Waste management is performed at acceptable cost. Regulators have an obligation to ensure that unnecessary costs are avoided without lowering standards. Thus, the best available technology that does not entail excessive cost (BATNEEC) principle should be the directive.

3 RISK ASSESSMENT

3.1 INTRODUCTION AND DEFINITIONS

The most effective method of addressing the problems that are associated with reclaimed mine residue deposits, would be to follow a path of evaluating the various risks that are associated and to address these risks in order of significance. The motivation for a risk-based approach is mainly to fit in with the BPEO approach. Contamination can create a range of hazards, depending on its composition and nature and the environmental context. The term "risk" has a multitude of uses and is not to be confused with "hazard":

- **Hazard:** the nature of the adverse effect posed by the contaminant.
- **Risk:** the probability of suffering harm or loss under specific circumstances.

In the context of contaminated land, the term "risk" is used widely across disciplines when referring to issues such as financial liability, risks to human health and the environment, the perceived consequences of exposure, etc. In terms of contaminated land, risk to the environment can be regarded as being comprised of the following components:

- **Source:** contaminated substance with the potential to cause harm.
- **Pathway:** a route by which a receptor could be exposed to, or affected by the contaminated substances.
- **Receptor:** a particular entity that is being adversely affected by the contaminated substance.

In the context of this document the source of pollution would be represented by the remaining tailings material, which are often left behind on reclaimed mine residue sites, as well as the top 30 to 50 cm of soil, which contains the bulk of contaminants that have been leached from the overlying material during the life of the residue deposit. The vadoze zone through which the water migrates and in which additional pollutants are being scavenged during water – rock interactions, would represent the pathway component. The receptor would be represented by the deeper aquifer in which the contaminants are being collected. The lateral distribution of pollution plumes takes place in the groundwater environment, thus, the geohydrological flow conditions determine the migration of the pollution plume away from the source of contamination.

In view of the above, the process of risk assessment could be defined as an evaluation of the probability of harm, and in the context of contaminated land, is concerned with the gathering and interpretation of information on the characteristics of sources, pathways and receptors at a specific site and understanding the uncertainties inherent to risk assessment. The requirements of the risk assessment set the scope of a site investigation and, together, these activities form the scientific part of the contaminated land investigation. In practice, this involves

characterization of the environmental chemistry of the contaminants, relevant properties of the soils encountered and the wider site characteristics that influence contaminant fate and transport.

The environmental properties of chemicals encountered at contaminated land sites determine the distribution, fate and transport of the contamination and play a major role in determining:

- The suite of chemical analyses undertaken as part of the site investigation.
- The exposure assessment component of the risk assessment.
- The screening of remedial technologies.

The process of risk assessment can be viewed as consisting of four key stages:

- Hazard identification.
- Exposure assessment (what are the key environmental pathways by which the contaminants can reach the receptors and what are the concentrations at the point of exposure?).
- Dose-response assessment.
- Risk characterization (what level of risk can be assigned to each source – pathway – receptor linkage?).

3.2 OTHER ASPECTS

In order to guide the risk assessment aimed at determining the most suitable rehabilitation method for a specific tailings footprint, there are a number of aspects that need to be considered. These include the following:

Context

The potential impact from a contaminated footprint, and consequently the apportionment of the appropriate financial resources must be seen in the context of the mining operation as a whole. Since the financial resources that can be allocated to rehabilitation are finite, the use of this resource must be optimised in terms of addressing potential environmental impact. It is therefore critical to understand whether all possible impacts from the operation as a whole have been identified.

Legislative requirements

As stated earlier, there may be different requirements, role players and interested and affected parties depending on the physical location and physical parameters applicable to the various sites. A thorough understanding of these requirements on a site-specific basis is required in order to place the rehabilitation requirements in perspective.

Interested and affected parties

The role of interested and affected parties is critical in determining the optimal rehabilitation route for a specific situation. The new constitution paves the way for a greater public say in environmental issues, through greater access to information, greater public access to the courts, and entrenched environmental rights. The I&AP issues will need to be accommodated within the overall environmental risk management process.

The methodology recommended to be followed in the risk-based approach has the following main features:

- The decision making process passes through increasing levels of detail and complexity, with checks and balances at various stages to ensure that the assessment process is cost-effective and remains focused.
- All potential hazards and aspects must be identified and assessed according to a defined methodology. This methodology will not necessarily be identical for the various role-players, but it must be internally consistent.

3.3 LEVELS OF RISK ASSESSMENT

Methodologies for contaminated land risk assessment vary widely, but can essentially be categorized as qualitative, semi-quantitative and quantitative in their approach (Figure 3.1). In most cases, a qualitative assessment of risk is sufficient to identify the key issues at a contaminated site, providing it includes the full range of contaminants encountered, takes account of the direct and indirect exposure pathways and considers relevant receptors on and off site. Where the source – pathway – receptor linkage is established, the qualitative approach can usefully provide an initial ranking of risks as insignificant, low, medium and high, depending on the site-specific factors. Within the context of a tiered approach to risk assessment, semi-quantitative and quantitative risk assessment (QRA) methodologies are reserved for situations where greater resolution is required between risks in order to select between risk management options. QRA has become a highly specialized tool that relies heavily on the expert understanding and interpretation of baseline contaminant and toxicological data. It can be applied only where contaminated sites are very well characterized and hazards are well defined.

