# Workshop
## on Environmental Management

Goldfields Environmental Management Group

# PROCEEDINGS 2004

**May 26, 27, 28**

*Kalgoorlie - Boulder*

**Western Australia**

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# GEMG FOREWORD 2004

In 2004 Sinclair Knight Merz celebrates forty years assisting the mining industry develop, construct, operate, expand and close its operations throughout Australia and internationally. While we take time to reflect on our successes, our focus and our vision is fixed firmly on what we believe is the exciting and challenging journey ahead.

We believe that this journey will see us continue to grow as part of a sustainable mining industry and that our success, like that of the mining industry in general, will be built on leading edge technological innovation, sound environmental principles and strong community values.

Paramount to this vision are the ongoing sharing of knowledge and the development of relationships with our clients, competitors and partners, required to meet the economic, environmental and social challenges ahead. Forums such as the biennial Goldfields Environmental Management Group Workshop are vital to meeting these challenges and are the lifeblood of environmental innovation and improvement. Nowhere else can environmental practitioners come together with their peers on common ground to discuss topical issues, forge lasting relationships and re-energise the enthusiasm that drives us all towards enhancing the way that the mining industry is perceived and how it operates.

It is with this acknowledgment that SKM is proud to sponsor the 2004 GEMG Workshop and continue our commitment to the development of 'best practice' environmental performance within the Goldfields region.

The program for the Workshop not only demonstrates the broad range of environmental issues facing the mining industry today, but is also indicative of how professional environmental management has become an integral and critical component of the mining industry. This is particular evidenced by the diverse range of highly experienced and skilled speakers who will share their knowledge with us over the next few days.

SKM looks forward to continuing its involvement with the GEMG over the coming years and wishes all delegates the best for what we believe will be a rewarding and fascinating Workshop.

**Darren Murphy**

Manager Environmental Mining Services
Sinclair Knight Merz

# GOLDFIELDS ENVIRONMENTAL MANAGEMENT GROUP
# 2004 WORKSHOP ON ENVIRONMENTAL MANAGEMENT IN ARID AND SEMI-ARID AREAS - PROCEEDINGS

**Session Two - Waste Dump Rehabilitation**



*CD of Proceedings available with some colour images.*

*Papers not available at time of printing may be accessed at www.gemg.org after the conference.*

# INTRODUCTION AND MEMBERSHIP TO THE GEMG

## INTRODUCTION

The Goldfields Environmental Management Group (GEMG) is a technical and professional body of people working to achieve environmental best practice. The GEMG promotes good environmental management practices in arid and semi-arid areas by providing a source of expertise and resource for land rehabilitation and environmental management.

This is achieved through providing information and education to the public and industry on vegetation and environmental management and by identifying areas where rehabilitation knowledge is limited and research will be beneficial.

The group was formed in 1988 by a small number of individuals involved in land rehabilitation in the Eastern Goldfields region of Western Australia.

Today we have a solid membership from a broad range of backgrounds such as government organisations, consultants, rehabilitation contractors and minesite environmental personnel.

The aim of the GEMG is to promote sound environmental management practises throughout the region.

The GEMG has endeavoured to achieve these aims in several ways:

- Regular meetings with a guest speaker.
- Producing a plant identification handbook.
- Establishing the Goldfields Reference Herbarium.
- Conducting a biennial conference on relevant topics.

## PROJECTS

This is the 7th environmental workshop that GEMG have held in Kalgoorlie. The workshops are among the projects GEMG has undertaken to forward the aim of promoting sound environmental management practices and information exchange.

Other projects past and current include:

- Publishing a series of guidelines on topics such as topsoil management, seed collecting, waste dump revegetation and hypersaline water management.
- Producing a plant identification handbook.
- Establishing the Goldfields Reference Herbarium in conjunction with the Kalgoorlie College (Curtin University) and the Western Australian Herbarium.
- Development of a website.

The upgrade of the Herbarium and the website to expand the services offered by both are among our current projects. Public outreach will remain a key goal of the GEMG.

## AIMS

The overall aim of the Goldfields Environmental Management Group is to promote sound environmental management and awareness in the Goldfields region, particularly by:

1. Providing a source of expertise and resources for land rehabilitation in the Goldfields. This includes areas such as revegetation techniques, seed technology and site planning.
2. Providing information and education to the public on revegetation and environmental management.
3. Identifying areas where rehabilitation knowledge is limited and research will be beneficial.
4. Provide a forum for discussion and dissemination of information and knowledge regarding environmental issues.

## INTERESTED?

To apply for membership to the Goldfields Environmental Management Group, or to obtain further information about the group's activities, contact:

The Secretary
Goldfields Environmental Management Group
PO Box 2412
BOULDER WA 6432

www.gemg.org

The GEMG meets regularly to discuss environmental management issues.


# PROCEEDINGS 2004

May 26, 27, 28

Kalgoorlie - Boulder

Western Australia

# Day One

**Session 1**
**New Technology & Innovations**

**Session 2**
**Environmental Management Systems**

**Session 3**
**Salt Lakes & Mine Water Disposal**

**Session 4**
**Legal**

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# MAKING THE MOST OF MINE REHABILITATION MONITORING DATA

*Jamie Gerrard[1], David Jasper[2], Nick Galton-Fenzi[1], David Tongway[3] and Melanie Ward[2]*

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## ABSTRACT

*Increasingly, mining companies are faced with substantial quantities of monitoring data from rehabilitation or mining operations. This creates challenges for environmental staff to effectively integrate and respond to this information with appropriate strategies. In particular, as the complexity of the data increases, simple analyses and summarization become more difficult.*

*Database software has the capacity to store and query monitoring data and has been utilised extensively in many areas of our industry. A vast amount of data is collected through environmental monitoring programs. Improved data management has contributed significantly to the mineral industry through improved geological interpretation and it is expected that applying this technology to the management of environmental data will provide similar benefits. These benefits will be gained through the ability to systematically and easily interpret rehabilitation monitoring data and this is expected to lead to clearer understanding of the key factors that contribute to successful rehabilitation in the arid goldfields environment. More sophisticated questions that require information from diverse sources can be addressed. Rapid analysis is important, so that management decisions can be made in a timely manner.*

*At Harmony Gold's South Kal Mines operations, a front end has been designed for a database to specifically manage the data generated from landform rehabilitation monitoring. This database performs required calculations, enables the evaluation of trends between a wide variety of parameters and present results efficiently in an easily understood manner.*

*This paper will provide an overview of the development of the database and the challenges in the management and interpretation of the monitoring data. Using rehabilitated landforms at South Kal Mines as a case study, this paper demonstrate usefulness of the database in providing outputs that can be used to refine future rehabilitation strategies or to identify remedial action that may be required for existing landforms. Most importantly it will be demonstrated that improved data management will lead to better understanding of the factors which contribute to successful rehabilitation as well as the interaction between these factors.*

## INTRODUCTION

South Kalgoorlie Mines Pty Ltd is a wholly owned subsidiary of Harmony (Australia). South Kalgoorlie Mines consist of the Jubilee and New Celebration processing facilities, Mt Marion underground mine, three decommissioned underground mines and numerous satellite open pits and exploration activities spread over about 1,200 square kilometres of land.

The area has been explored and mined by over 20 different companies within the last 20 years and the quality of remedial works and recording of these works was not often as good as it could have been.

When Harmony (Australia) acquired South Kal Mines it was faced with numerous waste landforms, which require continued remedial works to complete rehabilitation to an acceptable level. The ability to make informed decisions based on quantitative data was not possible due to the lack of monitoring that had been conducted and where monitoring has been conducted this had been done by a variety of consultants using mutually inconsistent procedures. It is also worthwhile noting that there are many sites where information has been collected but its value diminished because of poor record keeping, incomplete documentation and commonly, a lack of geographical survey data.

Ecosystem Function Analysis monitoring was commenced on a broad scale in October 2002. Monitoring has commenced on 23 waste landforms, with 119 transects now established and 164 monitoring events have been completed. These 164 monitoring events have generated over 50,000 measurement recordings this is already a significant amount of data and much more data will be collected as the program continues. At South Kal Mines it has been calculated that the field work required for each monitoring event costs around $300, this equates to each measurement being worth about $1.

It has been an objective of South Kal Mines to formalize a systematic approach to housing the information on which to base the decisions that must be made to complete environmental remediation. An important part of achieving this is having a system for collection, management and evaluation of environmental data, that enables an ongoing measure of progress and ensures that the maximum value can be gained from the information collected.

### Development

Formal procedures have been developed based on the EFA monitoring technique and these have been incorporated into SKM's environmental management system. This is expected to ensure that monitoring is consistent from year to year and if changes are to be made to the monitoring techniques the changes are made in an open and explicit manner that ensures that comparison with previous recordings is possible.

Data collection forms have also been incorporated into South Kal Mines' EMS. Standardised forms assist with ensuring that data is collected in a systematic manner, helping to reduce the risk of omissions and mistakes.

The database has been developed to provide a user-friendly interface which:

- Allows data to be entered through forms, which have the same format as the field forms.
- Performs required calculations of indices from raw measurements enabling changes to be made to calculations if required as processes develop.
- Performs validation of data as it is inputted to assist in minimising the mistakes that are made in data entry, which helps to minimise human error.
- Allows for the incorporation other types of data from the variety of other monitoring programs, such as design parameters, rehabilitation techniques used, fauna monitoring or soil chemistry monitoring.
- Allows data to be queried and relationships between a variety of results to be compared and trends evaluated.
- Presents results in an easily-understood manner, to enable efficient generation of progress reports.
- Allows output of data in a manner that allows data to be reviewed using other types of software such as graphing or GIS packages that may be more appropriate for review and interpretation of the results.

It is expected that monitoring strategies will continue to evolve as scientific and technological progress continues, and it will become important to systematically review and update the information management and interpretation techniques in a systematic manner, to ensure continued improvement.

## OBJECTIVES

There are numerous examples of relationships that can be seen on rehabilitated waste landforms that are quite obvious. For example, landforms that have low batter angles often perform better than those with steep batter angles and waste landforms with rocky slopes often perform better than those where the surface has no exposed rock. It is however more difficult to quantify how important these factors are in ensuring the rehabilitation we do meets the completion criteria that are set by the industry and its stakeholders.

South Kal Mines has inherited many waste landforms from previous owners that have been constructed and rehabilitated to differing standards. While there are some that are performing well there are also those that are not performing as well as we would desire. Through the monitoring program that we have initiated it is expected that we will have a systematic means of identifying the limiting factors that are preventing poorly-rehabilitated areas from progressing, of objectively testing potential remediation methods and rectifing the relevant problems in an efficient manner.

As we accumulate monitoring data from more and more waste landforms it is expected that we will encounter similarities and based on these we will be able to then begin to generate predictive models. An ability to better predict physical, chemical and ecological evolution of a waste landform at the design stage or re-design stage would be a useful tool in ensuring that the risks of failing to meet completion criteria are minimized.

## Results

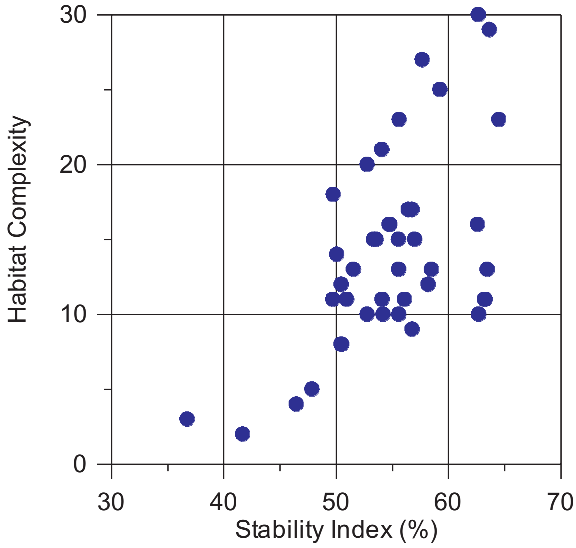
While the data that has been collected on waste landforms monitored on South Kal Mines' operations only covers two years and a limited number of sites, significant trends have already been noted.

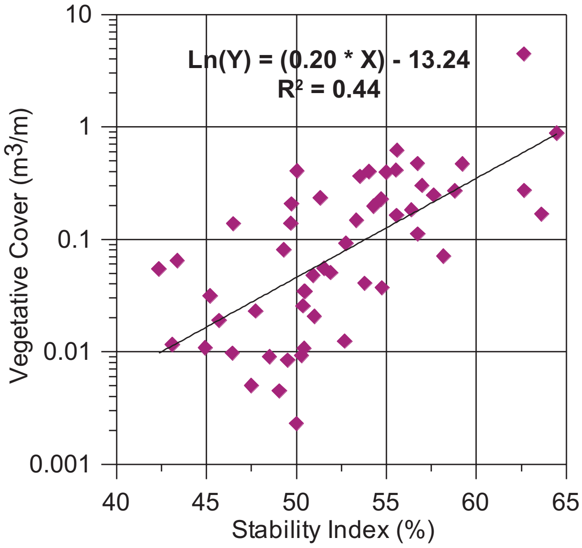
- A relationship is indicated between Stability Index and the measure for Habitat Complexity (Figure 1).
- A moderately verified exponential relationship can also be seen between Stability Index and Foliar Cover (Figure 2).
- To date there are only 10 sites where Vegetative Cover can be directly compared with measured soil salinity. The salinity levels are relatively low and there is no clear relationship with vegetative performance. It is anticipated that as the available data set grows and with more focused querying of the data it will be possible to better quantify the effects of saline soils on rehabilitation progress (Figure 2). Other factors such as the conditions at the time of germination and establishment may still be more important influences on vegetative performance and it is expected that these will be better quantified with improved data management.
- Comparing waste landform batter angle slopes and Stability Index shows the expected, however weak trend indicating that a lower slope angle will provide a greater chance of a stable landform surface than a steeper one (Figure 4).

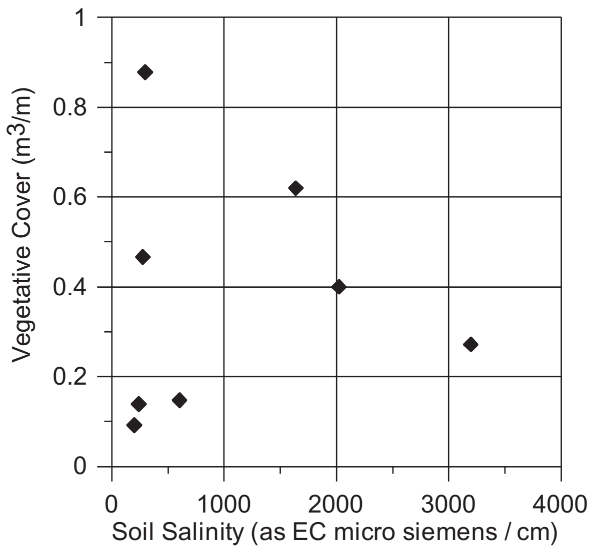
The range of Stability Index results has been plotted against ages of rehabilitation (Figure 5). A curve has been fitted to results at the upper end of the Stability Index spectrum, which ends at results for analogue sites included at 20 years since rehabilitation. The curve approximates an acceptable trajectory for a rehabilitated landform in regard to Stability Index.

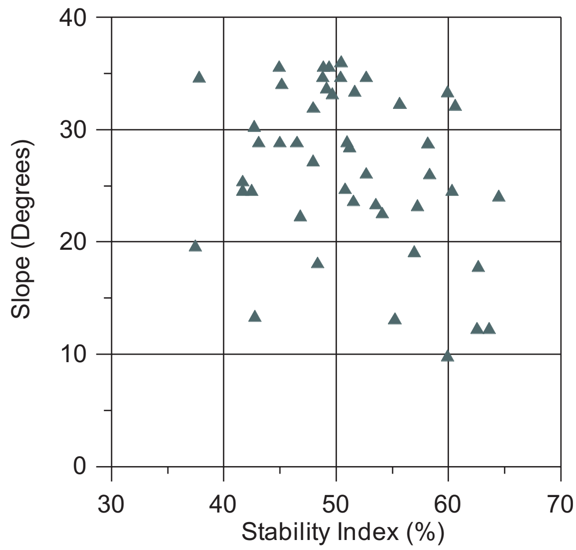
The graph has been divided into four sections:

- Section A represents sites where stability has exceeded a critical threshold for stability. Completion criteria in regard to this index have been met.
- Section B represents sites where measurements are progressing toward the desired level.
- Section C represents rhe range within which sites are not progressing as well as would be desired, however may naturally improve to a level where stability would be acceptable.
- Section D represents the range within which external intervention is required to ensure rehabilitation objectives will be met.




## CONCLUSION

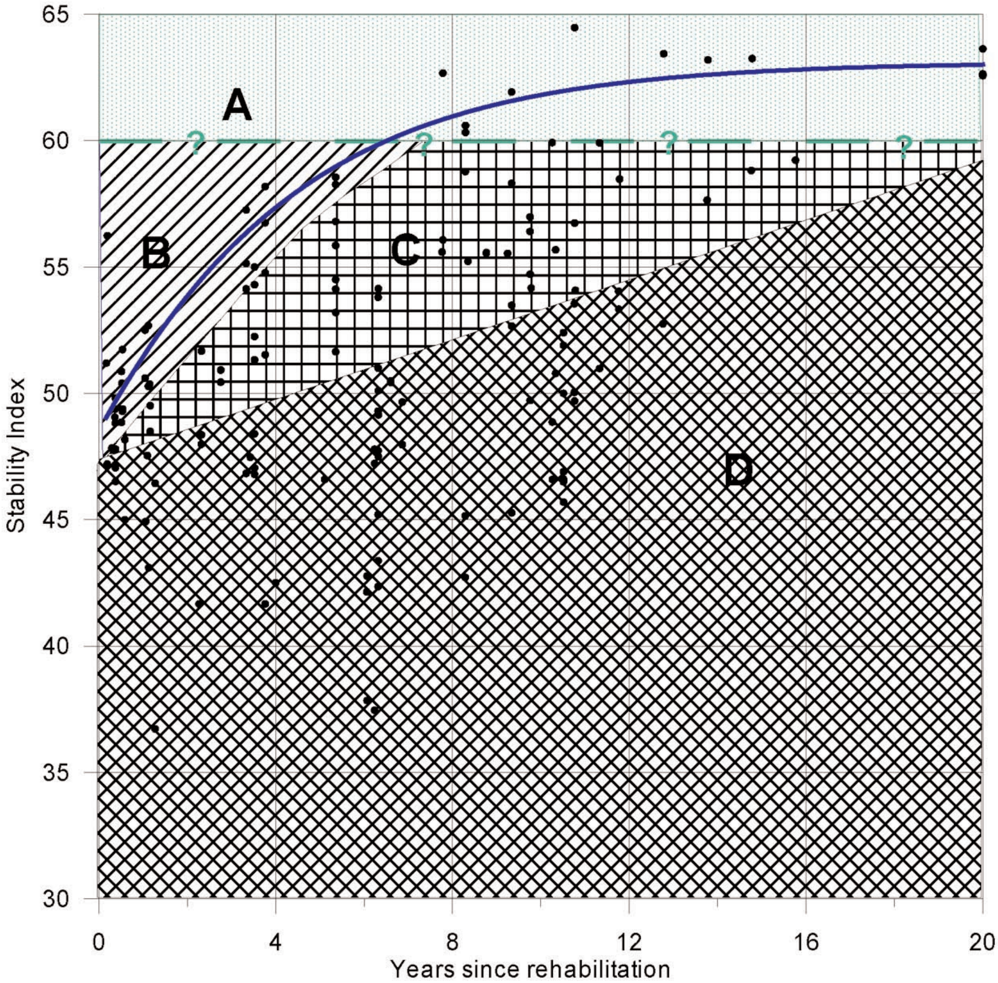
It is important to recognise that the rehabilitation and monitoring of waste landforms brings together a wide range of scientific disciplines. The use of a database for the housing and management of environmental monitoring is a valuable tool, which enables the data that is collected, can be processed to provide increased evaluation and interpretation opportunity.

Through improved management of data it is expected we be able to better quantify the importance of the many components, which determine the progress of a rehabilitated landform. This is inturn expected to lead to a greater understanding of dynamics of a rehabilitated waste landform.

Data management systems with the express intention of interpreting information across a range of data sources and analysis over time will provide a solid basis for both on-going management of rehabilitation and in the presentation of information about rehabilitation effectiveness to Regulators. Complex questions and emergent properties arising from a rational analysis can be addressed. Local area and 'regional" values may emerge, suitable for use as threshold values and targets. This approach also emphasises the need to commence monitoring as early in the life of rehabilitation as possible, in order to properly capture early trends.