3.3.1 Screening-level risk assessment

The environmental risk assessment process should start with a conservative, screening-level risk assessment. The key features of this phase are that it is qualitative and conservative in nature. It may very well be that the rehabilitation option can be finalised on the basis of this level of risk assessment, but it should be noted that the rehabilitation option might then not necessarily be the optimal solution for the area.

The screening-level assessment is characterised by the following elements:

- All possible environmental risks are identified, including those that appear to be insignificant.
- The process is based on the input from existing data, specialists and persons with a detailed long-standing knowledge of site operations and history.
- In the absence of data, conservative assumptions are made and documented.

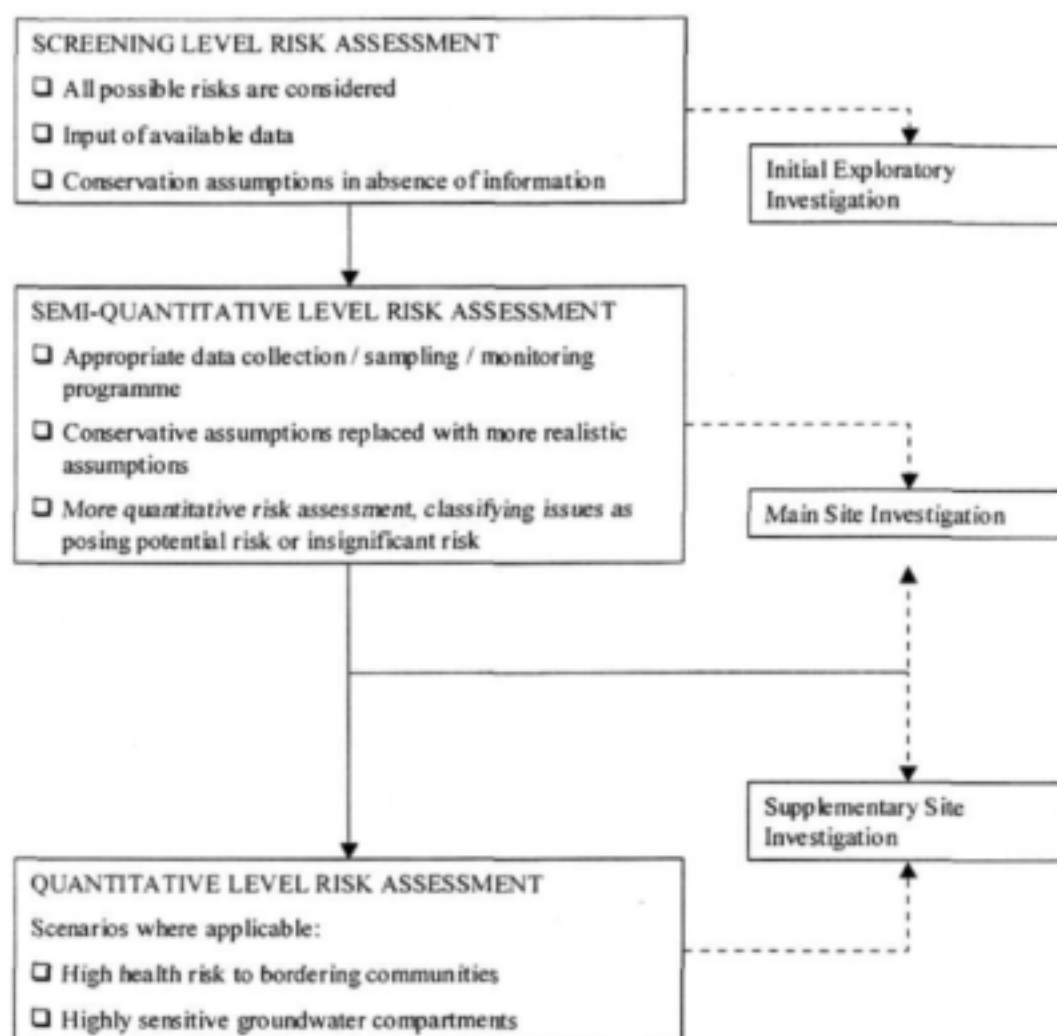


Figure 3.1 Diagram depicting the important aspects of different levels of risk assessment.

This approach implies that the issues classified as insignificant risks will have been classified as such on the basis of a conservative approach. There is therefore confidence that these issues indeed do constitute insignificant risk and do not warrant any further attention. This assessment of insignificant risks must however be communicated, discussed and agreed with all stakeholders concerned. Those issues, which are classified as uncertain, would typically require that a simple data-gathering programme be defined and undertaken to provide key data to enable an assessment of risk to be made. With this assessment, all issues earlier characterised as "uncertain risks" will be reclassified as either potential or insignificant risks.

3.3.2 Semi-quantitative risk assessment

There are various drivers that may force the risk assessment to a second stage, which is less qualitative, and can best be described as semi-quantitative. These may typically include the following:

- The rehabilitation option identified in the first level may be too costly.
- The regulatory authorities may require a more detailed assessment.
- The screening-level assessment is conservative, and may have over-emphasized potential environmental impacts.

In terms of methodology, the semi-quantitative approach may either follow from a screening-level assessment, or be the first step in the process. This decision is a function of the basic knowledge of the site and sensitivities around it. In this type of assessment, potential risks are addressed as follows:

- An appropriate data collection / sampling / monitoring programme is defined and carried out.
- Conservative assumptions are replaced with more realistic assumptions and actual measurements.
- A more quantitative risk assessment is undertaken, again classifying issues as posing potential risk or insignificant risk.

It is important to realise that those issues that are identified as posing potential significant risk during the conservative screening-level assessment process, may not, in fact, be significant risks. As conservative assumptions are replaced with more realistic assumptions and measured data, both the level of conservatism and the estimated risk decrease.

3.3.3 Quantitative risk assessment

The third or fully quantitative level of risk assessment will rarely be required. The typical scenarios under which this costly exercise may take place include the following:

- High potential risk to the health and safety of bordering communities.
- Highly sensitive groundwater compartments.

This process logically follows on a screening-level risk assessment or semi-quantitative risk assessment. The process of collecting additional data to replace conservative assumptions continues until the real risks are finally identified. These real risks are then subjected to detailed, fully quantitative risk assessments that have a high degree of certainty and are typically supported by extensive site-specific data. However, the number of issues subjected to a detailed fully quantitative risk assessment is typically a small fraction of the total range of issues that are evaluated in a screening-level assessment.

4 RISK MANAGEMENT

Risk management involves the evaluation of alternative options taking into account available economic, regulatory, scientific and technical information in order to select the most appropriate means of reducing risk. In practice, risks are managed by isolating, treating or removing contaminant sources, intercepting exposure pathways or isolating, treating or removing receptors. However, the guiding principal is to break the source – pathway – receptor linkage. The process of risk management employs the scientific output of the risk assessment, but considers other factors such as the financial and technical feasibility of remedial technologies, planning constraints and risk perception issues.

It is imperative to develop environmental criteria to determine when is a site contaminated and how clean is clean. In general, it could be stated that land would be classified as contaminated only where connectivity between source, pathway and receptor could be established and there is at least one of the following:

- Evidence of significant harm, or;
- The significant probability of harm, or;
- The pollution of controlled water, or;
- The likelihood of pollution of controlled water.

The potential risks should be managed by implementing the best practicable environmental option (BPEO) for all aspects of the rehabilitation process. Wherever measures are not meeting the required environmental objectives, other measures should be implemented that would ensure that the objectives are met.

The following environmental classification scheme was proposed in the SABS code of practice for mine residue deposits. All mine residue deposits were classified into two environmental categories:

- Residue deposits having a potentially significant impact on any environmental component; and
- Residue deposits having no potential to impact significantly on the environment.

The following aspects should form part of the environmental classification of residue deposits:

- The nature of the residue and any associated fluid in terms of chemical and physical properties.
- Location and dimensions of the deposit.
- The importance and vulnerability of the environmental components that are at risk.
- The spatial extent, duration and intensity of potential impacts.

A preliminary determination of the significance of the impact of the residue deposits on any environmental component may be made on the basis of the following criteria:

- For any environmental component the residue deposit shall be classified as having a potentially significant impact if the presence of the deposit will alter the state of that component.
- Impact may be considered significant by the authorities or interested and affected parties.

The classification is simplistic, but addresses the aspect regarding the influence of the residue deposits on the environment. Similar criteria could be applied to the site after remediation of the mine residue deposit.

5 GUIDELINE FOR SITE INVESTIGATIONS

Irrespective of the level of risk assessment, site investigation provides the means by which the basic data blocks required for risk assessment are assembled. When designing an investigation, it is imperative that the result should be tailor-made to serve several purposes. The following data are required for contamination assessment:

- **Definition of sources of contamination**
 - Location of contaminant
 - Nature of contaminant
 - Concentration
 - Total loading
 - Kinetic behaviour and equilibrium behaviour
- **Identification of pathways**
 - Site topography
 - Soil / rock permeability
 - Density of fractures
 - Stratigraphy / bedding systems
 - Man-made pathways
 - Surface drainage channels
- **Location of sensitive receptors**
 - Depth to groundwater
 - Proximity of surface water

At the same time that data are being collated for contamination assessment, it would also be appropriate to consider aspects such ground stability, which could affect the nature of the remediation measures. A practical approach to conducting such an investigation would be to consider the following steps:

- Desktop study.
- Main intrusive investigation.
- Supplementary intrusive investigation.