Figure 5 provides us with a management tool which can be used assess the progress of a rehabilitated landform at a given point in time and alert management of deviations in the expected trajectory of a landform, enabling more rapid response to problems that may arise. Similar types of graphs for other progress indicators are being developed so that progress can be quantitatively assessed on an ongoing basis across the spectrum of completion criteria.

*Figure 5*




It is hoped that as this work continues we will develop an ability to better predict ecosystem development on a waste landform and more quantitatively assess the risk of a waste landform not meeting the completion objectives.

This could have great benefits across the industry from assisting with improving designs to accelerating the completion and bond release process.

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# THE APPLICATION OF DIGITAL PHOTOGRAMMETRY TO ASSESS LONG TERM STABILITY OF MINESITE WASTE ROCK DUMPS

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## ABSTRACT

*The use of Digital Photogrammetry to obtain accurate three-dimensional coordinates of a surface has improved substantially with recent advances in cameras and software. The investigation of gully erosion is an ideal application for photogrammetric methods as site accessibility has little impact on the ability to collect data. In comparison, obtaining detailed information on gully morphology through traditional survey techniques is more labour intensive and, in some cases, potentially hazardous to field operators given the possible instability and surface roughness of sites requiring investigation. Photogrammetric methods enable large quantities of data to be acquired simply and efficiently. Additionally, photogrammetry offers considerable advantages over traditional instrumented erosion plots used for erosion monitoring, including the ability to study areas with high spatial variability, and low site maintenance requirements.*

*Terrestrial close range digital photogrammetric methods were used to obtain detailed three-dimensional data on erosion gullies associated with waste rock dumps at the Newmont Australia Limited's Jundee gold mining operations, located near Wiluna in central Western Australia. Digital stereo pairs of photographs were taken at each site and three-dimensional images produced. Difficulties associated with producing accurate three-dimensional images included: aspect; complex gully morphology; and excessive vegetation in and around gullies. However, provided a sufficient number and diversity of images were obtained, the impact of these difficulties was minimised. Data from each image were then imported into the GIS program ArcView, where gully volumes were calculated and gully morphology (profile shape and length) was investigated.*

*The erosion data were then used to develop parameters for the landform evolution model SIBERIA. The three main parameters of the model were adjusted until the simulated gullies were of similar morphology to those measured in the field. The model was then used to predict the evolution of the waste dumps through periods of up to several hundred years using the derived parameters.*

*Photogrammetry is a promising management tool in the assessment and long term monitoring of erosion of rehabilitated areas, and assisting with the formulation of critical performance indicators for landform stability as part of the mine closure planning process.*

## INTRODUCTION

The Newmont Jundee Operation (NJO) near Wiluna in central Western Australia has a number of waste rock dumps that are visibly affected by gullying. In at least some instances, that gullying has been triggered by tunnel erosion of berms, with the failed berm directing concentrated flows onto lower batter slopes. The situation is exacerbated by the potential for such failures to cascade downslope when 40 m high slopes are constructed as a series of lifts and berms.

Landloch staff visited NJO from 16-18 July 2003 to carry out an initial assessment of erosion gullies located on its waste rock dumps via digital photogrammetric methods. The data collected are to be used for ongoing monitoring of erosion rates experienced by the gullies and also for derivation of input parameters for the landform evolution model SIBERIA to model the long-term erosion and landform stability of the older waste rock dumps.

This paper describes the method employed in both the acquisition and processing of photogrammetry data and the subsequent use of that data to derive SIBERIA parameters based on waste rock dump W1/W2/WN3S. Erosion rates predicted by the SIBERIA model using those derived parameters are presented and recommendations for future work in this area suggested.

## MATERIALS AND METHODS

### Data acquisition

Photogrammetry is defined as: "The science, and art, of determining the size and shape of objects as a consequence of analysing images recorded on film or electronic media" (Fryer in Atkinson, 2001). Photogrammetry can either be terrestrial or aerial; long or close range. "Close range" is defined as images taken at a distance less than 100 m from the object or surface of interest. Close range terrestrial photogrammetry was employed for the acquisition of site data at Jundee.

Gullies on three of the existing mine waste rock dumps at NJO (waste rock dumps W1/W2/WN3S, WN1/WN6 and Gourdis) were photographed in July 2003, using a Kodak Pro 14n camera fitted with a Nikor 60 mm lens. This lens/camera combination can provide accuracy of up to 1 mm, when images are taken from a distance of 10 m or 8 mm or less when taken from a distance of less than 100 m.

Stereo digital pairs of photographs were taken with known camera locations at close range (<100 m) from the surface of interest.

At least one control point was positioned to appear within each image. Survey support provided the exact locations of both the camera positions and the control points. Tilt was minimised via the use of a spirit level positioned on top of the camera. Convergence angles were maintained at approximately 8-10 degrees, where possible, to enhance the accuracy of data obtained from the images. To increase the suitability of images for processing, three digital stereo pairs of images were obtained from each site, employing slightly different views and different aperture settings and shutter speeds. Large gullies without a clear, straight path and could not be captured in an image set due to occluded regions, were divided into sections with separate sets of images taken to view the occluded regions. The largest gully had a total of four sets of images taken in an attempt to achieve complete coverage of the gully. Data acquisition was efficient with a total of 14 gullies photographed within two days in the field.

## Data processing and analysis

The resulting stereo digital pairs of images were processed using the SIRO3D (Mapper3D) software developed by CSIRO's Division of Mining and Exploration. SIRO3D produces a three-dimensional model of the object or surface of interest.

The software requires the position of both camera locations and a control point in the photo. Combined with image data, the software uses triangulation to determine a mass of 3D points (CSIRO, 2000). This model is presented in SIRO3D as a point 'cloud' of X, Y and Z values. To create this 'cloud', pixel-by-pixel matching between the two images needs to be performed. The greater the matching, the more accurate the final 3D data will be.

Difficulties were encountered during data processing in achieving a high level matching between the stereo pairs of images.

Vegetation and rocky spoil in images reduced the level of matching achieved due to occlusion (Figure 1). Complex gully morphology also led to occlusion (Figure 1) of large portions of gullies behind gully walls, as well-developed gullies had evolved distinctly sinuous morphologies. Occlusion was by far the greatest difficulty encountered when producing accurate three-dimensional images.

SIRO3D was originally developed for production of 3D images of pit walls, with close to a 90-degree angle between the camera line of site and the wall. It also has difficulty matching images with extreme changes in perspective that is created when the images are taken from a short distance or with the camera positioned on a berm, which was necessary in some situations due to limited available space around subject gullies. Low slope gradients (<30%) reduce the desired 90-degree angle, increasing perspective changes and therefore also reduce matching levels.

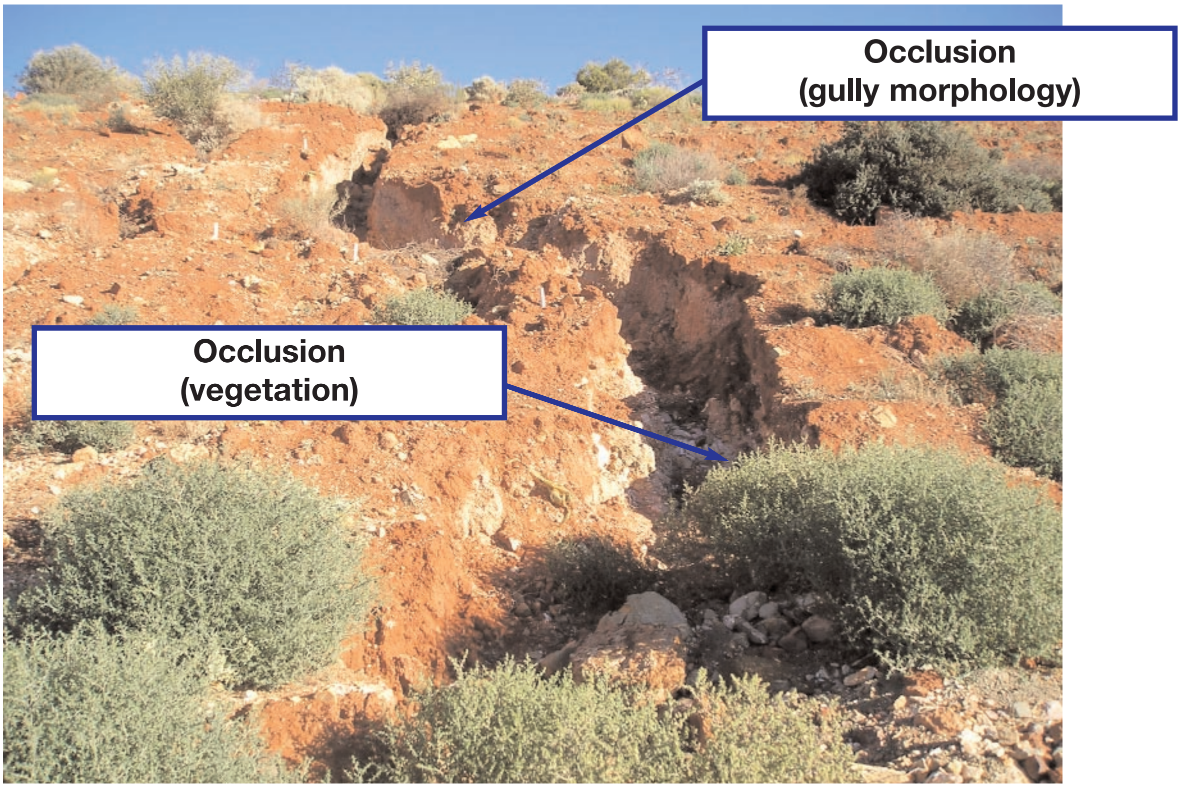


*Figure 1: Occlusion areas within a gully*

In addition, unless large aperture numbers are used (creating a greater depth of field), then only a section of the photograph will be focused adequately for successful matching. Images taken from a short distance (1-2 m) from the gully of interest led to high convergence angles between the camera lines of sight.

A number of processing techniques were used to minimise the effects of these factors, including:

- Sectioning images into segments in which high levels of matching could be achieved (low vegetation cover and uniform planes present in both images) using the SIRO3D software's irregular area feature and then 'mosaicking' the image back together. 'Mosaicking' was by far the most common processing technique employed;
- Processing data to remove outliers.

Although these practices were effective in improving the quality of the data obtained, they also significantly increased processing time.

In response to these difficulties, CSIRO's Division of Mining and Exploration developed a new matching algorithm designed to cope with low slope angles and extreme geometry. This new algorithm significantly improved the gully representations.

Once data of a sufficiently high quality were obtained for each of the sites, volumes of spoil lost due to erosion were determined for the derivation of SIBERIA parameters. Data were exported as XYZ files into ArcView GIS for analysis as the data analysis capabilities in SIRO3D are limited. ArcView created 3D representations of the data 'cloud', interpolating areas without data through a Triangulated Irregular Network (TIN). Volumes for each of the sections of gullies were determined using the cut and fill feature contained in the ArcView Spatial Analyst extension. Gully profiles were extracted using the PE 6.0 for 3D Analyst extension.

## SIBERIA parameter derivation

The SIBERIA model simulates runoff and erosion from a landform that evolves in response to predicted erosion and deposition. It is a 3-dimensional topographic evolution model that predicts the long-term evolution of channels and hillslopes in a catchment on the basis of runoff and erosion and has been successfully applied to explain aspects of geomorphology of natural landforms (Willgoose, 1994).

SIBERIA predicts the long-term average change in elevation of a point by predicting the volume of sediment lost from a node. Fluvial sediment transport rate through a point (qs) is determined by the equation:

$$q_s = \beta_1 \, q^{m1} \, S^{n1} \qquad (m^3/yr)\ldots\ldots\ldots\ldots(1)$$

(S = slope (m/m), q = discharge ($m^3/y$), and $n_1$, $m_1$ and $\beta_1$ are fitted parameters).

While the SIBERIA model has a large number of input parameters, $m_1$, $\beta_1$ and $n_1$ have been shown to have the most significant influence on the final output from the model.

The method used to determine the $n_1$, $m_1$ and $\beta_1$ parameters required SIBERIA simulations to be run on an 'ideal slope', based on the design specifications of the dump. These were:

- 10 m lifts at a 30% gradient;
- 5 m berm structures at the base of each lift.

Most gully formation at Jundee appears to occur through failure of the berms and subsequent concentration of flows. Berm failures, by functions such as tunnelling, cannot be simulated in SIBERIA as it will only failure through the process of erosion and deposition to cause sedimentation on berms leading to overtopping failure. Therefore, to simulate the berm failure condition; the 'ideal slope' file was adjusted to incorporate breaks at intervals representative of gully spacing on an actual slope observed at Jundee. (Gullies chosen were selected based on their origin from a berm failure and running the complete length of the lift, 48 m in length.) Based on these criteria, the breaks were spaced 30 m apart on the bottom berm, 50 m apart on the second berm and 80m apart on the third berm. An assumption was made for the simulations that all erosion experienced on the slope was in the form of gully erosion.

A general investigation of the effect of each of the parameters on gully size and morphology was then performed using this "ideal" test slope. Approximately 130 simulations were performed on the "ideal slope" with various combinations of the three parameters. Resultant gully morphologies were documented after a 10-year period (a typical dump age). From this investigation the general effect of each of the parameters on gully morphology was determined. Due to the interrelatedness of the parameters (refer to Equation 1), it was difficult to determine the precise effect of each parameter. Certain patterns were evident however. Gully length was clearly maximised by reduction of the $n_1$ parameter, whilst adjusting the $\beta_1$ parameter and $m_1$ parameter had notable effects on gully width and depth respectively. Reduction of the $n_1$ parameter below 1 led to erroneous results in the output from the model for long-term simulations and as such was avoided. The $m_1$ parameter increased the incision experienced by the slope and led to significant rilling on the slope in areas other than below a forced berm break.

As an assumption for the modelling had been made that all erosion was gully erosion due to berm failure, the $m_1$ value was maintained at a level where excessive rilling was avoided.

Parameter values were then developed for each of the waste rock dumps. All simulations to determine parameters were performed using SIBERIA version 8.18 with a 0.5 m grid and a 0.005 time-step. An $n_1$ value of 1.01 was set to maximise gully lengths whilst avoiding the problems associated with $n_1$ values less than 1. An iterative approach was then used to establish $\beta_1$ and $m_1$ values, these parameters being adjusted until comparable gully volumes and similar gully morphology was obtained for gullies present on each dump (standard gully width of 1 m, standard gully depth of 0.5 m and standard gully volume of 25 $m^3$). As gully length of 48 m could not be achieved with $n_1$ set at above 1, depth and gully width were allowed to increase slightly to ensure gully volumes were preserved.

The rainfall experienced at the Jundee site since the beginning of 1995 was significantly higher than the long-term average at the site. In the 8-year period from 1995 to 2003, average annual rainfall at the nearby Wiluna site was 380 mm. In comparison, long-term average annual rainfall at Wiluna was 260 mm (information acquired from the Bureau of Meteorology website). This raised concern as to the accuracy of long-term erosion predictions based on the gully erosion experienced at Jundee during this period. An investigation of the rainfall patterns revealed that the occurrence of Cyclone Bobby in February 1995, prior to construction of W1/W2/WN3S dump, contributed to the higher than average rainfall experienced at the site. An assessment of rainfall events excluding the influence of Cyclone Bobby in the 8-year period from 1995 to 2003 indicated that the rainfall erosivity over this period closely resembled the long-term annual average rainfall erosivity. Due to this, no adjustments to the modelling method were necessary to account for the increased rainfall over this period.

## SIBERIA landform evolution modeling

For this study the SIBERIA landform evolution model was run through an ArcView extension, ArcEvolve 1.3. The use of the ArcView environment allows for the correction of Digital Elevation Model (DEM) files; the definition of boundary and region files; and hydrological analysis to be performed on the DEM before processing (Boggs, et al. 2001). ArcEvolve also allows for resultant DEM files produced to be imported back into ArcView for subsequent analysis and display of the erosion predicted by the SIBERIA model.

The SIBERIA Landform Evolution Model requires accurate DEMs of the waste rock dumps as input into the model. A DEM created via photogrammetric methods performed on an aerial shot of the Jundee site was supplied to Landloch for the purposes of analysis. The DEM was of insufficient quality for input into the SIBERIA model and was therefore corrected based on observations from an aerial shot of the site. As a consequence, the resulting DEM of the waste rock dumps can only be considered an approximate representation.

The model was run, using the derived parameters, for a period of 500 years and output requested for 100, 200 and 500 years. These simulations were performed with a grid size of 10 m, using SIBERIA version 8.18 and a 0.05 time-step. Analyses to determine total spoil losses and average annual erosion rates for the whole of each dump were performed. Additional analyses excluding the dump tops and areas of deposition at the base of the slope were also performed to estimate erosion solely occurring from the waste rock dump batter slopes.

**Table 1: Comparison of gully morphology method and laboratory method SIBERIA parameters**

| Parameter | Gully volume and morphology fitting method | Derived from rainfall simulator data |
|---|---|---|
| $n_1$ | 1.01 | 1.5 |
| $m_1$ | 1.11 | 1.08 (Topsoil/rock (2:1)) |
| $\beta_1$ (1m) | 0.039 | 0.032 |

## RESULTS AND DISCUSSION

### Photogrammetry

Due to specific difficulties associated with the application of photogrammetry to the surveying of gullies discussed in the previous section, the results achieved from the photogrammetry method were variable. Gullies with simple morphology and clear of vegetation produced reasonable results. However, the results obtained from sites with larger, more complex geometries or sites with excessive vegetation could not be used for the purposes of analysis. Despite these difficulties, enough sites with a sufficient representation of the gullies were achieved for derivation of SIBERIA parameters.

The difficulties associated with complex gully morphology could potentially be avoided by taking a greater variety of images at these sites to ensure complete coverage of the gullies. While this does lead to a large number of images being acquired, the capacity of modern digital cameras allows for this with no additional expense being incurred.

### SIBERIA parameters

The present method for determining SIBERIA parameters $\beta_1$ and $m_1$, is somewhat subjective. Further work is required to determine the precise effect of each parameter on gully morphology. The constraints applied to the modelling ($n_1$ set to 1.01, conservation of gully volumes and the assumption of no sheet or rill erosion) do however constrain the $\beta_1$ and $m_1$ parameters, thus ensuring the uniqueness of a parameter set for a given site.

The final parameter estimations (gully morphology method) are presented in Table 1 along with parameters developed for SIBERIA during a previous study (laboratory method) of the site (Landloch 2001). The topsoil/rock combination studied in the laboratory had WEPP parameters similar to those measured for oxidised spoil in the field (though a slightly lower erosion rate overall). The parameters predicted by the gully morphology method employed in this study are comparable with those developed from previous studies.

### SIBERIA landform evolution modelling

The accuracy of the final landform morphology is dependent upon the detail of the original DEM provided. The use of a simplified DEM in this study resulted in the landform for this site consisting of fewer, larger gullies than would have occurred had a more detailed DEM, that included berm failures, been used.

The long-term erosion rates for 2 waste rock dumps (W1/W2/WN3S and WN1/WN6) were calculated based on the predicted total soil loss for the 500-year SIBERIA simulation (Table 2). As the majority of erosion on these sites was driven by erosion on the batter slopes, long-term erosion rates were also calculated by assuming that all erosion from the site occurred on the batter slope, excluding both the waste rock dump top and the area of deposition at the bottom of the dumps from the calculations. This was done to enable comparison with erosion rates estimated for a period of 43-years by the WEPP model in previous erosion studies (Landloch 2001).

The WEPP model was used to predict the annual average erosion rates for: topsoil, spoil, and spoil of lowest hydraulic conductivity. The predicted erosion rates for these materials were 6.9 (t/ha/yr), 15.2 (t/ha/yr) and 20 (t/ha/yr) respectively. It should be noted that the WEPP model erosion predictions were based on 5 m rill spacing and a slope length of approximately 33 m compared with the 195 m slope length and much wider gully spacing of the waste rock dump. As such, it is not surprising that in this study, predicted erosion rates are higher.

The estimated erosion rate for the Jundee site for the last 8-years is 18.9 t/ha/yr (based upon observed gully spacing and gully volumes established from photogrammetric data). The long-term erosion rates predicted in this study are therefore considered reasonable.

**Table 2: Long Term Erosion Rates for Both Waste Rock Dumps**

| Waste Rock | Dump Area (ha) | Batter Slope Area (ha) | Simulation Period (years) | Erosion Rates for Whole Dump (t/ha/yr) | Erosion Rates for Batter Slopes Only (t/ha/yr) |
|---|---|---|---|---|---|
| W1/W2/WN3S | 193 | 101 | 100 | 12.69 | 24.25 |
| | | | 200 | 13.08 | 25.00 |
| | | | 500 | 13.92 | 26.60 |
| WN1/WN6 | 75 | 28 | 100 | 11.17 | 29.91 |
| | | | 200 | 11.46 | 30.71 |
| | | | 500 | 11.24 | 30.11 |

## Landform stability assessment

Ongoing photogrammetry monitoring of the Jundee site will enable the verification of the erosion rates predicted and subsequent calibration of the method outlined. The major limitation on acquiring accurate representations of gully erosion on the waste rock dumps is due to occluded areas that occur on sites with larger, more complex gully geometries and/or sites with excessive vegetation. Taking a greater variety of images to ensure a complete coverage of gullies can reduce the difficulties associated with sites with complex gully morphologies. While this does lead to a large number of images being acquired, the capacity of modern digital cameras allows for this with no additional equipment expense being incurred.

Landform stability monitoring using photogrammetry is currently ineffective on sites with heavy vegetation established that obscures differing areas of the ground surface. Until there are further advances in the photogrammetry field to remove the influence of vegetative cover, on sites that produce high levels of vegetation the assessment of landform stability needs to be conducted to measure the soil and plant interaction on stability. Procedures such as, Ecosystem Function Analysis (Tongway and Hindley, 1995) and a similarly based Gully Assessment System (Landloch, 2003) provide an assessment of landform stability and gully stability respectively and can be utilised on sites were photogrammetry is ineffective.

## CONCLUSIONS

Acquisition of photogrammetric data was highly efficient. Some difficulties were encountered in processing the data to produce the final 3D gully representations (data matching difficulties by extreme changes in aspect and occlusions due to vegetation, rocks and complex gully morphology). Advances in field acquisition methods and the SIRO3D software will reduce these difficulties and hence increase the accuracy of the gully representations.

With improved available information on gully morphology and volumes, the accuracy of determined SIBERIA parameters should increase.

The constraints applied to the derivation of SIBERIA parameters from the gully data ($n_1$ set to 1.01, conservation of gully volumes and the assumption of no sheet or rill erosion) produced a unique set of parameters for the site ($\beta_1$ of 0.039 and $m_1$ of 1.11). The resulting parameters generated by this method compared favourably with parameters derived in previous erosion studies at the site.

Long-term erosion rates predicted by the SIBERIA model, for waste rock dump W1/W2/WN3S, using those derived parameters ranged between 12.7 t/ha/year (over the entire waste rock dump) and 26.6 t/ha/year (on batter slopes only). The estimated erosion rate for the Jundee site for the last 8-years, based on current gully volumes and spacings, is 18.9 t/ha/yr. As such, the predicted long-term erosion rates in this study are considered reasonable.

The accuracy of final landform morphology predicted using the SIBERIA model is dependent upon the detail of the original DEM input. However, a simplified DEM still appears to provide reasonable predictions of erosion rates using the method outlined in this paper. Utilising an improved DEM for simulations should improve the accuracy of both predicted erosion rates and final landform morphology.

## ACKNOWLEDGEMENTS

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# THE EVOLUTION OF AN ENVIRONMENTAL MANAGEMENT SYSTEM TO A SUSTAINABILITY MANAGEMENT SYSTEM

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## ABSTRACT

*Environmental Management Systems (EMSs) are evolving, becoming more holistic and contributing more to business strategy and risk management. They are becoming Sustainability Management Systems (SMSs). Many thoughts have been captured on sustainability management, but there is still hesitation to fully embrace and implement the concept in many organisations throughout Australia. The business case for sustainability management has already been well established by leading organisations and industry associations and is similar to the business case for environmental management. Therefore, the hesitation for uptake by organisations is possibly due to:*

- *Lack of time, money and expertise to invest into another system of management;*
- *Uncertainty on how sustainability could be implemented into a specific organisation to gain benefit; or*
- *Doubt in how sustainability will benefit an organisation and conscious resistance to the promises and marketing hype of sustainability management.*

*Given these apprehensions, the most efficient method to move more convincingly towards sustainability is to expand a system that is currently being implemented. The mining industry in Australia is one of the more progressive industries when it comes to EMS implementation, so it is well positioned to initiate the transition to SMSs. The transition from environmental management to sustainability management is a continuum when the cycle of "Plan-Do-Check-Act" is maintained.*

*However, sustainability management occurs on a more strategic level than environmental management. This subtlety requires a different skill set. Sustainability management calls for a more holistic framework of trust management: part stakeholder engagement, part risk assessment, part governance and part technical know-how. The emphasis on each component will be influenced by the management philosophy of the organisation, as well as the actual and perceived impacts of both the organisation and the industry.*

*This paper describes a practical method for evolving an EMS into a SMS and to overcome the very real challenges of SMS implementation in industry.*

## FROM AMBIGUITY TO CLARITY

The word "sustainable" has been associated with everything from forestry, agriculture, economic growth, and consumption to society and energy. The widespread use of the term indicates that many people conclude that the dominant, industrial models of production are unsustainable. Many papers, research groups and industry forums have produced information on position, progress and potential for industry to move towards sustainability. However, many have mistreated the language of sustainability so that confusion and uncertainty is evident and advancement towards sustainable industries is impeded. While sustainability discussion is abundant, pragmatic methods of implementation are harder to come by.

The task at hand is to simplify sustainability – its concepts, implementation and motherhood statements - and ensure a management approach for industry can utilise well established concepts and structures to improve the credibility of organisations, improve productivity and operate within society's values. It is from this position that Environmental Management Systems (EMSs) are an obvious vehicle to develop Sustainability Management Systems (SMSs). The undertaking of SMS development thus becomes more of an exercise in evolution than initiation, where the time, expertise and money invested in EMS is re-used and broadened to form a SMS.

Within the mining industry in Western Australia some companies have taken great strides towards sustainability. Companies such as Rio Tinto, WMC and BHP Billiton provide information on projects and stories that are the essence of sustainability, and it would be prudent to state that many mining companies in Australia are already implementing sustainability strategies, plans and systems. However, there is little information on such implemented approaches which co-ordinate and measure the performance of the projects and stories.

The Plan-Do-Check-Act cycle, with continual improvement at its core, plays a major role in many standards and frameworks that can be linked to sustainability (ISO 14001, ISO 9000, AS/NZS 4581 – Management System Integration Guidance, The SIGMA Management Framework). The EMS to SMS approach also needs to adhere to this cycle to ensure compatibility with these standards without incurring duplication and to ensure it is consistent with other management systems that may already be implemented in organisations and advocated in industry.

It needs to be stated that implementation of a SMS will not alter the fact that the activity of resource extraction is finite and, as such, unsustainable. What a SMS will facilitate is a mining organisation that is more capable of operating to the expectations of society, more flexible in its approach to anticipating those expectations and the prolonged existence of what has been described “as a sunset industry doomed to inevitable decline and irrelevance” (Sheehy & Dickie, 2002).

## SUSTAINABILITY POLICY

A SMS is a co-ordinated method of putting sustainability into practice in industrial organisations. The system is based on a sustainability policy, developed by senior management, has risk management at its centre and provides performance indicators that can be measured. The focus of a SMS, similarly to an EMS, needs to be stakeholder value and community expectation, where rigorous forms of consultation result in management understanding the sustainability expectations of key stakeholders.

The establishment of a sustainability policy is possibly the most important process in developing a SMS. It is this senior commitment dialogue process that is vital to ensure that sustainability is defined and implemented. A sustainability policy could be derived from issues relating to the organisations current activities, operating situation and vision for the future. The sustainability policy will provide guiding statements or objectives on the three “pillars” of sustainability: economics, environment and society. The emphasis placed on each pillar will be influenced by the management philosophy of the organisation, and recent performance. It is unrealistic to assume that each of these three pillars will receive identical attention, simultaneously.

The function of a SMS must be to implement the sustainability policy; to achieve the statements of commitment that provide direction for the organisation. The development of the policy must involve the input of key multi-stakeholder groups. It is important that key stakeholders have “bought in” to the statements that the organisation is making to improve the organisations credibility and trustworthiness. It is the lack of trust that may negatively propagate community’s perception of environmental and social impacts, and shareholders ability to let go of shares resulting in immediate reputational and financial damage.

## BUSINESS INTEGRATION

Implementation of a SMS requires a different skill set than an EMS. A SMS’s position within the company needs to be at a more strategic business level than an EMS. It is from this vantage point that stakeholder opinion and expectations can be integrated with business decisions that have been derived from board level discussions. The approach to corporate governance is crucial; the exercise of power for increased accountability and democracy is vital.

The role of the environmental professional has, in the past, been to help an organisation meet its regulatory demands and to provide “green wash” about an industrial process that inevitably impacts the environment. If organisations can be encouraged to make a strong commitment to sustainability, the position of an environmental professional will be dramatically strengthened. Rather than being a seen as a ‘loose cog’ (as in the past) – suddenly the environmental professional is seemingly tied into organisational direction and strategy – a constituent part of a machine with a defined purpose.

However, implementation of a SMS requires a multi-disciplinary approach where engineers, financiers, scientists, human resource, safety and environmental experts are involved in its design and implementation. Different disciplines will possess different approaches and technical know-how to help define a roadmap to sustainability. While senior management commitment is generally a prerequisite for action, understanding and commitment at other levels must be developed to ensure an organisation-wide approach to leadership for sustainability.

The SMS needs to be integrated into other systems in the organisation. Priority areas for action can then be “fed” into other operational systems within the organisation such as the EMS, Safety Management System, Asset Risk Management and Human Resource activities. This process also aids the integration of the whole organisation to anticipate and respond to society’s changing values, threats from climate change, emerging markets and other global sustainability issues.

## CULTURAL CHANGE

The aims of sustainability are currently beyond most statutory requirements in Australia. The prospect to operate beyond statutory requirements, to be guided by company values and internal policy statements determined at board level, rather than outside forces, will be a significant part of the cultural shift that is needed to implement sustainability.

Cultural change will take time and continued diligence. Sustainability is going to “look” different in each organisation. The “look” is going to require time to develop and will vary depending on the opportunities of sustainability within the organisation, its products, its markets, the way the organisation has defined indicators of success and the interpretation of external sustainability standards and guidelines. It is important for these reasons that sustainability implementation remains voluntary, driven by industry rather than regulators.

The identification and evaluation of organisational specific indicators that measure success will need to be broadened beyond previously used financial indicators. Indicators need to be rigorously developed through risk assessment and cost benefit analysis. It is absolutely necessary that company management can answer, "What is the benefit of sustainability to my company?" However, it is proving just as important for a company that the "answer" has more than just an economic flavour.

Another area for broadening is the organisation's balance sheet. Intangibles such as social equity, environmental protection, reputation and the cost of not operating sustainability must be calculated. It has been stated that at least 50% of a company's value is in its intangibles – its invisible advantage. This 50% is based on intangibles like strategy execution, brand, human capital, innovation and leadership. Methods have been developed to quantify what was previously immeasurable and organisations can use that information to drive financial value (Low, 2002). It is with this type of accounting that shareholders and other stakeholders can determine a more accurate value of the organisation.

Take for example Dow, in 1995 it established its 2005 environmental and safety goals including:

- 90% reduction in injuries and illnesses;
- 50% reduction in emissions;
- 50% reduction in waste; and
- 20% reduction in energy.

Dow, which is well past the half way mark in meeting its targets, "expects to invest US$900 million that will generate direct and indirect returns of about US$3 billion" (Smalheiser, 2002).

## COMMUNICATION & PARTNERSHIPS

As previously discussed, uncertainty and relatively slow progression of SMS implementation is possibly due to the requirement of a cultural shift. "We are not asking corporations to do something different from their normal business; we are asking them to do their normal business differently" (Annan, 2002). This "leap" for organisational culture can be difficult and will require top management direction, but a cultural shift can be achieved through motivation maintained through training, communication and creating stakeholder partnerships.

Internal communication will need to increase, be more efficient and consistent, and possibly best organised within a communication strategy. The communication strategy will outline communication methods, levels and multi-functional communication paths. Internal exchange that fosters working situations where individuals, groups and departments can engage in regular dialogue, with the aim of exchanging and negotiating information on expectations, will aid cultural shift (The Sigma Project, 2003).

The key external stakeholders that can have the most influence on the organisation must be identified and engaged in discussions on issues and progress with the overall goal of gaining trust and credibility through transparency. The organisation's management need to assess the worth of moving from a default position of distrust to trust. This will highlight the internal drivers for sustainability and help to maintain relevance and momentum within the organisation. There is significant correlation between stakeholder perception and variables such as trust, benefit, and knowledge of an organisation's activities. Risk management is therefore highly dependent on stakeholder engagement.

Feedback from customers, employers, NGO's and regulators needs to be actively sought and acted upon. In this information age, technologies must be used effectively to ensure the concepts of sustainability are achieving the benefits as intended. Even though information is technically within reach of many stakeholders, via the media, reports and internet, the need to further the kind of awareness that influences perceptions, attitudes and behaviour is required for fact based information to fall on fertile stakeholder soil. One of the most useful forms of communication is interactive website information where the reader chooses the type of performance indicator information in which they are interested. An example of this is from the Danish pharmaceutical company Novo Nordisk's website (www.novonordisk.com).

## RISK MANAGMENT

Sustainability requires a wider appreciation of risk: The long-term sustainability of a business requires identifying systemic risks and understanding their impacts. Organisations must build a focus on the long-term: establish and communicate the value and approach to risk for the long-term performance of the organisation.

There is likely to be a difference in risk perception from a stakeholder's position and an organisation's position. Sustainability risks are those that are material, not only to meeting the organisation's vision, guiding principles and objectives, but also to meeting stakeholder's values.

Many organisations will already have risk management processes in place so it is important to use and expand these current methods rather than create a new layer of risk management. Indeed integrating sustainable development risks into existing risk management processes will improve organisational understanding of wider uncertainties and opportunities relating to sustainable development issues. This, in turn, will support cultural change in an organisation (The Sigma Project, 2003).

## CHALLENGES

Challenges that the mining industry may face through EMS evolution are essentially motivational and technical, and possibly rather similar to the challenges of EMS implementation a decade ago. Each organisation will implement sustainability differently (as they do EMS) and the organisational structure will be central to ensure governance is relevant and reflect the nature of the level and position at which decisions are made and challenges are overcome.

The information that a SMS may produce, the complexity of data analysis and the level of transparency required to ensure sustainability management delivers credibility may be overwhelming. Organisations need to ensure performance measurement helps progress the organisation towards its stated vision and guiding principles.

SMS implementation will only be effective when there is wide support from the major stakeholder groups resulting in multi-stakeholder buy-in. Schemes dominated by the industry will lack credibility, whereas schemes dominated by NGOs or regulators will lack uptake, impact, and linkage to key business drivers.

Sufficient funding and expertise must be made available to define sustainability requirements and assess the organisations performance against them. Many companies will attest there is money to be made and competitive edge to be gained in developing sustainable projects: sustainability is eco-efficiency, zero waste, improved production – cost reduction.

## CONCLUSION

There is not yet any proven recipe to achieve sustainable development and its unique nature requires an innovative and flexible approach. The method presented highlights that in a complex system, where no one is quite in charge, progress will only come through the cooperation of key system participants and beneficiaries.

The EMS to SMS approach recommends the maintenance of the Plan-Do-Check-Act cycle, where the process of developing and implementing a sustainability policy is paramount and cultural change is a necessity. Multi-disciplinary experts provide a road-map to sustainability and key external stakeholders are involved in decision making and provide feedback on performance. Intangibles are included on the balance sheet and sustainability risk management is broadened to assess organisational risks as well as stakeholder's values.

"Corporate social responsibility" is a term already synonymous with sustainability, and, in the case of the mining industry, perhaps a more accurate description of the challenge presented. However, the most important point to be made is that the business equation is changing, and that will have a significant impact on who prospers – across many sectors – in the 21st century. Those companies who are best positioned with respect to sustainability commitment – those which are already operating in partnership with stakeholders, risk management and high efficiency, will have a competitive advantage and be more prepared for the next revolution and the opportunities and challenges that brings to industry.

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# EXCESS SALINE MINE WATER MANAGEMENT IN THE GOLDFIELDS– A CASE STUDY (WHITE FOIL AND FROG'S LEG GOLD MINES)

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## ABSTRACT

*The management of excess mine water has become an increasing issue in the Goldfields, since the early 1990s when rainfall patterns and the increasing depth of mines meant that for the first time in modern mining history many mines were in a mine water surplus state rather than in deficit. Excess water management has been made more difficult by the fact that groundwater inflows (a major component of the mine water balance in many operations) are generally hypersaline. In the early 1990's the default management option was discharge to nearby salt lakes. However, increasing awareness of the ecology of the salt lakes and the potential impacts of uncontrolled hypersaline water discharge on the lakes resulted in regulatory restrictions on lake discharge and prompted the need to carefully evaluate all other discharge options.*

*This paper presents a case study of the Mines Resources Australia (MRA) operated White Foil and Frog's Leg gold mines, that were faced with very large excesses of hypersaline mine water. Some innovative short-term mine water management strategies were implemented and a long term strategy developed that involved a jointly operated salt lake discharge system with neighbouring operation, Placer's Kundana gold mine. A number of options for mine water management were investigated including aquifer re-injection, evaporation ponds, water supply to a distant mill and associated mined out pits, grout curtains to reduce inflows and discharge to a number of salt lakes. The investigation concluded that the optimum long term disposal strategy in terms of minimising environmental impact, costs and logistical manageability, was discharge to White Flag Lake.*

*MRA and Placer entered into an agreement to share discharge facilities and to jointly manage the mine water discharge system. The combined discharge system has been approved and licensed and is expected to be operational by mid 2004. During the development and regulatory approval of this long term strategy, other methodologies were adopted to maintain mining operations. These included limited aquifer re-injection, discharge to one of Placer's nearby mined out pits, and using the partially mined White Foil pit as temporary storage facility to allow for the initial development and dewatering of the Frog's Leg pit.*

## INTRODUCTION

Mines and Resources Australia Pty Ltd (MRA) are managers of and joint venture partners in the existing White Foil open cut mining project, located approximately 20km west of Kalgoorlie, and the proposed Frog's Leg open cut and underground mine, located 2km to the east of White Foil. The other JV partners are Placer Dome Asia Pacific (at White Foil) and Dioro Exploration (at Frog's Leg). Neither project includes milling and processing of ore and the only water demands at each site were potable requirements (sourced from water tankers) and dust suppression (to be met by dewatering discharge).

At the commencement of mining at White Foil, inflows of up to around 0.2ML/d had been expected (Townley and Associates, 2001). A disposal system based on injecting excess water into a nearby palaeochannel aquifer via specially constructed bores was commissioned. Note that both the dewatering discharge and receiving paleochannel aquifer were hypersaline, with salinities in excess of 100,000mg/L TDS.

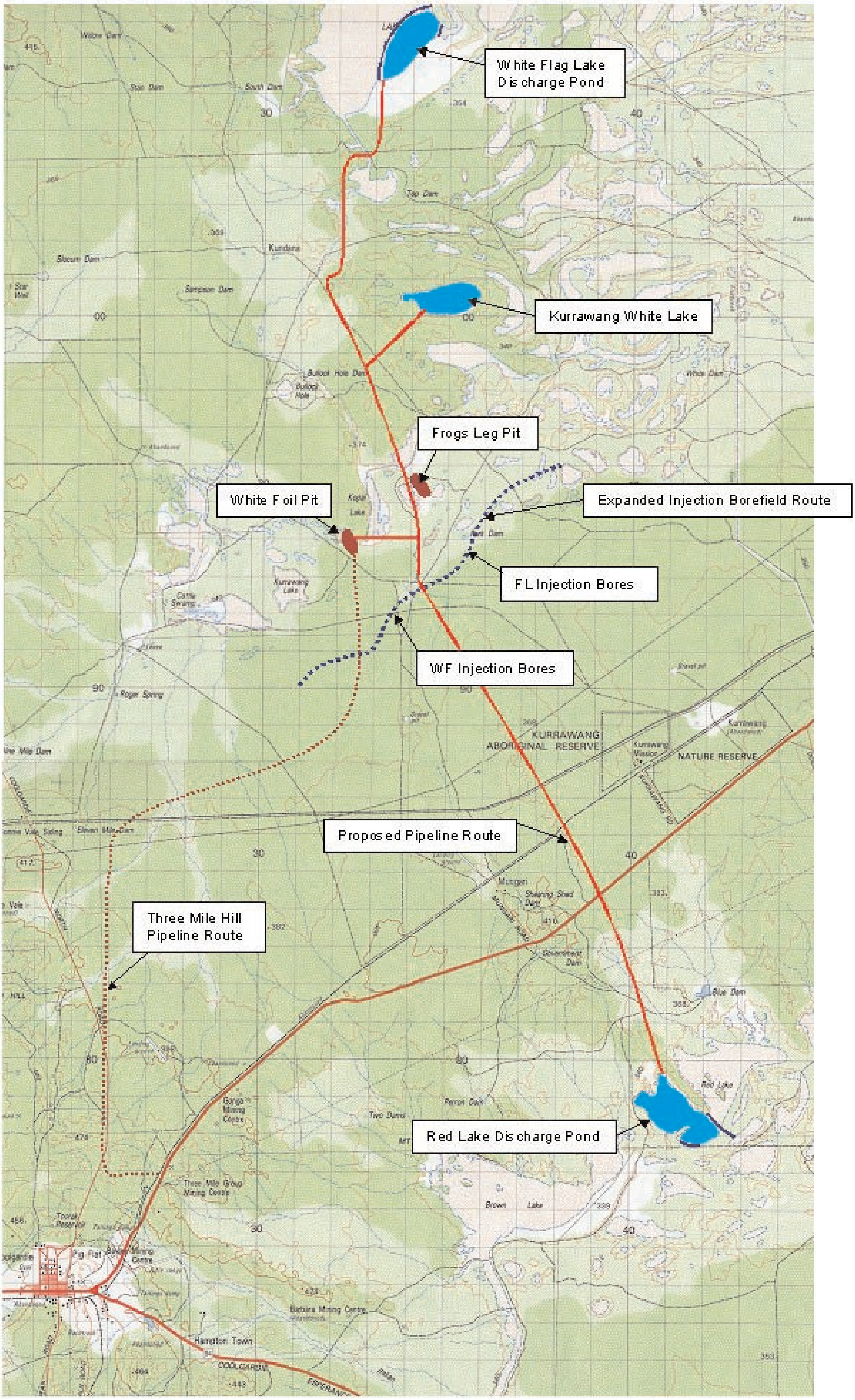
However, much higher than expected groundwater inflows were encountered with total pit sump dewatering rates reaching some 4.3ML/d by the end of 2002, with a cumulative dewatering total of around 700ML. To handle the increased dewatering volumes the injection borefield was expanded to ten injection bores and water was pumped to Placer's Moonbeam Pit (and thence to White Flag Lake) as part of Placer's excess water discharge system.