The framework for undertaking investigations of potentially contaminated land is depicted in Figure 5.1. Desk studies would include historic research from a range of sources to obtain the maximum available information on the site and the previous industrial uses. In addition, geological, hydrological and geohydrological records should be considered. On completion of the desk study, the main investigation could be designed, either as a single comprehensive survey or as a series of stages targeting specific high-risk areas or problems. The investigation

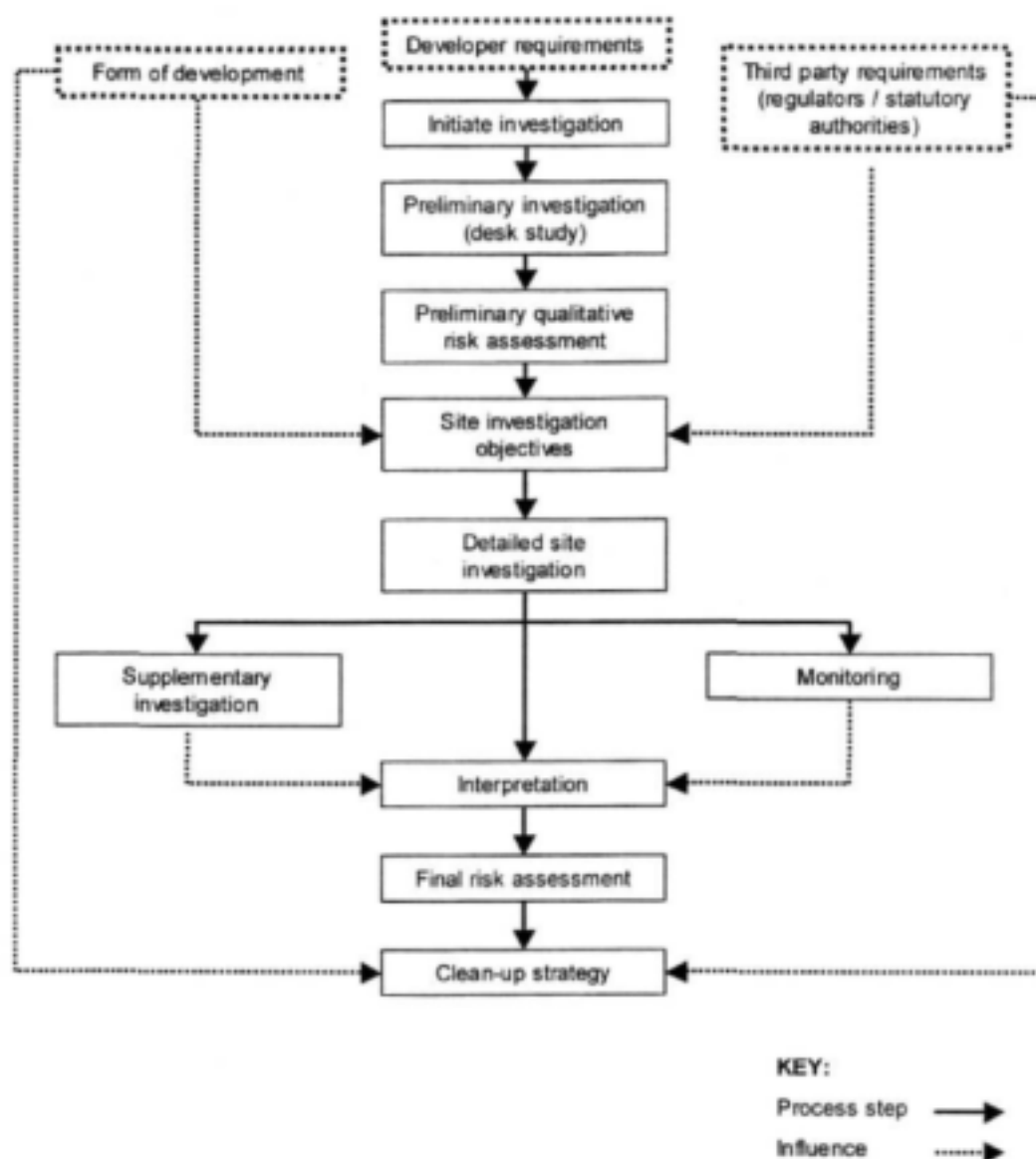


Figure 5.1 Investigation process for contaminated land.

may use a range of techniques, some of which involve non-intrusive activities and others that require physical sampling on site. These techniques are summarized below:

- **Non-intrusive techniques**

- site visit
- geophysical investigation (magnetic survey, IP survey, resistivity survey, etc.)
- false colour infrared photography
- thermography

- **Intrusive techniques**

- Boreholes
- Pits and trenches
- Probing techniques
- Window sampling

Data should be collated and assessed in a systematic manner. The extent of investigation of a site is a matter for professional judgement based upon an understanding of the history of site usage (derived from the desk study) and the proposed future use. The degree of confidence, which could be placed upon the results of an investigation, is a function of the following variables:

- The number of soil, rock and water samples collected (relative to the aerial extent of the site).
- The number of samples tested (relative to the aerial extent of the site).
- The number of exploratory holes and trenches or pits that these samples are collected from (relative to the aerial extent of the site).
- The spatial layout of the exploratory holes, trenches or pits.
- The extent of any *in situ* testing.
- The frequency and duration of subsequent monitoring.

An investigation should always seek to balance the degree of confidence required against the total cost of the work. Sampling strategies should be carried out in a manner as to provide a rational basis for the design of investigations.

6 GUIDELINE FOR REHABILITATION METHODS

If it is established during the risk assessment process that there is an unacceptable risk of pollution to a sensitive target area, the rehabilitation options generically fall into one of the following categories:

- Eliminate the hazard by removing the source of pollution.
- *In situ* treatment of the soil containing the contaminants.
- Minimising the infiltration of water into the contaminated soil.
- Designing a water management system that prevent any flow of surface water away from the contaminated site, i.e. paddocking.