However, the arrangement with Placer was subject to the water management requirements at Placer's nearby Kundana Operations and the pumping to Moonbeam was only ever a temporary measure. In addition to this, groundwater modelling for the White Foil pit (Aquaterra, 2003-1) based on observed historical groundwater inflows, predicted that groundwater inflows could be expected to increase to a peak of around 8.3ML/d before declining to around 5.9ML/d at the end of mining. At the same time, groundwater modelling carried out for the proposed Frog's Leg open cut mine (Aquaterra 2003-2) predicted possible pit inflows of hypersaline water of up to 8.6ML/d.

To cover the expected increase in total dewatering discharge requirements, MRA initiated two parallel investigations to explore the options for disposing of these potentially large volumes of excess dewatering production:

- Development of a joint discharge system with Placer, based on an expansion of the existing Placer discharge system to White Flag Lake. This is the subject of another paper being presented at this conference (Ariyaratnam et al, 2004).
- Assessment of a range of options for standalone MRA discharge systems. This forms the subject of this paper.

*Figure 1: Layout of Discharge Options*



Eight potential options were identified, investigated to concept level and ranked in terms of the following key criteria:

- Reliability, in terms of security of discharge capacity.
- Capital and operating costs.
- Investigation cost and timing required to "prove" each option.
- Environmental consequences.
- Regulatory/licensing issues.
- Manageability

The actual excess water discharge requirements were subject to the timing of the development of each of the mines, but for the purposes of this assessment each option was evaluated against an assumed constant discharge requirement of 8.6ML/d (100L/s) for a period of at least three years.

The eight potential options identified were:

1. Discharge to Kurrawang White Lake
2. Discharge to White Flag Lake
3. Discharge to Red Lake
4. Discharge to evaporation ponds
5. Discharge to an expanded injection borefield
6. Discharge to Three Mile Hill plant
7. Discharge of Frog's Leg dewatering to White Foil
8. Reduction of inflows to White Foil by grouting

Figure 1 shows schematic concept layouts of infrastructure required for most of the options.

## OPTION 1 - DISCHARGE TO KURRAWANG WHITE LAKE

### Background

Kurrawang White Lake (sometimes erroneously referred to as Kurrawang Lake) is a small lake located 4.5 km north of Frog's Leg Pit. The Lake has a surface area of 1.2km$^2$, and has an internally draining catchment area of around 4km$^2$. The Lake forms a shallow depression, bounded by a vegetated shoreline with low sandy ridges. The Lake would overflow from its central northern side to an adjacent lake to the east, at a water level around 2 to 3m above the lakebed.

In its natural state, the lake would typically be dry and would only contain water after rainfall. After rainfall, water on the lake would be relatively fresh, and then progressively turn saline as it evaporated. Some saline water would also likely seep into the lakebed sediments. In response to heavy rainfall, the average water depth on the lake is unlikely to exceed around 200 mm and this would evaporate over a few months, depending on the time of year. It is not known if the lake, in its natural state, had a salt crust, though based on other lakes in the area, the lakebed sediments would be naturally saline.

Hypersaline dewatering water from Placer's Kurrawang Pit was discharged into the Lake, for an 18 month period starting in May 1994. Around 7GL of water were discharged at a salinity of around 120,000 mg/L TDS.

### Assessment of Potential for Future Discharge

A monthly water balance model was developed for the Lake, and calibrated to observations made by Placer personnel during previous discharge. Key base case inputs to the water balance (for this and other options) were a total pan evaporation of 2,640mm/yr, a pan factor of 0.7 and an annual average rainfall of 270mm and no seepage losses. The water balance modelling predicted that Lake could accept the required full discharge 8.6ML/d for at least three years) and could accept up to 6.5M/d without filling past levels recorded during previous discharge.

At an average discharge TDS of 230,000mg/L (from White Foil), the dewatering discharges would form a surface salt crust on the lake that would build at a rate of around 400mm thickness per year. However, the existing salt crust (as a result of previous discharge) was only around 100mm thick, where as a simple salt accretion model predicted a crust of around 500mm. This suggested that most of the salt deposits have seeped into the lake bed sediments. Anecdotal evidence also suggested that the lateral extent of the salt crust has marginally reduced over the years, and new vegetation is colonising the lakeshore, indicating that rainfall (and runoff) is gradually flushing the salt crust deposits into the lake bed.

### Discharge System

The concept design of the discharge system comprised a 10km buried PE pipeline from White Foil to the Lake with a spur line from Frog's Leg, with one duty pump and one standby pump.

#### *Capital and Operating Costs*

The estimated costs of the system were:

- Capital cost: $800,000
- Operating cost: $100,000/yr

#### *Investigation/Proving Cost and Timing*

Sufficient work had been done to prove the viability of this scheme. Apart from some minor survey works to confirm the lakebed topography and spill level, and analysis and reporting to support a discharge licence application, no additional investigations were required. Estimated investigation costs were:

- Investigation costs: $10,000

This would have require only two weeks to complete.

### Environmental Consequences

Kurrawang White Lake is internally draining, and so long as Lake water levels are maintained below spill level then there would have been no discharge of hypersaline water beyond the confines of the Lake.

Kurrawang White Lake already has a salt crust as a result of previous dewatering discharge by Placer. The deposition of additional salt was not seen as a persistent, long-term environmental impact. While there was some initial impact on fringing vegetation, this has grown back, and so the impacts of filling the Lake to previous levels should have little long-term impact.

Discharge would have also resulted in an increased thickness of salt crust on the lakebed.

### Regulatory/Licensing Issues

The then Department of Environmental Protection (DEP) and the Department of Industry and Resources (DoIR) had indicated that they would support such a scheme. As such, no delay in approvals process was expected beyond the usual six week period for assessing a Works Approval application prior to construction of the discharge system and amendment of the existing DEP licence to include discharge to the lake which could coincide with the construction period. The Works Approval application would have also served as an NOI for DoIR approval.

However, the Lake (which was covered by Placer tenements) was also one of Placer's options for future disposal and they were reluctant to grant permission for MRA access until their future disposal plans had been confirmed.

### Manageability

This option involved all the water being discharged into one place that is close to both mines for the life of the mines. Few manageability issues were expected.

## OPTION 2 - DISCHARGE TO WHITE FLAG LAKE

### Background

#### *Regional Drainage*

The White Flag Lake Catchment, including the collection of lakes to the south and east, has a total area of approximately 2,000 km$^2$ and extends approximately 70 km to the west from Kalgoorlie. Although the catchment topography generally grades to White Flag Lake (and the adjacent lakes), there are numerous areas of depression storage in the catchment that require significant amounts of rainfall to fill before the downstream creeks begin to flow. Similarly, runoff from the catchment tends to fill one lake before overspilling into the next lake downgradient. Topographic data suggests that excess water collected on White Flag Lake would tend to overspill to Black Flag Lake in the north as well as to the adjacent smaller lakes to the east.

It is estimated that the Lake may receive about half the natural total runoff from its catchment, with the remaining runoff stored in the numerous other smaller lakes in the area. Assuming the average annual runoff from the catchments at around 4% of the average annual rainfall (Aquaterra, 1999), then the Lake would receive an average of around 11GL/yr from the total 2000 km$^2$ catchment. For the estimated lake surface area of 25 km$^2$, this would result in an average annual lake water inflow depth of 430 mm.

Rainfall with a typical TDS of 20 mg/L and runoff with a typical TDS around 200 mg/L (Aquaterra, 1999) provide natural salt accumulations in the lakes. With evaporation, these low salinity waters become more saline and seepage (albeit very low) results in the salts naturally migrating into the subsurface zones. The lakebeds in the Eastern Goldfields typically comprise an interbedded sequence of saline and gypsiferous clays and silts, with an average thickness of 10m (Johnson, 1993). Hence salt lakebeds typically contain vast salt deposits that have accumulated and are still accumulating by natural processes.

#### *Existing Dewatering Activities*

Placer's Kundana Gold Operations has been discharging excess mine dewatering production (with a salinity of around 140,000mg/L TDS) into the southern section of the Lake since 1988. Approximately 6GL of saline water has been discharged since records began in 1991/92, with recent annual totals around 2GL/yr (well short of Kundana's licences discharge limit of 4.8GL/yr.

The average area required to evaporate the recent annual discharges has been estimated at 120ha (less than 5% of the total Lake area)., although on a seasonal basis, the required discharge pool area was estimated to range between 60 and 500ha.

Based on estimates of the areal extent and thickness of the salt crust in late 2002 (Melanie Ward, pers. comm., February 2003) it was calculated that only 20% of the salt discharged to the Lake in dewatering discharge is present in the salt crust. That is, some 80% of the salt load had migrated into the subsurface zones, as a results of downward seepage possibly aided by rainfall (and runoff), flushing the salts into the lakebed sediments.

It has been observed (Melanie Ward, pers.-comm., February 2003) that a solid salt crust will stay intact for several months under fresh water ponding and will only slowly dissolve. Hence, while the active dewatering discharge pool may have been widely redistributed following a flood event, the salt contained in the salt crust appeared to remain local to the initial discharge pool site.

## Assessment of Future Discharge Potential

The average area required to evaporate the full target discharge from White Foil and Frog's Leg (ie 8.6ML/d) was estimated to be 200ha/yr, although on a seasonal basis, the average required discharge pool area was estimated to range from 100 to 800ha. Together with the existing Kundana discharges the required combined active discharge pool area was estimated to be around 320ha (or 13% of the Lake area), with a possible seasonal pool size up to around 1300ha (around half the Lake area). It was also estimated that the combined discharge salt crust could cover around 1100ha or 45% of the lakebed area.

Based on the average salinity the potential future dewatering discharges from White Foil and Frog's Leg Pits (230,000 mg/L TDS), some 2.2M tonnes of salt would be deposited onto the Lake over the three year period. However, based on the salt dissipation behaviour observed to date, only 20% of this would remain in the lakebed salt crust.

## Discharge System

The concept design of the discharge system comprised a 17km buried PE pipeline from White Foil to the Lake with a spur line from Frog's Leg, with one duty pump and one standby pump at White Foil. The design also included the provision for bunding on the lakebed to receive and contain the mine dewatering discharges, so as to prevent them being redistributed over the full lake area.

### *Capital and Operating Costs*

The estimated costs of the system were as follows:

- Capital costs: $1,400,000
- Operating costs: $120,000/yr

### *Investigation/Proving Cost and Timing*

Sufficient work had already been done to prove the viability of this scheme. Apart from some minor survey works to confirm the Lake bed topography in the area of the proposed bunding, and analysis and reporting to support a discharge licence application, no additional investigations were required. The estimated costs were:

- Investigation costs: $20,000

This work required less than a month to complete.

## Environmental Consequences

The long-term impact of discharge would be the increase in salt load on the Lake. However, the Lake was already being used for the discharge of hypersaline mine water (from Kundana) and additional discharge from White Foil and Frog's Leg would merely increase the rate of salt accumulation. With the proposed bunding in place, the spread of salt would have been restricted to an area away from the main freshwater flow paths into the lake and so little impact on the overall Lake system was expected.

## Regulatory/Licensing Issues

This option would have required a Works Approval and discharge licence from DEP. However, given that a similar discharge had already been approved for Kundana, it was believed that a licence would ultimately be granted, although a lengthy assessment period was likely due to the complexity of evaluating cumulative impacts. The Works Approval application would have also served as an NOI for DoIR approval.

Timely development of this option also required permission for access to Placer's and their East Kundana Joint Venture Partners' tenements for pipeline routes.

## Manageability

This option involved all the water being discharged into one place for the life of the mines. Few manageability issues were expected.

# OPTION 3 - DISCHARGE TO RED LAKE

## Background

Red Lake is located south of Great Eastern Highway, approximately 20km southwest of Kalgoorlie and 17km south-south east of the White Foil minesite. The Red Lake catchment, excluding the collection of smaller lakes to the south of the lake, has a total catchment area of approximately 35 $km^2$. The majority of the catchment is located to the north of the lake with runoff reaching Red Lake via several creeks. The lake has a surface area of approximately $5km^2$ and is isolated from Brown Lake to the west by a low ridge.

The average annual runoff from the catchment was estimated at around 4% of the average annual rainfall. Given the lack of smaller lakes to intercept runoff in the catchment, Red Lake is estimated to receive an average annual runoff of around 0.35 GL/yr from the $35km^2$ catchment, with an additional annual average 1.3GL/yr falling directly on the lake surface.

## Assessment of Discharge Potential

The average area required to evaporate the full target discharge from White Foil and Frog's Leg was estimated to be approximately 200ha/yr, although the discharge pool area would likely vary between 100 and 800ha seasonally. The average discharge pool area represents approximately 40% of the Lake area, although seasonally the discharge pool could fill the entire Lake area.

It was estimated that the projected total dewatering discharge would add some 2.2 million tonnes of salt to the Lake. This compared with an estimated natural accumulation of salt in the Lake (from runoff) of around 100 tonnes/year. Hence the active salt load to the lake would be significantly increased. However, based on the salt dissipation behaviour observed at White Flag and Kurrawang White Lakes to date, it was concluded that the Lake could physically absorb the discharges, although it was recognised that there could be some impact on fringing vegetation and/or Lake biota, especially as a result of catchment runoff, which would dilute and potentially redistribute the active saline discharge pool over the full lake area and also potentially redistribute some of the salt contained in the salt crust formed.

### Discharge System

The concept design of the discharge system comprised a 19.3km buried PE pipeline from White Foil to the Lake with a spur line from Frog's Leg, with one duty pump and one standby pump at White Foil.

#### *Capital and Operating Costs*

The estimated costs of the system are as follows:

- Capital costs: $1,800,000
- Operating costs: $150,000/yr.

#### *Investigation/Proving Cost and Timing*

Only desktop assessment of this option had been carried out at the time, and more detailed investigation was required to confirm the hydrological and ecological characteristics of the catchment and the baseline conditions of the proposed disposal area. There would also be required some survey work to confirm lakebed conditions and bunding requirements.

The estimated costs were:

- Investigation costs: $70,000

This work would require up to two months to complete.

### Environmental Consequences

The predicted environmental consequences were similar to those for the White Flag Lake option. That is, discharge would result in a long-term increase in salt load on the Lake.

Pre-discharge environmental surveys to establish baseline conditions and ongoing monitoring were planned.

### Regulatory/Licensing Issues.

Similar to previous options, a Works Approval and discharge licence would have been the minimum requirements. While it was believed that there were no technical reasons for these approvals being withheld, a contingency of several months was allowed for assessment and approval of this option. Furthermore, the DEP had been increasingly reluctant over the previous few years to grant new lake discharge licences and some proposals had attracted a higher level of assessment by the Environmental Protection Authority (EPA) resulting in a public review process extending over 12 months or so. (eg Red October and Wallaby).

The pipeline route was wholly within MRA tenements although some of these were still pending. The pipeline route also crossed the Perth to Kalgoorlie railway line and the Great Eastern Highway, and permission to cross under these would also have been required.

### Manageability

This option involved all the water being discharged into one place for the life of the mines. Apart from maintaining the pipeline beneath the railway and highway, few manageability issues were expected.

## OPTION 4 - DISCHARGE TO EVAPORATION PONDS

### Background

This option was developed to address and compare the use of a fully constructed, above ground evaporation pond structure compared with the use of natural salt lakes (with minor modification in some cases) as evaporation basins.

### Assessment of Discharge Potential

The discharge potential was largely related to the open area of the pond. There are design features that could have been incorporated to enhance evaporation (such as staged ponds with pump back systems, areal spraying etc). However, for this assessment only simple designs were investigated to test the viability of the concept.

Base on the same climatic data as for the lake discharge options the evaporation pond would have required an exposed surface water area of around 200ha, to contain a continuous 8.6ML/d discharge.

### Discharge System

No actual site for the evaporation pond was identified, but it was assumed that a suitable site could be found within a 3km pumping distance from White Foil/Frog's Leg. The concept design of the discharge system included a 3km buried HDPE pipeline with one duty and one standby pump at the mine site. It was also assumed that the design would need to incorporate zero (or near zero) seepage losses as an approvals pre-requisite. This would require either roller compacting insitu or imported clay, or a synthetic liner. For this assessment, a HDPE liner was assumed.

### *Capital and Operating Costs*

The estimated costs of the system were as follows:

- Capital costs: $12,900,000
- Operating costs: $30,000/yr

### *Investigation/Proving Cost and Timing*

Some detailed engineering work would have been required to optimise the design of the evaporation pond and to prepare design documents for regulatory approval and for construction. These costs were included in the capital cost estimate.

However, there was also a requirement to demonstrate that the concept was workable, assess the environmental implications, and develop contingency plans to cover possible seepage and/or spillage losses. The estimated costs of this, together with reporting to support a discharge licence application, were as follows:

- Investigation costs: $40,000

This work would have required up to three months to complete.

### Environmental Consequences

There were three main environmental consequences identified at the time. Firstly, the option required some 200ha of land to be cleared for construction of the pond. Secondly, the option required the above ground storage of saline water. The perceived risk here was one of possible overtopping or failure of the pond walls. These risks could have been engineered out, as could be the risk of seepage by including a liner, but they would likely be raised in the approvals process.

Thirdly, decommissioning would require either removal of the pond (and placement of the salts in to a pit) or rehabilitation plans similar to tailings storage facilities (capillary breaks and vegetated cover material). This would have added significant cost to the project.

### Regulatory/Licensing Issues

It was believed that the regulators would be reluctant to approve the evaporation pond option due to the area required for clearing and the perceived risks of spillage of saline water to the land surface and rehabilitation issues. This option would most likely have attracted a higher level of assessment by the EPA, including a period of public review.

### Manageability

This option involved all the water being discharged into one place for the life of the mines, and few manageability issues were expected.

## OPTION 5 - DISCHARGE TO EXPANDED INJECTION BOREFIELD

### Background

As outlined in the Introduction, an injection borefield comprising ten bores was progressively developed during 2002. However, injection borefields are notoriously difficult to maintain and sustainable injection rates are influenced by a range of factor including:

- Hydraulic properties of the receiving aquifer and depth to standing groundwater level in the injection bores – this effects the level of “upconing” in aquifer water/pressure levels and whether gravity or pressure injection is required.
- Mechanical blocking by silts - this occurs within a narrow zone immediately surrounding the bore screens either within the gravel packed bore annulus or within the natural formation matrix. This results in reduced water transmitting capacity and increased injection pressures and/or decreased injection rates.
- Air entrapment in the near bore formation material - this has a similar effect as mechanical blocking by silts. Operation of the borefield has not been without some difficulty.
- Biological fouling – although this is less common in hypersaline waters.
- Chemical incompatibility between the discharge and receiving waters.
- Maintenance of formation hydrostatic pressures below the “fracture limits“ of aquifer confining beds.

At the White Foil injection borefield, the receiving aquifer had only moderate transmissivity (in the order of 100 to $200m^2/d$) and a shallow depth to water (around 7m) and, at best, only minor injection rates could be maintained by gravity injection. The injection system was designed to maintain, as much as possible, air free injection and to a large extent this was successful although the required valve-works were prone to blocking with salt. Water quality had not been an issue.

The major issue at White Foil had been the mechanical blocking of the formation by silts. This was despite a series of settling ponds at the mine site (through which dewatering discharge is passed prior to pumping to the borefield) and regular airlift development of the bores. It was not uncommon for total borefield injection rates to decline from 15L/s to less than 5L/s over a few days.

A modified bore design, incorporating wire wound bore screens (to increase % open area) and a simpler, all plastic bore-headworks that included provision to backwash the bores by airlifting without having to remove the headworks, was trialled. However, it was found difficult to maintain injection rates without very frequent backwashing cycles.

### Assessment of Discharge Potential

From practical experience at White Foil, individual bores appeared capable of sustaining injection rates of up to 6L/s when new or having just been redeveloped. Allowing for improved bore maintenance and some back-up bores, but also allowing for decreased injection between backwashing or re-development, it was assumed that an average injection rate of 4L/s could be maintainable. This would require some twenty five bores to accept the discharge target.

Groundwater modelling was then carried out to assess the required bore spacings to maintain realistic injection pressures (taking the fracture limit of the clay confining layer). The model predicted that bore spacings in excess of 1km might be required. However, performance data from the existing borefield indicated that much closer bore spacings might be achievable, suggesting that significant leakage into surrounding basement rocks had taken place and that the "receiving aquifer" was much larger than just the palaeochannel.

For the purposes of this assessment, bore spacings of around 300m were adopted. As such, a 7.5km length of palaeochannel aquifer was required to be developed. Available hydrogeological information suggested that the required injection borefield could be developed within MRA tenements.

### Discharge System

The injection borefield design included five of the existing bores in the White Foil and Frog's Leg injection borefields can be used, and twenty six new bores (allowing for six standby bores) at twenty locations. Most of the new bores were downstream of the existing White Foil borefield, where greater aquifer thickness and permeability was expected.

The injection borefield also included nineteen paired deep and shallow bores. The schematic borefield layout is shown on Figure 1.

The concept pipeline design included a buried PE pipeline from the existing White Foil transfer ponds to the centre of the borefield, smaller diameter buried PE branch lines to the bores, one duty and one standby pump.

#### *Capital and Operating Costs*

The estimated costs of the system are as follows:

- Capital cost: $1,700,000
- Operating cost: $440,000/yr

Please note that the bore maintenance costs include provision for a full time site employee to manage the borefield.

#### *Investigation/Proving Cost and Timing*

Additional, more detailed modelling (taking into account leakage from the paleochannel into surrounding basement rock aquifers) would be required to confirm the optimum bore spacing. The general path of the palaeochannel is known and so broad investigations of the location of the aquifer would not have been required. However, some transect drilling (air-core) would have been required to target the injection bores.

The estimated costs were as follows:

- Investigation costs: $85,000

The above programme would have taken up to two months to complete.

### Environmental Consequences

This option had little to no environmental consequences. It involved pumping hypersaline dewatering discharge into a hypersaline aquifer. That is, a below ground storage system with no impact on beneficial use of the groundwater. If the borefield was operated correctly (ie so as to minimise aquifer pressures), there was little chance of the saline water finding its way to the surface, other than by a pipeline break, and the pipeline would have incorporated spill protection and containment in its design.

### Regulatory/Licensing Issues

There were no potential licensing issues with this option so long as a 300m bore spacing proved to be adequate. If larger bore spacings was found to be required, then Miscellaneous Licences (covering the bore and pipeline routes) over adjacent non-MRA tenements would have been required.

There remained some uncertainty as to exactly how an injection borefield would be licensed, via a normal DEP operating licence or by a WRC groundwater well licence, or both. A Works Approval application would have been required and approximately six weeks was allowed for approval. Necessary licence applications could have been prepared and submitted during this time so that approval to operate the system could coincide with the construction period.

### Manageability

This option relied on at least twenty five individual discharges (injection bores) spread over at least a 7.5km borefield. It would comprise at least twenty five sets of flow regulating valves and monitoring gauges (that would need to have been operated manually), and would require regular (possibly weekly) maintenance.

This was considered to be the least manageable option.

## OPTION 6 - DISCHARGE TO THREE MILE HILL

### Background

Half the ore from White Foil was being processed at the Three Mile Hill plant at Coolgardie, and possibly all of Frog's Leg ore was to be processed there as well. At the time, when operating at full capacity the plant required 3ML/d of process water. Sources of process water at the time included:

- Decant return from the tailings storage in the Three Mile pit (around 0.7ML/d).
- Pumping from the Roger Springs Borefield, a paleochannel borefield located upstream of White Foil (around 1.8ML/d of 30,000 to 50,000mg/L TDS water).
- The old Baileys Reward underground mine (1.1ML/d of sub 30,000mg/L TDS water).

The operators indicated that they would be prepared to accept dewatering discharge from MRA as the sole source of process water to the plant, subject to some compensation to cover the reduction in water quality. They have indicated that they would make available some mined out pits and underground mines for disposal of dewatering discharge. There was an indicated 350ML storage capacity in the dry CNX pit. Details on the Baileys Reward underground and pit indicated that there may have been be some 100,000ML storage capacity in the mine.

Three Mile Hill also provided some 1ML/d to the adjacent Greenfields plant, although anecdotal evidence suggested that the operators would be happy to take up to 1.5ML/d if it were available.

### Assessment of Discharge Potential

The potential maximum ongoing discharge potential to the Three Mile Hill plant is roughly as follows:

- Three Mile Hill plant usage: 3ML/d
- Provision to Greenfields: 1.5L/d

Assuming that the Baileys Reward underground could be filled at similar rates to historical pumping, then a further 1.1ML/d could have been discharged on an ongoing basis.

In terms of static storage, there appeared to be some 450ML available in the CNX pit and Baileys Reward mine. Over three years this could accommodate a steady pumping rate of 0.4ML/d. Both pits are small and so evaporative losses have been discounted.

The maximum total discharge capacity, then, over a three year period was estimated to be 6ML/d (or around 70L/s).

This option, then, could not meet the target discharge capacity alone. This option was then considered in conjunction with a partially expanded injection borefield (with a capacity of 2.6ML/d or 30L/s).

### Discharge System

The partially expanded injection borefield included five of the existing injection bores, and seven new bores (including four standby bores), installed between the existing White Foil and Frog's Leg bores. The system also included three new paired deep and shallow monitor bores.

The concept pipeline design included the following key components:

- New buried PE pipeline from the White Foil transfer ponds to the Roger Springs Borefield.
- New buried PE pipeline running adjacent to existing PVC pipeline from Roger Springs to Three Mile Hill.
- Use of existing PE pipeline from White Foil to the bore the existing injection borefield.
- New PE pipeline to connect the existing system to new bores.

#### *Capital and Operating Costs*

The estimated costs of the system were as follows:

- Capital cost: $2,700,000
- Operating cost: $250,000/yr

Please note that the above costs made no allowance for compensation to the operators of Three Mile Hill for using poorer quality water.

#### *Investigation/Proving Cost and Timing*

The environmental consequences of this option were considered to be low and no real problems with licensing/approvals were expected. However, further, more detailed work was required to confirm the discharge capacity of the mines, particularly Baileys Reward, including some simple modelling.

Additional modelling and some transect drilling would be required to confirm the optimum bore spacing and locations, as with the previous option.

The estimated investigation costs are as follows:

- Investigation costs: $50,000

The above program would require around two months to complete.

### Environmental Consequences

This option was deemed to have little to no environmental consequences. It involved consumption of much of the dewatering discharge in gold processing with the rest being discharged into worked out mines and into saline aquifers (that is, below ground storage systems with no impact on beneficial use of the groundwater). The major possible chance of saline water spillage to the surface was identified as a possible pipeline break, and the pipeline design incorporated spill protection and containment measures.

### Regulatory/Licensing Issues

Pumping to Three Mile Hill (and the pits) would all have been within existing Three Mile Hill Miscellaneous Licences and Mining Leases and so there was no issues with land tenure. DEP Works Approval and licencing would be required for the discharge to the CNX and Baileys Reward mines, but no major problems were expected with this as the discharge option had very low environmental consequence.

### Manageability

This option involved managing some eleven different discharge destinations in two broad but separate locations. This was considered to be one of the least manageable options.

## OPTION 7 - DISCHARGE OF FROG'S LEG DEWATERING TO WHITE FOIL

### Background

There were several potential options available for the discharge of Frog's Leg dewatering production to White Foil, as follows:

- Complete mining of White Foil before commencing mining at Frog's Leg and discharge all Frog's Leg dewatering to the White Foil Pit. This would require some other discharge option to be implemented to accommodate discharge from White Foil for around fifteen months.
- Maintain water levels in White Foil as low as possible using the existing injection borefield until the commencement of mining at Frog's Leg, and then discharge all Frog's Leg production to White Foil.

The latter option would effectively require suspension of mining at White Foil until at least the end of open cut mining at Frog's Leg. It would also require the pumping out of accumulated storage in the pit as well as ongoing inflow dewatering re-dewatering when mining at White Foil recommenced.

### Assessment of Discharge Potential

An existing Frog's Leg groundwater model was verified and re-calibrated against the results of an extended pumping and injection trial. The model predicted inflows to the open pit of up to 8.6ML/d, with residual inflows at the end of open pit mining of around 3.5ML/d (Aquaterra, 2003-2).

An existing White Foil groundwater model was verified and recalibrated against some pit lake recovery data after the main pit dewatering system has been shut down for several months, while mining continued in above water table areas (Aquaterra, 2003-3). The model was then used to predict the rates of infilling of the pit by groundwater inflows from two potential starting conditions, as follows:

- From the current situation at the time – assuming no further mining at the time and accounting for filling that has already taken place.
- From the end of mining – assuming that the pit was fully dewatered during mining.

These results were then used in conjunction with a simple void depth-volume model to determine the residual available volume of the pit over time. These results were compared with predicted dewatering rates for Frog's Leg, assuming that the injection borefield would continue to operate at 1.3ML/d, to determine disposal capacity. The results indicate the following:

- If White Foil pit was allowed to continue refilling, and that dewatering of Frog's leg commenced in mid 2003, White Foil pit could accept all predicted dewatering for three years (refer Figure 2).
- If White Foil was mined and dewatered to full depth, it could then accept predicted Frog's Leg discharge for almost five years.

### Discharge System

The concept design included a buried PE pipeline from the existing Frog's Leg transfer dam to White Foil, with a duty and standby pumps at Frog's Leg.

#### *Capital and Operating Costs*

The estimated costs of the system were as follows:

- Capital cost: $300,000
- Operating cost: $40,000/yr

#### *Investigation/Proving Cost and Timing*

The feasibility of this option had already been demonstrated, and apart from preparing a report in support of a Works Approval and discharge licence application, there was no requirement for additional work.

The investigation costs (ie cost of reporting) were:

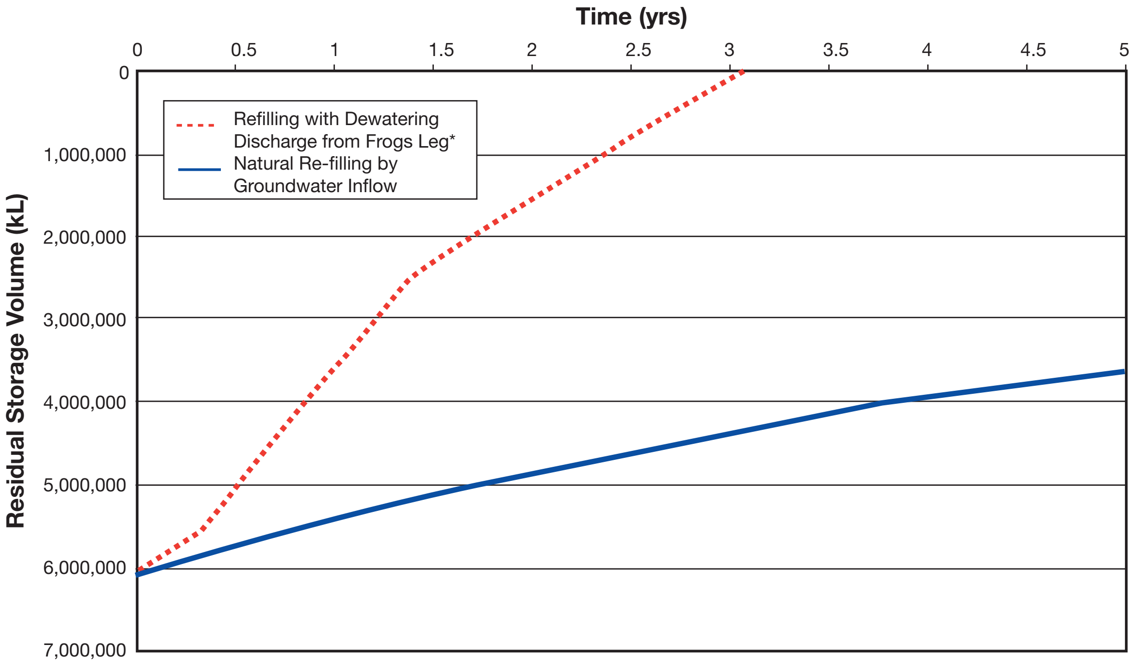
- Investigation costs: $5,000.

The report would have taken less than two weeks to prepare.

### Environmental Consequences

This option had little to no environmental consequences. It involved the transfer of water over a short distance with discharge to a sub-grade storage. As with other many of the other options, the major possible chance of saline water

*Figure 2: Storage Capacity of White Foil Pit - Transfer of Frogs Leg Dewatering to Current White Foil Pit*




spillage to the surface would have been a possible pipeline break, and the pipeline design incorporated spill protection and containment measures.

### Regulatory/Licensing Issues.

No regulatory or licensing issues were anticipated.

### Manageability

This option had all the water from one pit being discharged to the other over a short distance. There were no anticipated manageability issues.

## OPTION 8 - REDUCTION OF INFLOWS TO WHITE FOIL BY GROUTING

### Background

A possible option for reducing inflows to the pits was to reduce the permeability of main inflow zones (structures) by the placement of "grout curtains" (cementaceous and/or other grout compounds). The technology existed to place such grout curtains (it is common in the construction industry and has been used elsewhere for mining applications).

However, before examining grouting methodologies and costs, it was important to gain an understanding of the likely achievable grouting in terms of permeability reduction, and the impacts of realistic permeability reduction on inflows and dewatering rates.

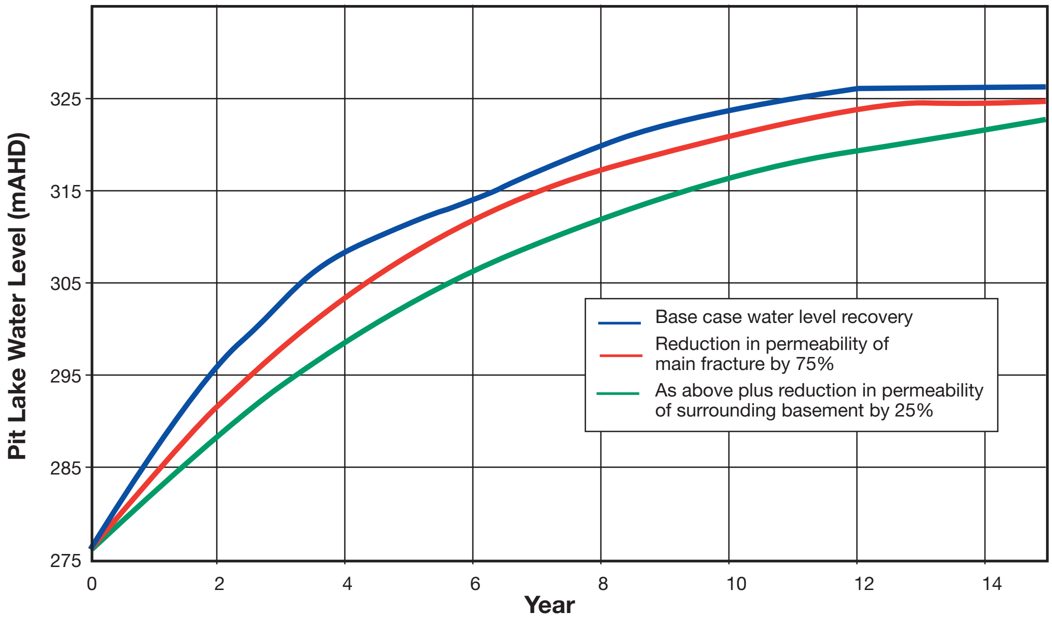
As the geostructural conditions at White Foil (the major control on aquifer properties) were better understood, this assessment was restricted to White Foil. At White Foil there is one major fracture system running along the strike of the orebody, that provides obvious inflows to the pit (eg the north wall "waterfall"). However, there are also numerous cross-cutting minor fracture systems that contribute a large proportion of the pit inflows (refer Aquaterra, 2003-1). To assess the likely impact of a successful grouting program, the recalibrated White Foil groundwater model (refer Aquaterra, 2003-3) was used to predict the following:

- Scenario 1: reduction in permeability of the main structure by 75%.
- Scenario 2: reduction in permeability of surrounding basement rock by 25%. This may appear to be conservative, but given that the basement permeability is a result of numerous small and less defined structures, a 25% reduction is considered to be a realistic upper limit (for cost effective grouting).

The results of the groundwater modelling are plotted on Figure 3. This shows only minimal reduction in predicted inflows for either scenario.

Another factor that will influence the effectiveness of grouting is the current state of the pit-groundwater system. The best locations for siting grouting injection bores would be close to the pit where the locations of the major inflow structures are more reliably known. However, at present, with the structures flowing into the pit, groundwater velocities through the target grouting zones will be considerable. This will make grouting more difficult, although there are methods available (at a cost) to overcome this problem.

*Figure 3: Pit Lake Water Level Recovery in Current White Foil Pit - Impact of Grouting*




At the time grouting was dismissed as a viable option, although recent reported technological developments in grouting compounds make grouting a potential for future inflow control at White Foil.

## SUMMARY

The results of the assessment are summarised in the attached table (Table 1). In terms of satisfying the target discharge adopted for the study (ie dewatering both White Foil and Frog's leg at 8.6ML/d for three years), the following were concluded:

- The best possible scheme in terms of all ranking criteria was Option 1 (Kurrawang White Lake) closely followed by Options 2 and 3 (White Flag and Red Lakes).
- Option 7, also looked good but only covered the mining of Frog's Leg, although a combination of Options 1 and 7 would allow for dewatering of both mines.
- None of the other options was considered to be workable.

However, when considering the potential for longer periods of dewatering as a result of delays to implementing some systems and/or potential expansions to mining plans as a result of increased proven reserves, the following were concluded:

- Option 2 (White Flag Lake) provided the best possible outcome.
- A combination of Options 1 and 7, and Option 3, were the next best options.

## ADOPTED APPROACH

As outlined in the Introduction, MRA were also pursuing the option of developing a joint discharge system to White Flag Lake in conjunction with Placer. When considering a joint discharge system the White Flag Lake option scores even higher in terms of the environmental consequences, regulatory issues and manageability criteria.

Shortly after the completion of this study, MRA and Placer formerly agreed to the joint discharge approach and initiated design and impact assessment investigations and the approvals process. The joint discharge system has recently been approved and is due for implementation in late 2004 (Ariyaratnam, 2004).

To cover the period between the implementation of the joint discharge system and thew commencement of mining at Frog's Leg, MRA adopted Option 7, and has been pumping dewatering discharge from Fogs Leg into the White Foil pit since the commencement of mining in April 2004.

Once the joint discharge system is up and running, dewatering discharge will be directed to White Flag Lake. Also, once open pit mining at Frog's Leg has been completed and residual inflows have declines to background levels (during underground mining), White Foil pit can be again dewatered and mining recommenced.