The rehabilitation should invariably be evaluated in view of the future land use. If redevelopment is not proposed, it may still be necessary to carry out work on land to guard against future liability. Furthermore, if the work is to be undertaken without any prospect of enhanced value, then a further stage to risk assessment should be considered which compares the magnitude and likelihood of financial penalties against the cost of clean-up. Thus, any person considering the financial aspects of damage to the environment should also take legal advice on the additional risks. When determining the best course of action for rehabilitation, the following factors must be taken into account:

- Engineering feasibility
- Economics
- Health and safety
- Environmental impact
- Current and future standards/codes of practice
- Legislation

The primary aims of rehabilitation in the context of this document are as follows:

- Reduction of actual or potential environmental threat.
- Reduction of potential risks so that unacceptable risks are reduced to acceptable levels.

One or more of the following goals achieves rehabilitation of a contaminated site:

- Removal of the contaminants
- *In situ* treatment of the contaminated soil
- Isolation of the contaminant from the target by interrupting the exposure pathway

The remediation strategy determined for a particular site should be capable of removing any actual or potential threat to the environment and of reducing any risk associated with the contamination to an acceptable level. However, in addition to offering the necessary degree of protection the strategy should be practical and meet cost requirements. Factors to be considered include:

- **Applicability:** the rehabilitation process has to be applicable to both the contaminants and the contaminated medium in order to meet the desired level of rehabilitation.
- **Effectiveness:** long-term effectiveness should be a major criterion in the evaluation and selection of any rehabilitation process. The rehabilitation must be capable of achieving the level of treatment and risk reduction required.
- **Limitations:** various factors may constrain the use of remedial methods owing to the limitations imposed by the process or the site.
- **Cost:** probably the most important non-technical parameter to be considered when selecting the method of rehabilitation for any site.
- **Developmental status:** the development of a rehabilitation process evolves over a period of time and undergoes transition from an emerging technology, through an innovative stage to an established technology. In this regard the understanding of performance need to improve.
- **Availability:** the availability of particular rehabilitation processes will depend to some extent on the development status of the process and market demand for it.
- **Operational requirements:** these requirements include all measures and activities necessary to undertake the rehabilitation. Operational aspects to be considered include:
 - health and safety requirements
 - legal / regulatory issues
 - access and transport issues
 - infrastructural requirements
 - environmental protection
 - time constraints
 - quality assurance requirements
- **Information requirements:** an appropriate rehabilitation strategy can only be determined based on appropriate site information.
- **Monitoring needs:** this is essential in order to provide:
 - quality assurance
 - process control and optimisation
 - environmental protection
 - compliance with health and safety requirements

- **Potential environmental impact:** process-based rehabilitation methods require monitoring to verify that treatment targets have been achieved.
- **Health and safety needs:** requirements depend on the nature of the contaminants on the site.
- **Post-treatment management needs:** these aspects need to be addressed to verify the success of the rehabilitation process.

The rehabilitation options each have advantages (and by implication disadvantages), which are listed in a summary manner in Table 1.8.1 in the introduction to this document. The criteria that were used to evaluate the effectiveness of the different techniques are focussed at the practical aspects of remediation. A number of considerations apply to all the options listed in the table. Cost would be a common consideration. It follows logically that transport of contaminated material away from the reclaimed site introduces a major cost, as would be the case with complex ameliorating techniques. Furthermore, monitoring would be required in all of the remediation options. It is imperative to understand the effect that rehabilitation options has on the environment and the only effective manner to quantify the assessment would be to install a monitoring program. It must be stressed that each reclaimed site would be unique in terms of the advantages and disadvantages posed by the various rehabilitation options. However, the thoughts summarized in Table 1.8.1 encompass the general conceptual applicability of these options.

6.1 REMOVAL OF SOURCE TERM

Contaminated sites could be rehabilitated by excavation of contaminated soil and subsequent disposal. The approach represents a rapid method of dealing with a contaminated site. However, it involves the transfer of contaminated material from one location to another rather than a final solution. The major advantage would be that a wide range of pollution problems could be addressed in this manner, with excavation providing the additional advantage of potentially improving ground conditions.

6.2 PADDOCKING

The concept of paddocking deals with the containment of surface water (rainfall) on the contaminated land and the prevention of flow onto adjacent land. The containment of water has the direct disadvantage of maximizing the infiltration into the contaminated soil, thus giving rise to an enhanced rate of pollution migration into the aquifer. This migration may occur in the form of pulses, depending on the hydrological parameters of the specific design.

Although the environmental impact on the surface area is contained in a reasonably effective manner, the impact on the underlying soils and groundwater is dramatically enhanced. High infiltration rates mobilize secondary precipitates that have formed and results in a second pollution front migrating through the underlying soils. Paddockking may be a method used to contain surface migration of contaminants, but should not be considered as a rehabilitation method. The effectiveness of paddocking varies according to the types and nature of contaminants present, e.g. inorganic chemical components or radioactive materials, the physical conditions of the site and the design life of the paddocking system. The long-term integrity of the construction materials may, in some cases where specific contaminants are present, not be known. Furthermore, there appears to be a significant public resistance to paddocking, in particular because of the risk of drowning associated with the unprotected

open paddock system. For all practical purposes the land is being sterilized in terms its use for any alternative activity. This option must be considered as an interim rehabilitation method only.