**Table 1: Summary of Options and Potential Performance Against Ranking Criteria**

| Option | Reliability | Cost | | Investigation Cost and Timing | Environmental Consequences | Regulatory & Licensing Issues | Manageability | Overall Rank |
|---|---|---|---|---|---|---|---|---|
| | | Capital | Operating | | | | | |
| **1. Kurrawang/White Lake** | High-<br>Could take all discharge | $0.8M | $100K/yr | $10K<br><month | Low to moderate-<br>Internally draining lake, some minor vegetation impacts | Minor-<br>An indicated regulator preference* | High | High* |
| **2. White Flag Lake** | High-<br>Could take all discharge | $1.4M | $120K/yr | $20K<br>I month | Moderate-<br>Pristine lake but can engineer separation from main lake | Minor to moderate-<br>No approvals in place but discharge already occurring* | High | High* |
| **3. Red Lake** | High-<br>Could take all discharge | $1.8M | $150K/yr | $70K<br>2 months | Low to moderate-<br>Can engineer separation from main lake | Moderate-<br>No approvals in place and possibly complex licensing, tenements still pending and need to cross rail/road | High | Moderate to high |
| **4. Evaporation Ponds** | High-<br>Could be designed to take all discharge | $12.9M | $30K/yr | $40K<br>3 months | Moderate to high-<br>Above ground storage of saline water<br>Large scale clearing<br>High rehab costs | Major-<br>Generally not preferred by regulator and difficult licensing procedures | High | Low |
| **5. Expanded Injection Borefield** | Moderate-<br>Capacity subject to variable bore performance | $1.7M | $440K/yr | $85K<br>2 months | Low-<br>All water below ground within hypersaline aquifer | Minor-<br>A regulator preference | Very low | Low |
| **6. Three Mile Hill (and partially expanded injection borefield)** | Moderate-<br>Subject to ongoing third party agreement, plant throughput and performance of injection bores and seepage from underground mine | $2.7M | $250K/yr** | $50K<br>2 months | Low-<br>All water consumed in process or stored below ground in saline aquifers | Minor-<br>A regulator preference | Low | Low to Moderate |
| **7. Frog's Leg to White Foil** | High-<br>But only covers Frog's Leg, also limited life (3 years) if White Foil not fully mined | $0.3M | $40K/yr | $5K<br><I month | Low-<br>All water stored below ground | Minor-<br>A regulator preference | High | High-<br>Subject to plan for White Foil |
| **8. Grouting** | Suspect-<br>Could likely only achieve minimal inflow reduction at best | Option not considered practical and not evaluated further | | | | | | Low |

* Timely implementation of these options would be subject to agreement with Placer over access to tenements.
** Did not allow for compensation costs for Three Mile Hill operators for using poorer quality water.

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# SEEKING JOINT APPROVALS FOR THE DISPOSAL OF DEWATERING DISCHARGE

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## ABSTRACT

*The Kundana Gold Mine has been discharging excess mine dewater to White Flag Lake (WFL) since 1988. Hydrological and ecological monitoring of the lake over the past five years has shown that the current level of discharge is sustainable.*

*However, plans to commission new open pit and underground operations over the next five years, and the associated increase in dewatering discharge has resulted in the need to increase the amount of discharge to the lake. The increase in dewatering discharge is also due to Placer Dome Asia Pacific (PDAP) managing discharge to the lake from nearby mines operated by MRA/Cogema. The management of all discharge to the lake by a single licence holder presents significant environmental and logistical advantages, and also promotes the 'environmental' relationship between the involved parties.*

*This paper presents the process of seeking 'joint venture' regulatory approvals for the increased discharge licence, and the results of hydrological and ecological studies to quantify the impact of the increased discharge to the lake.*

*The hydrological work involved the use of a simple water balance model, together with detailed lake bathymetry data to predict the expansion of the lake inundation area with time for different climatic and discharge scenarios, and under different rainfall conditions (eg. 1 in 10 or 1 in 50 year rainfall event). Desk-top and field based studies were also completed to assess the ecological impact of various discharge scenarios.*

*In considering all potential sources of impact from the increased dewatering discharge to WFL, the results showed that there was no evidence that there would be irreversible, long term damage to the lake's ecosystem.*

## INTRODUCTION

Water resource issues at Placer Dome Asia Pacific's (PDAP's) Kundana mining operation are currently licensed through the Department of Environment (DoE).

The DoE Licence includes provisions for the discharge of excess dewatering production to White Flag Lake (WFL) and to the abandoned Kurrawang Pit. Figure 1 presents an aerial photograph of White Flag Lake taken in December 2000.

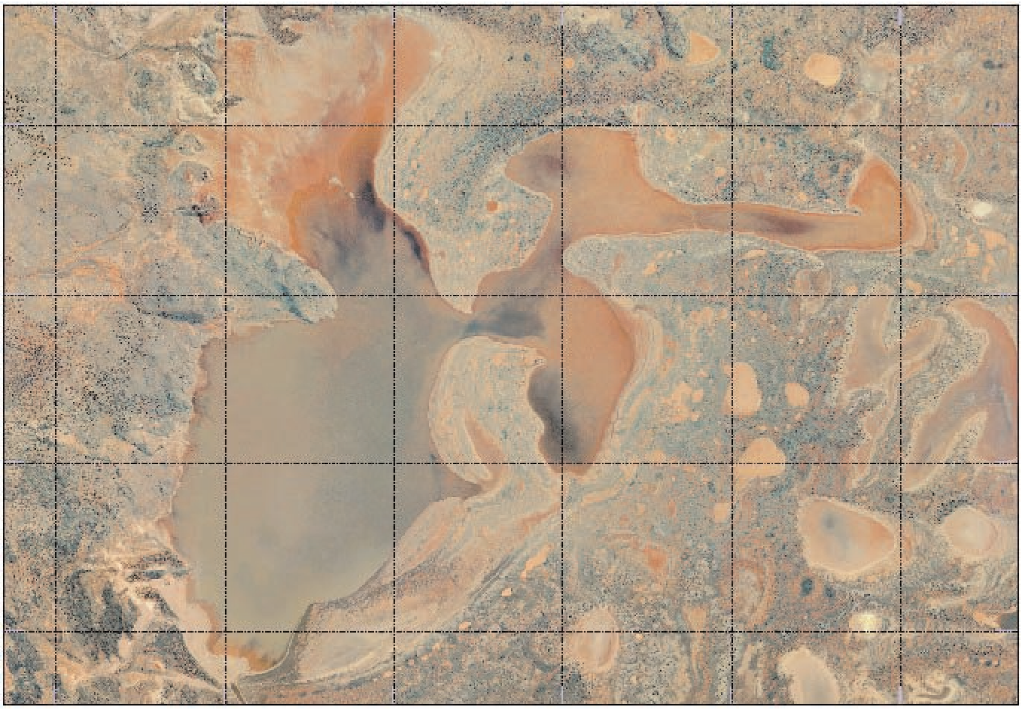


*Figure 1: White Flag Lake*

## BACKGROUND

### Regional Drainage of White Flag Lake

White Flag Lake is located approximately 5km north of the Kundana mine site, with discharge of mine dewatering to the Lake having occurred since mining operations began in 1988.

The catchment of White Flag Lake (and the adjacent collection of salt lakes to the south and east) has an area of approximately 1,990 $km^2$ and extends approximately 70km to the west from Kalgoorlie (Figure 2). The main creek draining the large Western Catchment passes approximately 2km to the south of the mine site. The majority of flow in the White Flag Lake Catchment is from the Western Catchment, with an area in excess of 1,200 $km^2$. Although the catchment topography generally grades to White Flag Lake (and the adjacent lakes), there are numerous areas of depression storage in the catchment that require significant amounts of rainfall to fill before the downstream creeks begin to flow. Similarly, runoff from the catchment tends to fill one lake before overspilling into the next lake down gradient.

Flood discharge flow and level data are not recorded on the Western Catchment or in the general area and as such, accurate relationships between rainfall, runoff and flood level cannot be derived. However, based on the rainfall data associated with recent flood events, the Western Catchment typically produces a significant flood event following a minimum 100 mm of rainfall spread over a few days. Then, while the catchment is still relatively wet, a second significant flood event could result from a rainfall of less than 100 mm. During low flow events, runoff to White Flag Lake is likely to only be from a small local catchment estimated at around 200$km^2$. It is only during the larger runoff events that runoff from the main catchment area would overspill into White Flag Lake.

Over the past ten years, rainfall events of over 100 mm have occurred on five occasions, three of which were over 150 mm. Based on historical data, these last ten years form a period containing above average high rainfall events, which has resulted in several significant flood events. During this period, the more extreme flood events are estimated to represent floods with an Average Recurrence Interval (ARI) of around 20 years.

Historically, runoff from the Western Catchment feeds into the Kopai Lake system with overspill from the main channel flowing northwards through the Kundana area into White Flag Lake. With construction of Bullock Hole Dam (initially for use by the pastoralist) and the Kundana mine infrastructure, all but the most extreme flood flows from the main creek will now be diverted northwards. These flows will generally follow the natural flood flow routes within the Kundana mine area into either a disused pit for reuse by the minesite, or to White Flag Lake. During extreme floods, some flows will bypass the dam and discharge into the Kopai Lake system.

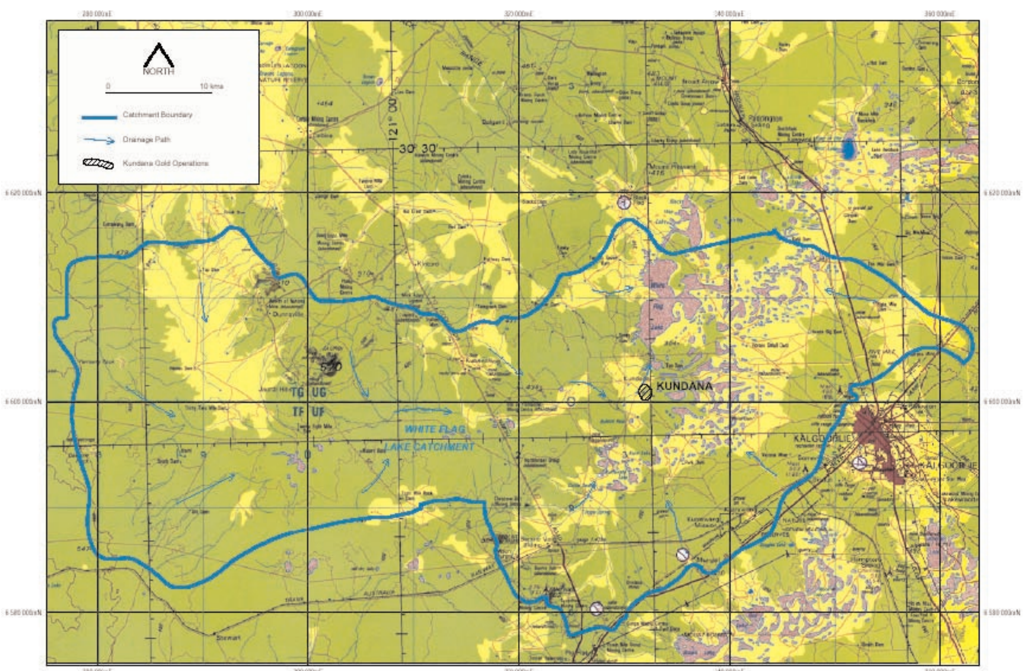
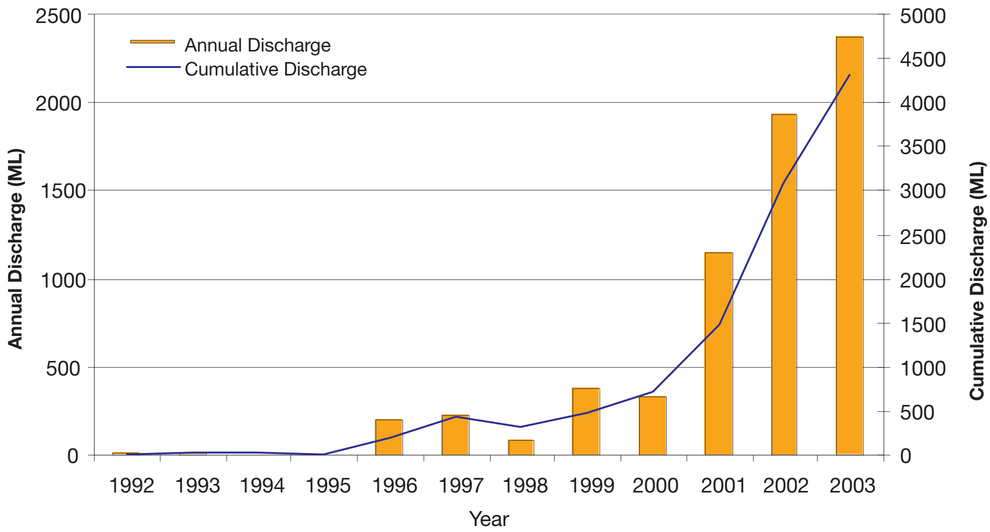



*Figure 2: Regional Drainage of White Flag Lake*

*Figure 3: Historical Discharge Volumes to White Flag Lake*




## Historical Dewatering Activities

Kundana Gold Operations commenced discharging hypersaline mine dewatering water in to the southern part of White Flag Lake in 1988. Up to December 2003, a total of 6,704 ML had been discharged to the lake since records began in 1991/92, with 2,375 ML discharged in the last licence reporting period (November 2002 to December 2003). These annual discharge volumes are within their current discharge licence limit of 4,800 ML/yr. Mean TDS of the dewatering discharges is 140,000 mg/L. Figure 3 presents a summary of annual and cumulative discharge volume to White Flag Lake since 1992.

## Future Dewatering Requirements

A number of new open pit and underground operations are due to come on line in the Kundana region over the next three years. Assessment of dewatering requirements for these operations indicated that the current licence permitting discharge to White Flag Lake would need to be increased to allow disposal of saline discharge resulting from dewatering activities.

Dewatering requirements for the nearby White Foil and Frogs Leg pits, operated by Mines and Resources Australia (MRA), have also been high. The White Foil pit is jointly owned by MRA and PDAP. A proposal was put forward by PDAP to manage disposal of excess dewatering discharge from the White Foil and Frogs Leg pits, on behalf of MRA. The management of all discharge to the lake by a single licence holder has many advantages, both from an environmental and logistical view point.

Hydrological and ecological investigations were undertaken to quantify the impact of the increased discharge to the lake. A brief discussion of some of the components of this investigation is presented below.

# HYDROLOGICAL INVESTIGATIONS

## Water Balance Model

A simple water balance model was set up for White Flag Lake to assess the hydrological impact of a number of increased discharge scenarios. Detailed topographical data for the lake (Figure 4) was used to determine lake surface area and volume for different scenarios. The water balance model calculates lake surface water level using monthly time steps, based on the specified inputs and outputs. The base of the lake at its deepest point is approximately 336.2 mRL, and the lake overspill level is at about 338.5 mRL. The storage volume of the lake at this overtopping level is about 34 GL. A brief description of inputs and outputs to the model is presented below.

- Average monthly rainfall directly on lake water surface.
- Runoff from rainfall directly falling on the lake surface.
- Average monthly pan evaporation directly on lake water surface.
- Average monthly discharge from dewatering activities.

The approximate location of the discharge point is also shown on Figure 4. The discharge point is ideally located near the deepest part of the lake. The inundation area due to surface water inflow and dewatering discharge increases to the north and eventually flows towards the eastern arm of the lake once the water level in the lake is greater than about 337.2 mRL. The deepest part of the western arm of the lake is about 336.8 mRL. The northern extent of the lake drains to the south towards the area of discharge.

*Figure 4a: Bathymetry of White Flag Lake*

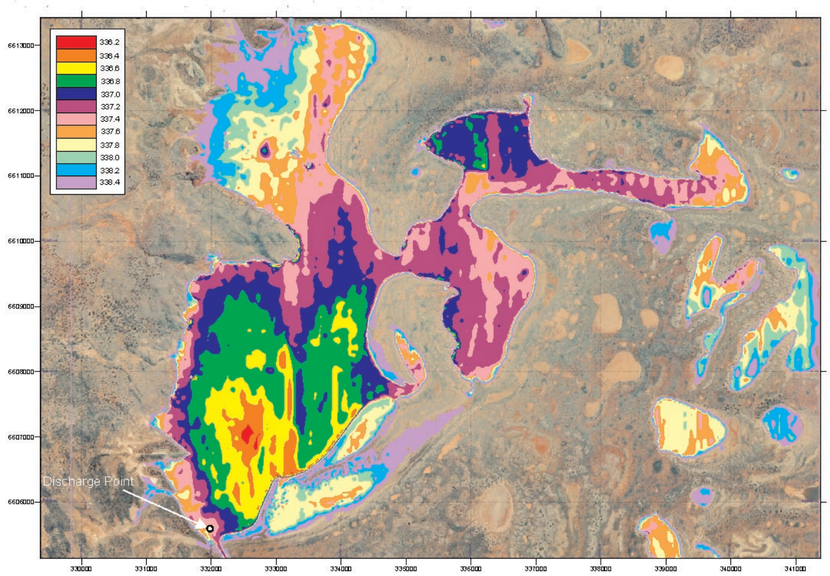
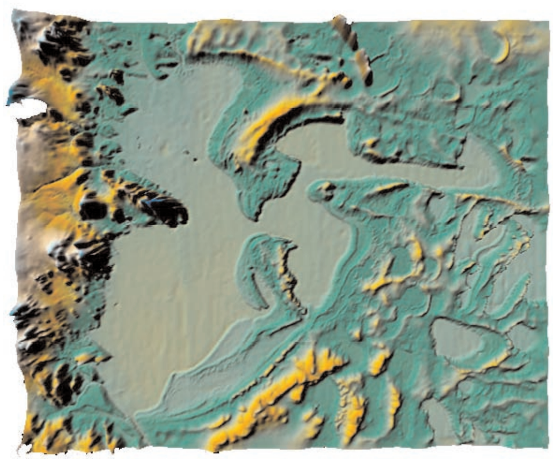



*Figure 4b: Surface view of White Flag Lake*



The water balance model was used to assess the impact on lake inundation area and lake water level for a number of increased discharge scenarios. The calculated maximum monthly lake water level, inundation area and lake volume for the increased discharge scenario is presented in Table 1.

A comparison is also made to the results predicted by the model for the currently licensed discharge volume to the lake (4.8 GL/yr). Note that even though the licensed discharge is 4,800 ML/yr, the maximum annual volume ever discharged to the lake was 2,375 ML over a 14 month period.

The predicted monthly variation in lake water level, inundation area and lake volume is shown in Figure 5a to 5d. The total lake area and lake volume is also shown on Figures 5b and 5d.

The results show that under the increased discharge scenario, about 55% of the lake area will be inundated during the wetter months. A relatively small proportion of the lake storage capacity is predicted to be filled under this increased discharge scenario. Figures 5a, 5b and 5d also show that there is no increase over time in the predicted maximum lake water level, lake inundation area and lake volume.

The maximum and minimum extent of the inundation area is shown in Figure 5c. Under the current licence scenario, the lake is predicted to be dry for one to three months of the year (monthly average). However, on a daily basis, there is likely to be a discharge pool present.

**Table 1: Predicted Lake Water Level, Inundation Area and Volume**

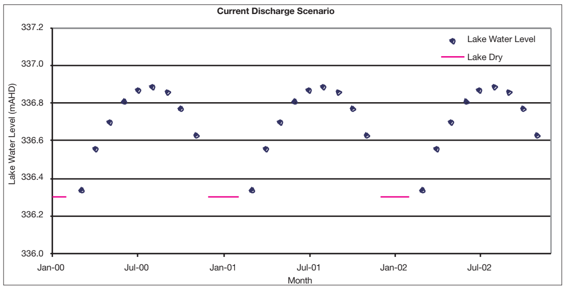
| Scenario | Maximum Water Level | Maximum Discharge Area | % of Total Lake Area | Maximum Volume in Lake | % of Total Lake Volume (t/ha/yr) |
|---|---|---|---|---|---|
| Current Scenario | 336.9 mRL | 8,606,000 $m^2$ | 34% | 2,024,000 $m^3$ | 6% |
| Increased Discharge Scenario | 337.2 mRL | 14,014,000 $m^2$ | 55% | 4,750,000 $m^3$ | 14% |

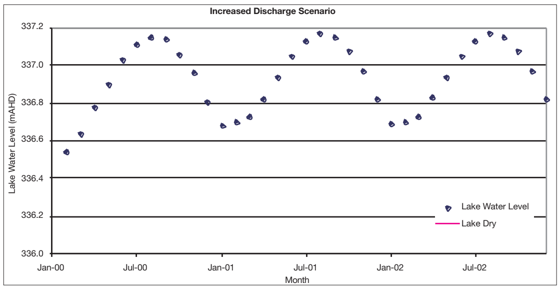
The increased discharge scenario results in inundation of a section of the lake with water for the whole year.

The current licence scenario also results in the lake inundation area being restricted to the western portion of the lake. The increased discharge scenario results in flow towards the eastern arm of the lake, although the depression to the north is not predicted to be impacted. Note that this northern pool is inundated during certain parts of the year due to natural surface water inflow from the eastern arm of the lake.

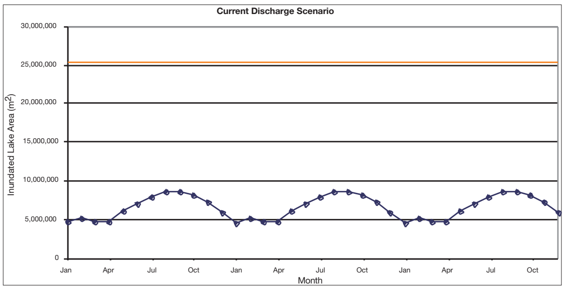
*Figure 5: Monthly Variation in Lake Water Level, Inundation Area & Lake Volume*

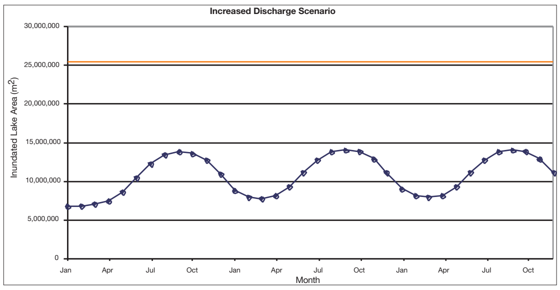
*(a) Lake Water Level*

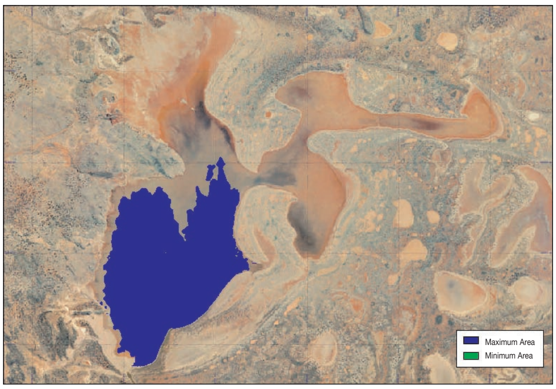


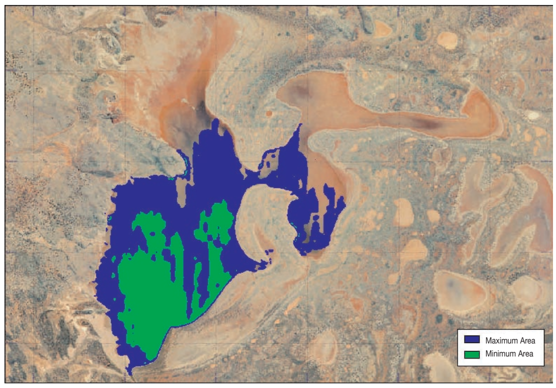




*(b) Lake Inundation Area*

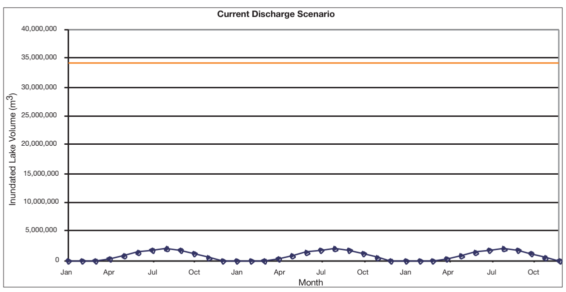


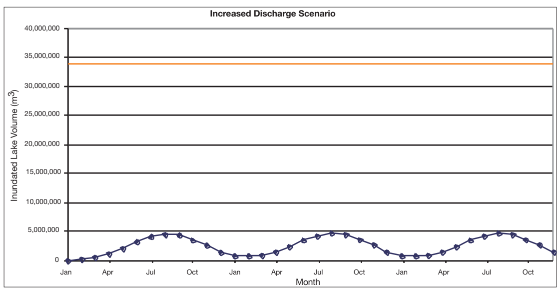




*(c) Lake Volume*



### Impact of Peak Flow Events

Runoff from the large lake catchment was not included in the average water balance. Average monthly rainfall experienced in the area is not likely to generate significant amounts of runoff from the large catchment. The influence of catchment inflows was addressed by examining the impact of peak flow events to the lake.

Based on the large western catchment area (1,200 km$^2$), volumes likely to be generated for different rainfall events (72 hr) are summarised in Table 2.

The more extreme flood events over the last 10 years are estimated to represent floods with an average recurrence interval (ARI) of around 20 years. A 1 in 20 year event is predicted to generate a volume of approximately 12 GL. If such a peak flow event occurred during the wetter months (ie when the volume of the lake is at a maximum), the total volume of water in the lake would be about 17 GL. This is well below the storage capacity of the lake (about 34 GL). Therefore, a 1 in 20 year rainfall event would be comfortably contained within the lake. Under this scenario, about 87% of the lake surface area will be inundated. The predicted extent of lake coverage under this scenario is shown in Figure 6.

The large storage volume of the lake could be filled if extreme flood events were to flow into the lake (1 in 100 year events) resulting in an overspill and discharge to downstream areas. A simple mass balance approach was used to assess the water quality of the lake should the overspill level be reached and the lake were to discharge downstream. The average TDS of the potential future dewatering discharges from White Foil and/or Frog's Leg Pits has been estimated at 230,000 mg/L. The average concentration of discharge from Kundana pits is about 140,000 mg/L.

Based on an average discharge concentration of 180,000 mg/L, and assuming full mixing within the lake during a peak flood event, the salinity of water that would overtop the lake would be about 25,000 mg/L (under the increased discharge scenario). Under the current licence discharge scenario, this concentration would be about 11,000 mg/L. During this type of flood event, the overtopped water would be quickly diluted further as it enters downstream systems. The main broad areas where the lake is predicted to initially overtop during a peak flow event is in the north western and southern parts of the lake.

## ECOLOGICAL ASSESSMENT

The main changes expected to occur in the ecosystem in White Flag Lake, as a result of increased dewatering discharge volume, were related to increased salinity. These changes were not considered to be a threat to lake ecology for a few reasons, based on results of three years of ecological assessment and hydrological predictions about salt load.

Previous terrestrial and aquatic studies have not identified any rare or endangered species, to date, and the playa (and fringe) appears relatively homogeneous in terms of species distribution.

In dry conditions, 55% (or less) of the lake area (14% of volume) is affected by elevated salinity due to dewatering discharge. Hydrological assessment shows that in this scenario, pooled dewatering discharge will be segregated from other significant sub-basins in the lake that can provide refuge for biota.

Based on salt-load predictions in 'typical' significant rainfall events (1 in 20 year events), the salinity of surface water would be dilute enough to allow opportunistic breeding of aquatic invertebrates, as occurs in normal wet cycles. In 1 in 100 year rainfall events, overtopping to surrounding wetlands would likely occur, but salinity would be extremely

**Table 2: Predicted Catchment Inflow Volumes to White Flag Lake**

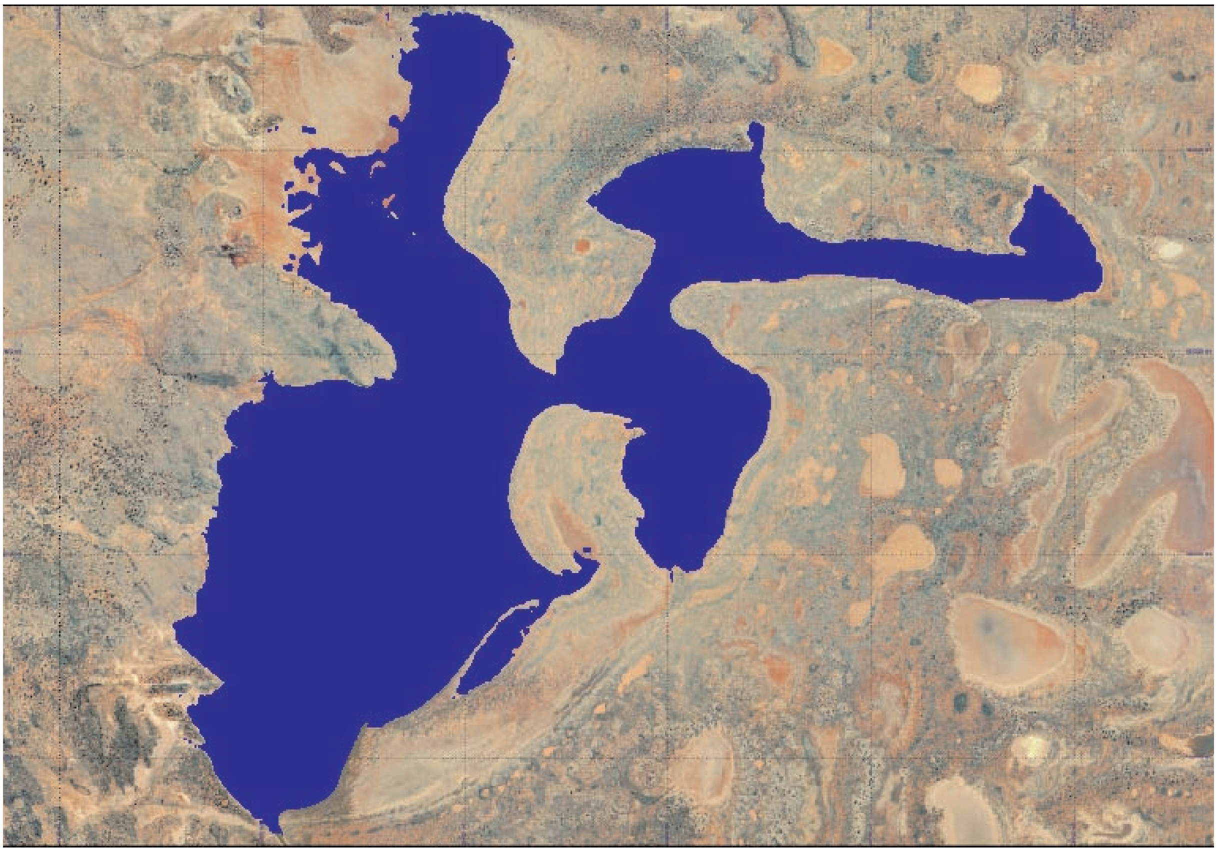
| Average Recurrence Interval | Rainfall Intensity (mm/hr) [1] | Effective Runoff Coefficient [2] | Volume (kL) |
|---|---|---|---|
| 1 in 2 Year | 0.67 | 0.01 | 580,000 |
| 1 in 5 Year | 0.98 | 0.04 | 3,390,000 |
| 1 in 10 Year | 1.21 | 0.07 | 7,320,000 |
| 1 in 20 Year | 1.52 | 0.09 | 11,820,000 |
| 1 in 50 Year | 1.99 | 0.15 | 25,790,000 |
| 1 in 100 Year | 2.40 | 0.17 | 35,250,000 |

Notes:

[1] Peak rainfall intensities for 72hr rainfall event

[2] Runoff coefficients based on catchment studies at Lake Turner

*Figure 6: Predicted Lake Coverage after Peak (1 in 20 year) Rainfall Event*



diluted and therefore would not pose a significant risk to surrounding ecosystems (including fringing flora). In addition, White Flag Lake is fed by several large creeks to the north of the lake, which contribute to biological productivity in wet conditions (when the creeks flow).

Based on available data, dewatering discharge will most likely pool in the south eastern portion of the western arm of White Flag Lake, and there will be a temporal and likely short-term impact to the ecology of this area. Six recommendations (related to intensive monitoring of ecology) were made to limit impact and protect the ecosystems in this area.

## REGULATORY APPROVAL

Once the in-principle decision had been made to seek a joint discharge approval, initial discussions were held with regulators to discuss the potential for this approach. The concept was viewed positively by the regulators, who had been in discussion with MRA to seek an independent licencing route for the White Foil and Frogs Leg projects. The proposed joint discharge approach was seen as providing benefits in that it enabled clear accountabilities under a single licence holder, and avoided the situation of multiple discharge sources (eg Lake Carey) or a new discharge area.

PDAP then proceeded with the hydrological and ecological studies previously discussed to confirm the technical feasibility of the project for the volumes of discharge predicted. Once these studies were completed a second round of consultation was conducted. This second round of consultation involved a wider audience with briefings and discussions held with stakeholders such as the Conservation Council of WA, Department of Industry and Resources, Department of Conservation and Land Management, Aboriginal Claimant Groups and the City Council. Comments and concerns from these consultations were incorporated into the final submission.

Upon completion of the final reports, an amendment to the existing Kundana DEP Licence was submitted. The proposed amendment was referred to the Environmental Protection Authority by PDAP (Proponent Referral), due to the increased volumes sought. However due to the studies completed and the degree of stakeholder consultation conducted, the project was deemed to not require formal assessment by the Authority. Subsequently, the proposed amendment to the licence was processed under the licencing and works approval provisions of Part V of the Environmental Protection Act 1986.

# SALT LAKES AND MINE DEWATERING DISCHARGE: CAUSE, EFFECT, AND RECOVERY

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## ABSTRACT

*Ecosystems are naturally dynamic entities. Lakes are routinely disturbed by many kinds of events. Fluctuations include changes in climate, rainfall input, nutrient input, and alterations to the watershed can also have an impact. Episodic or ephemeral lakes, such as the salt lakes of Western Australia, experience extreme changes over the course of time. Despite such disturbances in the lake, its watershed or airshed, ecosystem processes are maintained. However, salt lakes may exhibit apparently altered system dynamics when subject to considerable impacts.*

*Alterations to the salt lake system that may cause significant degradation are many and varied. Along with variation in the catchments of salt lakes, the basins can also be subject to several types of disturbance. Salt lakes receive as many different substances as are dumped into rivers, freshwater lakes and the sea. However, unlike freshwater lakes and rivers that ultimately discharge to the sea (which has a large capacity to absorb wastes), salt lakes represent the terminal foci of inland drainage. Thus the basins have a finite capacity to absorb these materials. What goes into the salt lake system remains within the basin unless lost to the atmosphere and/or by seepage to underlying drainage.*

*Mining operations in the Goldfields commonly discharge groundwater inflow to nearby salt lakes to evaporate excess water. The Mine Water Discharge (MWD) contains fresh rock particles removed from the operations as well as water quality equivalent to the aquifers intersected. The impacts of MWD on salt lakes can be substantial depending on: quantity and quality of MWD; size of the salt lake; natural geochemistry of the receiving environment; current climatic and edaphic conditions; nature of the riparian environment; and proximity of salt lakes to groundwater aquifers.*

*To learn the effects of impacts from Mine Water Discharge, an understanding on how salt lake systems change over time in response to impact events (natural and anthropogenic) must first be achieved. Salt lake systems are not the simple systems as first thought, and an understanding is only gradually being realised. This paper examines the impacts of MWD on small salt lake systems and discusses the ecosystem dynamics of salt lake structure and function.*

*The examination of ecosystem models will be useful in the determination of critical thresholds, and the mapping of system recovery from impact. Impacted systems may require assistance in recovery, particularly where the system's resilience is reduced, or where natural recovery processes are considered to be too slow to achieve (regulatory or management) ambitions.*

## INTRODUCTION

When early explorers stumbled across "vast, low and dreary waste(s)" [Eyre] and large expanses of "unbroken sterility" [Warburton] in the interior of Australia, they began the first scientific documentation about the structure and function of salt lakes. Unfortunately, the persistence of the mindset that salt lakes represented sterile wastelands has been stereotyped into the Australian psyche, reflected by romantic stereotypical literature of modern authors: "If any rare rain did fall, the lakes quickly drained the surrounding land, and soon returned to shimmering salt" (Drewe, *The Drowner*). Such documentation details four important characteristics that define salt lakes. The early explorers noted that salt lakes occupy large (generally) and flat areas, obviously away from the coast. Drewe succinctly places salt lakes in topographic lows that draining surrounding land, and also indicates a large evaporation rate removing water, leaving behind the shimmering salt as an apparently steady state.

Salt lakes do not persist in a stable state, they are dynamic ecosystems, in constant flux, just the same as classically examined in the attempts to describe arboreal forest succession, and in faunal communities existing in zonal gradients influenced by the stress of constantly changing tides and the abilities of each taxa to successfully compete for light, space, and nutrients. Salt lakes exist as the component of many geologic, edaphic, climatic, and topographical factors. While salt lakes may not be seen to behave as a tidal rock platform, nor as a forest is supposed to responds to a tree fall, as unique, dynamic ecosystems, they do change in response to impact. The measurement of such changes in response to impact, and how the salt lake ecosystems respond is rarely detailed in the literature.

### Types of Impact

Impacts upon the salt lake ecosystem can be many and varied. Rainfall events provide a good demonstration of the ability of the system to change from the apparently dry stable state of a salt lake. Lakes can fill, and life appears in a brief flush, determined to take advantage of suitable conditions for procreation and survival of species. All the while, the salt lake ecosystem is changing. From the freshwater filling of the lake, through the dissolution of salt on and in the bed of the lake, and the evaporation and subsequent reconcentration of salts as the lake dries again, the lake conditions alter. Such a natural impact occurs with startling rapidity, for all the fact that salt lakes exist in an environment where episodic or ephemeral rainfalls are the prescribed norm.

However, impacts upon the salt lake ecosystem are not just limited to climatic events. Impacts do not have to be large-scale, encompassing the entire regional watershed of the salt lake, for change to occur in the system. Changes can occur in any section of the lake environment that will fundamentally alter the dynamics of a salt lake ecosystem. Many such impacts and subsequent changes have been wrought from anthropogenic interactions with salt lakes, evolving from beyond one low dreary waste to reflect influences shown by increasingly important human uses.

## Anthropogenic Impacts

Anthropogenic use of salt lakes and resources in their drainage basins has resulted impacts that are significant, diverse comprehensive and mostly irreversible. As Williams (1993) states: "Impacts have been many and diverse, of short or long-term duration, affecting part of the biota or the ecosystem as a whole, of limited extent or totally destructive." Williams (1993) further identifies six broad categories of impacts to salt lakes resulting from human activities. These impacts are:

- Catchment or drainage basin activities;
- Diversions of inflowing waters;
- The addition of unnatural waste products or pollutants;
- Direct impacts on the biota;
- Physical changes to the lake basins; and
- Changes caused by global climatic and atmospheric alterations.

A significant reason for human interaction with a salt lake ecosystem results from an economic source. Salt lakes are a source of mineral information. From detailing catchment element content through the slow process of erosion and runoff from their surrounds, through allogenic production, to hiding a wealth of ore bodies beneath their beds, salt lakes are linked to human activities. Mining operations dot the landscape in the Salinaland of Western Australia are all linked to a salt lake ecosystem in some fashion, whether it be by direct means such as mining in the lake bed or apparently indirect where mining occurs in the catchment, far away from the surface expression of rainfall capture and runoff.

## CAUSE:

Mining operations commonly delve below water tables – local and regional – in the search for economic ore bodies. When intersecting such water tables, the removal of inflowing water must occur to maintain both productivity and a safe working environment. Some of the inflowing water may be utilised in the mining process itself, such as for dust suppressant on adjacent roads, or as process water if the mine is close enough to the nearest mill to be utilised. Depending on the size of aquifer intersected, a significant proportion will be deemed a waste product. Mine Water Discharge to salt lakes is the most common practice used by mining operations to remove excess mine water inflows.

The choice of which particular salt lake is to be used as a location to receive MWD is coming under stricter regulatory control. Baseline information of the ecology of the salt lake system chosen is required such that potential impact effects of MWD can be examined, and, managed in adherence to regulatory guidelines.

Most mining operations discharge to large salt lakes, but not all. Not all mining operations are located on or adjacent to large systems. A focus on smaller salt lake systems allows a complete system study, rather than specific areas, improving an understanding of potential impacts. This paper focuses on salt lake systems of the Goldfields of Western Australia in an attempt to understand effect of impact and patterns of ecosystem recovery.

Three lakes are examined with different discharge regimes. Lake Josh represents a control system where no mine water discharge has occurred, Lake Fore represents a sustainable mine water discharge system, and Lake Tee represents a system where mine water discharge has exceeded a sustainable level of input. These salt lakes are associated with Nickel mining operations in the Kambalda region.

## EFFECT:

There are facets of MWD that should be examined to explain the level of impact on salt lake ecosystems: quantity and quality. Salt lakes are constructed of three main components – catchment, basin, and sediments. As Mine Water is (generally) discharged directly to the basins of the salt lake ecosystem, impact assessment is generally focussed on the interactions between the basin, sediments, and received MWD. However, depending on the quantity of the MWD, the lower catchment – particularly the riparian zone – may also be impacted.

## Quantity and Lake Size:

The quantity of Mine Water Discharge depends on the size of aquifer intersected during the mining process. The greater the volume of mine water discharged to the salt lake, the greater the impact. Likewise, with a smaller salt lake, impacts of MWD will be increased. An excess of Mine Water Discharge to a salt lake ecosystem can lead to the inundation of the lower riparian zones of a catchment, a result far more likely in a small salt lake than large.

Over the life of discharge at Lake Tee (1991-1998), some 850 000 kL of Mine Water was discharged to the basin. 650 000 kL was discharged to Lake Tee in 1998 alone, following an increase in water inflows caused by hanging wall failures in the mine. This caused the lake to overflow, inundating the lower catchment.