6.3 MINIMIZATION OF INFILTRATION

There is a range of possibilities under this option. Conversion of the land surface to a built up area (such as a shopping mall and associated parking) will effectively equate to the capping of the site. This option could however also involve the covering of a contaminated area with a single layer, or succession of layers, of uncontaminated material. The result of the implementation of an option where infiltration is minimised is that one or more of the following will be achieved:

- Prevention of exposure of at-risk targets to potentially harmful substances.
- Sustained growth of vegetation (capping option only).
- Control of infiltration to, and subsequently from, the site.

The requirements of a system where infiltration is minimised are as follows:

- Minimize the potential effect of the upper layers of soil.
- Limit surface water percolation and minimize leachate.
- Minimize capillary movement of contaminants.
- Prevent soil erosion and dust generation.
- Support vegetation (capping option only).
- Inhibit root penetration into contaminated layers.
- Improve aesthetics.

There is a wide choice of materials suitable for use as a paving system, which would depend on the physical properties required by any particular component layer. Possible materials include:

- Natural clays, sub-soils and soils.
- Amended soils incorporating materials like lime and sludges.
- Synthetic membranes and geotextiles.
- Concrete, asphalt, etc.

Economic factors, in addition to physical properties, would influence the material selected and a compromise between ideal and locally available materials might be necessary. The minimisation of infiltration could represent an effective treatment procedure at reasonable cost. The main advantage of such a rehabilitation option would be the fact that large areas could be isolated in a reasonably effective manner. However, the contaminants are not being removed from the site and thus continue to pose a problem, which effectively sterilize land-use. The possibility of failure of such a cover over the long-term always exists, which introduce a certain component of risk.

6.4 *IN SITU* TREATMENT OPTIONS

The range of processes to treat contaminated soils includes a diverse variety of methods that include both *in situ* and *ex situ* approaches. This variation could be classified into two main groups:

- Washing and sorting treatments

- Extraction treatments

For the purpose of this document, the focus is on the *in situ* processes. The majority of methods that form part of this group of rehabilitation options are well established and a wide range of contaminants can be isolated. The use of some solvents may have health and safety implications. For the treatment options to be effective, optimum soil – treatment interaction needs to take place. Such an interaction is severely impeded in clay-rich soils. Thus, the effectiveness of the latter rehabilitation technique depends on a variety of factors, among others the soil conditions.

6.4.1 Extraction treatments

The main aim of these processes is to concentrate the contaminants into a relatively small volume so that the cost associated with disposal and further treatment are related to the reduced volume of process residues. Washing and extraction treatments are an effective manner to transfer contaminants from particle surfaces into an aqueous phase by leaching using liquid extractants. The aqueous phase could be treated as wastewater. Extraction treatments involve processes that remove the contaminants from the soil matrix. Two of the more important categories are:

- Soil flushing and chemical extraction: processes that use chemical reagents or solutions to mobilize and extract contaminants from soils. Mobilization refers to the release of dissolved contaminant ions from sorbed or precipitated forms in soils.
- Electroremediation: an *in situ* process where an electric current is passed through an array of electrodes that is embedded in the soil. When the current is applied, movement of contaminants in the pore water towards the electrodes is induced by electrolysis, electro-osmosis and electrophoresis.

6.4.2 Chemical treatments

Chemical treatment processes for the rehabilitation of contaminated soil are designed to either destroy contaminants or to convert them to less environmentally hazardous forms. A range of chemical processes is at various stages of development, for both *in situ* and *ex situ* applications. The major types of processes include:

- Oxidation – reduction: redox processes can treat a range of contaminants, including organic compounds and toxic heavy metals. Oxidizing agents can include oxygen-bearing components and ultraviolet light.
- Extraction: can be used for the treatment of contaminated soil and metal extraction. The extraction liquid containing the contaminant has to be collected for treatment.
- pH adjustment: application of weak acidic or basic materials to the soil to adjust the pH to acceptable levels.

Of major importance is the effective interaction between soil type and solvent added for treatment. Clay-rich soil invariably poses a problem in optimising the treatment. If the technique were applied correctly, a high degree of chemical specificity would be possible. Unreacted chemical should not be allowed to remain in the soil, a fact that would defeat the purpose of the rehabilitation exercise.

6.4.3 Biological treatments

Biological rehabilitation methods, such as the use of micro bacterial activity and wetlands, enable the degradation of some contaminants to harmless intermediate phases and end products. The ultimate aim is the mineralization of contaminants to carbon dioxide, water and harmless inorganic compounds. Biological processes have considerable scope for integration with other rehabilitation processes and are applicable to both contaminated soil and groundwater. An advantage of the simpler biological treatments is their potential to be cost effective, although long treatment times may be required. Furthermore, biological methods may be highly contaminant specific. The presence of some contaminants may inhibit the biological degradation, often because of the formation of hazardous intermediate products. Some inorganic and organic contaminants may not be treatable using the biological remediation options.

7 GUIDELINE FOR REHABILITATION MANAGEMENT

A management system should be developed which would achieve a consistent and professional approach by ensuring that:

- Appropriate technical procedures are used to identify, investigate, assess and, where necessary, rehabilitate contaminated land.
- Appropriate management procedures are used to confirm the validity and effectiveness of technical measures.
- The cost-effective management of the rehabilitation of the land is achieved.

Project managers should be required to adopt procedures aimed at ensuring that all contaminated land sites follow a systematic, rigorous and fully documented process of investigation, assessment and rehabilitation. The site-specific nature of contamination should be recognized, in order to prevent the application of prescriptive solutions for the treatment of a site. Each site would be required to have a comprehensive project brief in order to define the objectives of the project and the scope of the work required. Some flexibility in the design process would be advisable.

Engineering feasibility must be considered for any physical solution that is deemed necessary at a contaminated site. This means that the solution must be practical and appropriate to the ground conditions. Schemes that require separation of the contaminated soil from the clean when the two are visually indistinguishable must be designed with the time delays of chemical testing in mind. Chemical testing should also form an integral part of the rehabilitation option that deals with the *in situ* treatment of soil.

When designing the rehabilitation strategy, health and safety, as well as environmental impact issues must be considered such that when a solution is finally chosen, it can be demonstrated to have considered all issues in addition to basic cost. The chosen solution should balance all environmental impacts against cost and final site condition to provide the required reduction in risk, the minimization of environmental impacts and a reasonable cost. Whatever solution is chosen, it is imperative to ensure a high standard of implementation. This may be done via both the normal controls of construction contract and the quality assurance procedures which most companies embrace. Verification of the rehabilitation via a systematic sampling and

testing programme is often the best way of demonstrating the achievement of the set objectives.

The essence of effective rehabilitation management is quality assurance and clearly presented reports and documentation. Even where specialist investigation or rehabilitation techniques are being implemented, the value of the site work is dependent on effective reporting of findings and actions carried out. Third parties may require understanding what has been done to manage contaminated land. In Figure 7.1 a guideline is proposed and the reports that may form part of a site-specific project are listed. It should be noted that the level of investigation would to some extent influence the specific detail to be contained in the reports.

8 CONCLUSIONS

The introduction of a risk assessment approach, a phased and chemically orientated approach to site investigation, and the selection of remediating strategies from a number of technologies are all intrinsic components in the rehabilitation of reclaimed tailings dams. Evaluating the degree and extent of contamination is a complex process. The approach presented in this document addresses the key processes that are active underneath mine residue deposits and takes account of the availability and pathways of key contaminants. The link has also been made between the soil and water environments so that contaminated land assessment and remediation should succeed in addressing all potential impacts in one overall risk-based approach. Awareness of the rapidly developing technological base is required, whether in investigation, risk assessment or remediation.

Identifying the most appropriate method for rehabilitation of a given site is a difficult process and requires consideration of a number of factors. These include process applicability, effectiveness and costs, process development status and availability and operational requirements. Additional factors to be considered are process limitations, monitoring needs, potential environmental impact, health and safety needs and post-management requirements. The amount of information that is required for an effective appraisal of available options is considerable and may, in many situations, not be available. It is pertinent to note that the details of a site investigation needed to determine that a site is contaminated and requires rehabilitation is generally not sufficient to identify what rehabilitation option would be most effective.

During the rehabilitation process, adequate quality control measures are needed to ensure that the methodology conforms to specification or that treatment targets have been achieved. By implication, this requires environmental monitoring while rehabilitation is in progress. In addition, upon completion of the rehabilitation, additional monitoring and management activities may be necessary, in particular, if contamination remains in any form on the site.

PROJECT STAGE TYPICAL REPORTS CONTENT CHECKLIST FOR KEY REPORTS

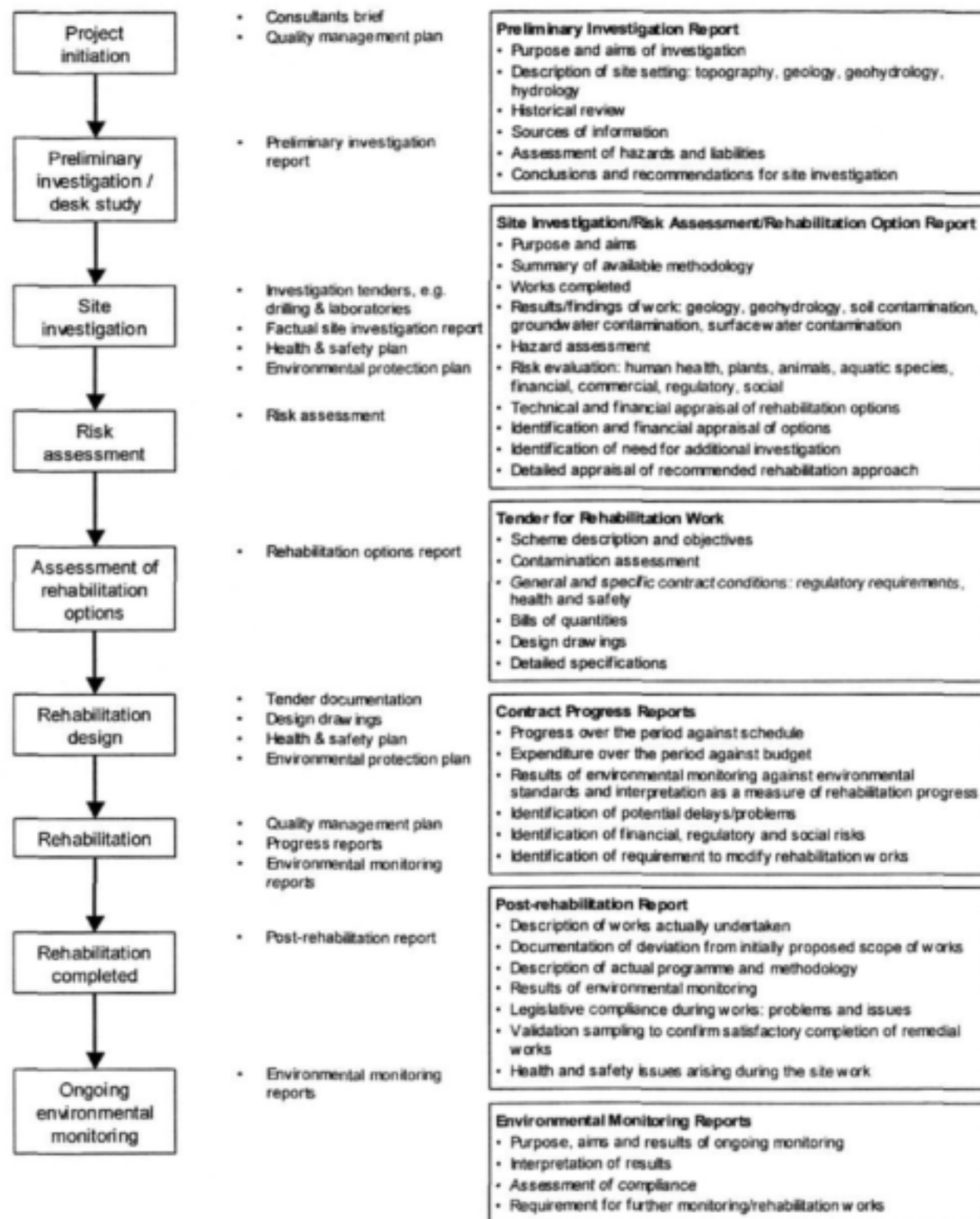


Figure 7.1 Guideline for key reports that are required for site-specific investigations

In terms of recommendations to address future challenges, the following aspects should be considered:

- A risk assessment approach in dealing with contaminated land seems to have been accepted as the preferred route. However, the future aim should be to quantify the associated risks in a numerical manner.
- Considerable scope exists for research into the behaviour of pollutants in terms of their availability, mobility and impact upon specific targets, as well as the development of existing and new rehabilitation techniques.
- Public participation should become an integral part of rehabilitation strategies.
- Legislative issues regarding identification of the polluter, the pollution that may be caused, and agreement on adequate treatment options for individual sites.

Radionuclides were not specifically focused on during this investigation. Mining industry assessments of the radiological impact of gold mining have already shown that uranium and radium-226 (and, for fish consumption, lead-210) are the only radionuclides likely to have any significant environmental/health impact via water pathways. Given their long radiological half-lives, the relevant uranium and lead isotopes can be treated as heavy metals with known toxicities for the purposes of assessing their potential environmental/health impacts. Further work on the mobility and transport pathways of uranium and lead-210 in the footprint environment, as with any other heavy metals, would most likely need to be site-specific. Radium-226 might however need further consideration. Because of its low mobility, it is likely to remain on site where it may potentially give rise to increased radon exposure in homes built on the site.

The generic case studies on the Witwatersrand Supergroup and Karoo Supergroup has shown that there is adequate reason to believe that the underlying geology plays a major role in the behaviour of contaminants in the vadose zone. It has also been demonstrated that sites overlying the same geological environment may show significant differences, mainly as a function of the soil forms that occur on these sites. Further generic research based on the underlying geology may therefore not yield additional information, due to the site specificity demonstrated here. It is therefore recommended that any additional work should be on a site-specific basis, for the specific purpose of identifying the most appropriate rehabilitation option for the individual sites.

Other related WRC reports available:

A preliminary assessment of pollution contained in the unsaturated and saturated zone beneath reclaimed gold-mine residue deposits

T Rösner, R Boer, R Reyneke, P Aucamp and J Vermaak

Water pollution is an increasingly important socio-economic issue in South Africa. Experience overseas has shown that the costs involved in the remediation of large-scale polluted areas are far too high, owing to too large quantities of contaminated material being treated. The uncontrolled release of acid mine drainage (AMD) as a direct result of poor operational management is unequivocally the single most important impact of mining activities on the environment.

A number of tailings dams (approximately 70) in the Gauteng Province are being reclaimed and reprocessed in order to extract gold still present in economically viable concentrations in the tailings material. Once the tailings material has been removed, the land has a certain potential for land development. But it is important to take into account that the reclaimed tailings material leaves a contaminated footprint on the subsurface and the land situated in the prevailing wind direction has also been affected by the deposition of wind-blown tailings material.

The *current contamination impact* was assessed by comparing extractable element specific ratios to the total concentration contained in the solid phase (mobility, bio-availability).

The *future contamination impact* was assessed by implementing a geochemical load index, which classifies various pollution levels into six classes.

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