**Table 1: Salt Lakes Catchment and Basin Sizes**

| Salt Lake | Catchment Size (km$^2$) | Basin Size (km$^2$) |
|---|---|---|
| Josh | 0.85 | 0.152 |
| Fore | 3.35 | 1.182 |
| Tee | 3.30 | 0.164 |
| Lefroy | 3974 | 554 |

**Table 2: Mean Water Quality and pH of Salt Lakes Studied**

| Salt Lake | Water Quality (g/L TDS) | pH |
|---|---|---|
| Josh | 129 | 4.14 |
| Fore Baseline | 290 | 4.1 |
| Fore Discharge | 260 | 6.7 |
| Fore Post-Discharge | 295 | 4.7 |
| Tee Discharge | 282 | 6.75 |
| Tee Post-Discharge | 360 | 7.01 |

The inundation, combined with the quality (hypersaline) of the Mine Water, killed riparian vegetation.

Lake Fore also received MWD (1997-2000), with some 1 400 000 kL discharged to the basin. The waters on the lake did not reach beyond the shoreline. Lake Josh is used as the control salt lake, having not received Mine Water Discharge.

## Quality (Water):

Natural rainfall adds approximately 30 kg/ha/year of salt to the land surface in the southern Goldfields (Malcolm, 1983; Taylor, 1991; George, *et al.*, 1997). If it could be assumed all the salt deposited in a year on the catchment of Lake Tee by rainfall alone (ignoring runoff coefficients) flowed into the basin, then this would equate to 9900 tonnes of salt.

However, quality of MWD received by Lake Tee was hypersaline – on average 285 g/L total dissolved solids (TDS). The large quantity of Mine Water discharged to Lake Tee evaporated in the summer of 1998-1999, precipitating 240 000 tonnes of salt onto the surface of the lake. This roughly equates to 24240 years worth of natural salt deposited by MWD on the basin surface.

The final crust on Lake Tee was calculated to have a mean thickness of 0.69m, and stretched up to 20 metres above the shoreline. Capillary action caused a salt creep up the catchment, reaching up to a further 40 m on the shallower and sandier slopes of the east and south of the lake.

No baseline studies were performed at Lake Tee, due to regulations at the time not requiring such information.

## Quality (Sediment):

The depth profiles of parameters in the sediment have been examined for each of the salt lakes studied in this project. The data was taken from cores augured into each salt lake. The cores in Lake Fore and Lake Tee were collected from increasing distances from the discharge point.

Suspended sediment in the MWD dropped out in a brief plume and has remained on the surface of the lake sediments since discharge to Lake Tee ceased. As a result, the nickel (Ni) value at the surface of Lake Tee is inflated by a large concentration at the discharge point. Apart from the pH values, and nickel, copper and arsenic concentrations, which are elevated at the surface of Lake Tee, all metals measured are similar to those in Lake Josh. The presence of high levels of iron throughout the sediments of Lake Tee is an indication of the geological makeup of the Lake Tee catchment.

## Riparian Zone:

The Mine Water Discharge has effectively shrunk the riparian zone of Lake Tee. The increase in level of salt crust above the original shoreline has reduced the riparian zone. This is due to the fact that resources continue to move down the catchment from the watershed as is the case in a salt lake unaffected by MWD. The salt creep has been flushed from the riparian zone, allowing the rapid recovery of vegetation. This can be more easily expressed graphically (Figure 4).

*Figure 1: Salt Lake Cores – pH values*

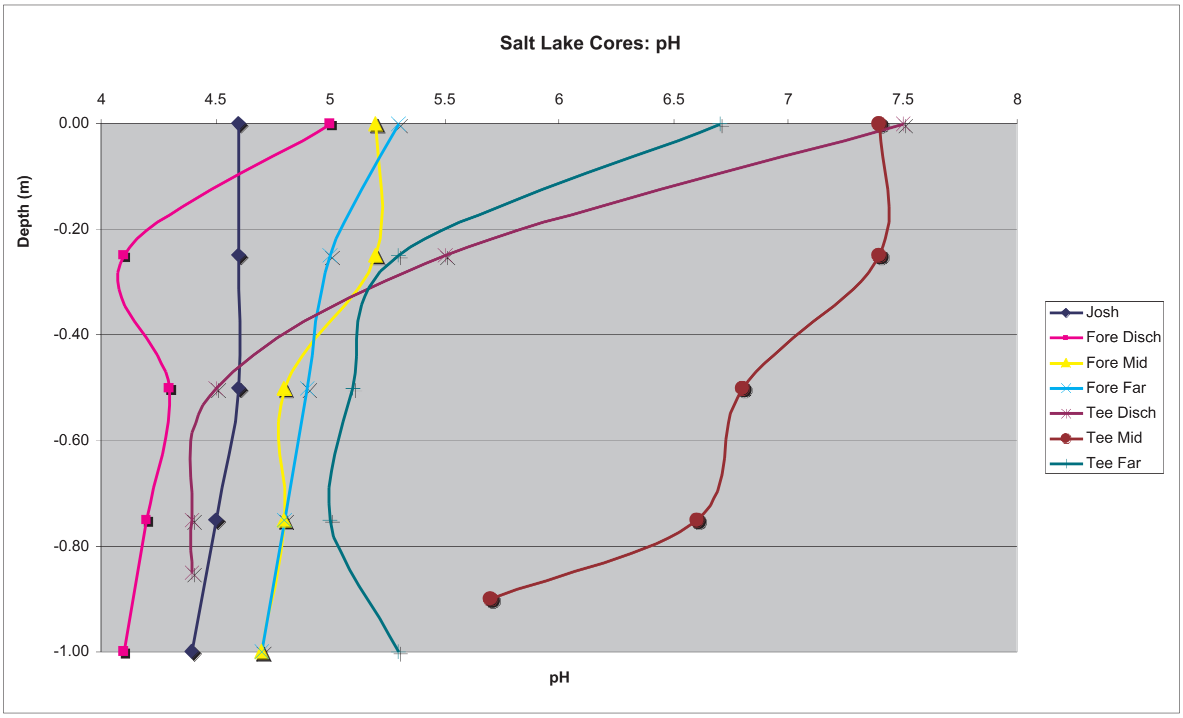



*Figure 2: Salt Lake Cores - Nickel Concentration (mg/kg)*

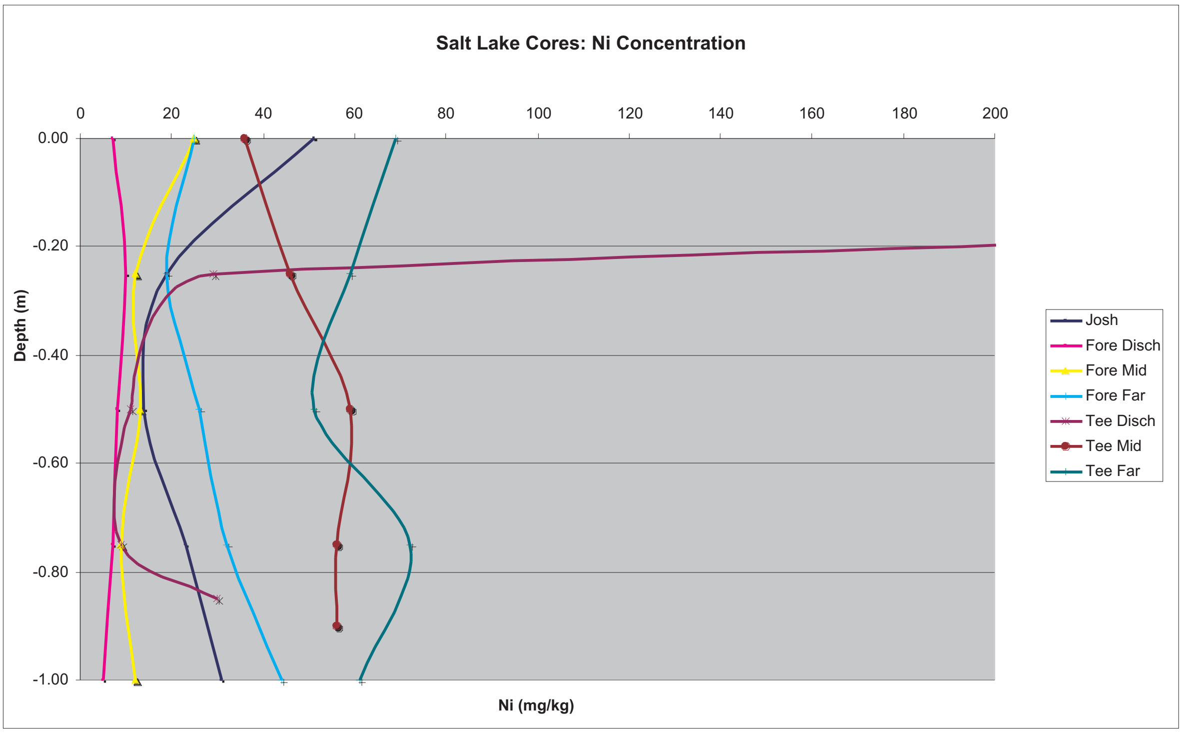


*Figure 3: Salt Lake Cores – Iron Concentration (mg/kg)*

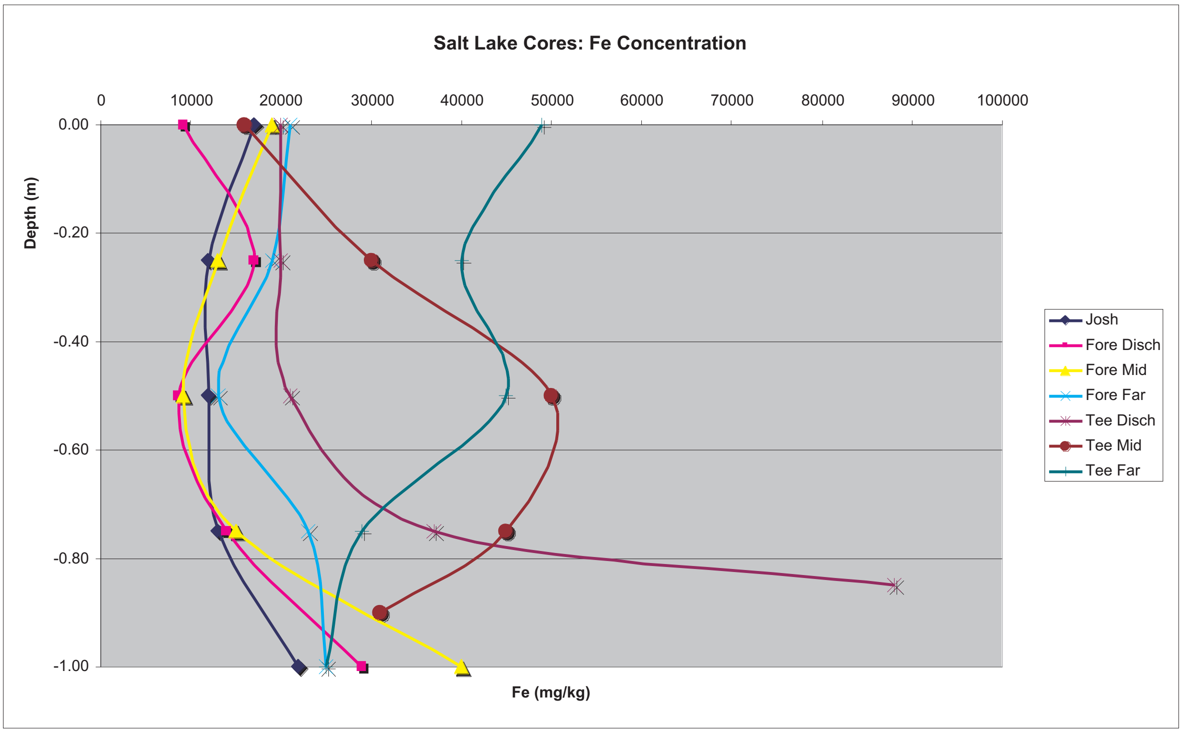
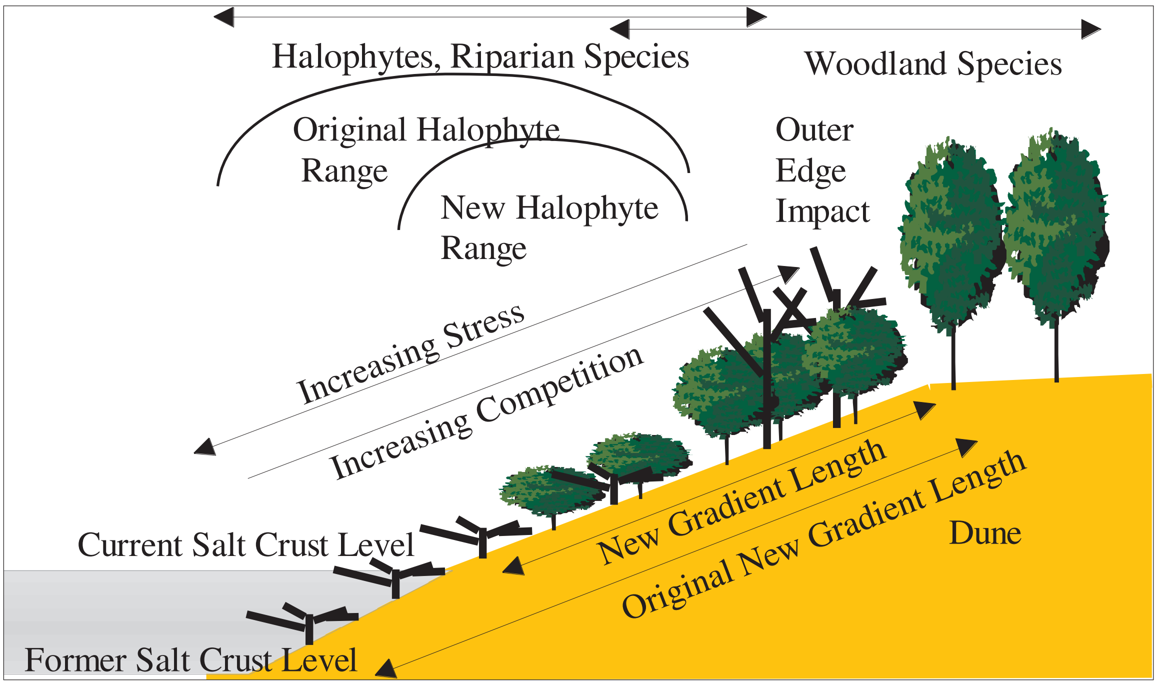



*Figure 4: Vegetation Gradient Changes from MWD Impact*



## IMPACT:

Impact of Mine Water Discharge, affects the structure and function of a salt lake ecosystem, albeit not completely. MWD is generally limited to the basins and riparian zone, depending on quantity of discharge. However, as basins occupy the topographic low of a salt lake ecosystem, the upper catchments remain unaffected in structure and function. All systems leak downwards. From the watershed, resources continually move down the catchment toward the basin. From the basin, resources may be lost to the groundwater, or evaporated.

### Basin:

The covering of the basin by a salt crust in Lake Tee changes the geochemical properties of the lake. The basin is covered by a deoxygenated layer of hypersaline water in the interstices of the crust itself. Combined with different Precipitates from the hypersaline water interacting with the iron rich sediments forms a layer, relatively impervious to the passage of resources through to the groundwater.

### Riparian Zone:

Disturbance impacts have been briefly examined, primarily looking at the responses of vegetation to grazing pressures (Pringle, 1994), and models of vegetation dynamics have been developed in an attempt to explain such responses (Westoby, 1979/80, Westoby *et al.*, 1989). Only very recent literature (Finucane *et al.*, 2001, Finucane *et al.*, 2002) briefly document vegetation community descriptions following a disturbance impact to both the salt lake itself and the vegetation communities of the surrounding catchment.

Monitoring the establishment and re-establishment of vegetation on the flood-damaged fringes of a salt lake will provide information about ecological succession in these communities. A range of questions arise from such a regime. Will succession follow a determined pathway to an equilibrium community of the same composition as other local lakes? Will the disturbance of a hypersaline flooding event trigger a transition to a different, non-equilibrium state that differs from the local lakes? An examination of response of flood-damaged fringe should show a trend in the change of vegetation structure over time and indicate where the vegetation community and, ultimately, the whole lake ecosystem is headed.

## RECOVERY:

The biggest impact that Mine Water Discharge has on a salt lake ecosystem is the addition of salt. The addition of material in the form of suspended solids is considered insignificant in comparison with the addition salt to salt lake ecosystems. Natural salt lakes are found on a hydroperiod continuum scale ranging from a dry condition to wet condition. Salt lakes are described to be dry 75% of the time by definition. Rainfall shifts the lake system from dry to wet. There are natural salts from the surrounding landscape washed into the basin from runoff, and the fresher water dissolves salts on the basin before evaporating back to dryness. The time taken to dissolve the salts on the basin surface by the runoff will depend on the stored volume of salts. The addition of MWD to a salt lake basin will increase the volume of salt on the basin. The same volume of runoff will not dissolve the extra salt. This effectively shifts the balance of the salt lake ecosystems further along the hydroperiod continuum towards the dry end of the scale.

At Lake Tee, most of the original lake shore environment remains under the direct influence of salt in soils and are located close to or under the fringes of the salt crust. Away from the edge of the lake, where rainfall and runoff have removed the crust, halophytic species have begun recolonising. Recruitment for these halophytes are likely to have come from further up the catchment, or blown in from adjacent lake system communities. The location of the recruited halophytic vegetation appears to indicate that whole vegetation community is shifting higher in the catchment in a response to the concentration of salt in the soil. Eucalyptus species impacted at the outer edge of the salt creep have responded with large numbers of recruits, taking advantage of conditions as soon as rainfall flushed the creep back down the catchment.

The suggestion is that there has been a compression of the vegetation gradation away from the edge of the impacted lake, due to the presence of the higher salinity levels in the lower landscape of the catchment. This gradation is being examined to provide an indication whether the compression remains stable, or shows a level of recovery in progressing towards a similar vegetation community structure that existed before impact occurred.

## CONCLUSIONS:

One of the great difficulties in examining salt lakes is a lack of adequate comparative literature pertaining to the same field. Salt lakes represent extreme environments. During the course of a year, they can be regarded as “dry” and therefore virtually a terrestrial environment, and range to an aquatic system given the input of enough rainfall (or mine water discharge). From a geochemical perspective, salt lakes exhibit oxidating and reducing conditions, depending on the stage of the hydroperiod they are at.

What then, are the limiting factors that either hold geochemical change in check, or drive the system through dynamic change? Water, ultimately is the key to what a salt lake environment will do. When wet, sediment resuspension can occur, allowing the transport of metals and ions throughout the lake, and increasing the potential hydraulic head drive through the sediments towards the groundwater.

A wet period will generally not minimise oxygen movement throughout the system, due to the (generally) shallow nature of the wet lake, and the large volume of mixing that occurs through wind action. Stratification is a rare, although not unheard of event, during the wet phase exhibited by salt lakes.

Dry salt lakes represent another extreme. Despite being desiccated, water still drives the geochemical processes. Evaporation will move ions (especially) and compounds towards the surface, should the groundwater below a salt lake be shallow enough (<2m). With such an evapoconcentration the contents in sediment water can happily interact and precipitate. Evaporite minerals are a good example of the geochemical nature of a salt lake when dry. Of course, in a natural salt lake system, the variation in evaporite mineral speciation and concentration will depend on what materials enter the salt lake sediments from runoff from the surrounding catchment, or deposited with rainfall and dust.

The alteration of a salt lake environment via the processes of mine water discharge will have a fundamental impact on the geochemical nature of the system. Concentration and balance of additional material will result in change.

Every salt lake in the Salinaland of Western Australia experiences ephemeral and/or episodic rainfall events. In terms of their natural state, the addition of quantities of natural water will not alter a system greatly. Salt lake systems are a reactive environment, rather than a predictive environment, and can only respond to what is added or changed. The "closest available comparison" to salt lake environments, salt marsh systems, receive a twice-daily injection of seawater through tidal pulses with a monotonous regularity that allows prediction (of biological lifecycles) to occur.

Water as a limiting factor can not be ignored. The presence of water in a salt lake system remains the predominant driving force for change, and response to impact. In this project, the addition of a large quantity of MWD has altered the dynamic equilibrium of a natural lake, to give the appearance that the environment has somewhat stalled in its response to natural events.

If water is the limiting factor, the volume of salt deposited on the salt lakes examined in this project becomes the critical threshold. Resilience is always going to occur, speed dependent on the volume of water and frequency of addition by rainfall events, but with such a large volume of salt on Lakes Fore and Tee (in particular), the dynamics will be slowed.

While biological activity may act as an early warning system of ecosystem degradation in salt lakes, any measurement of the decline in productivity will only be limited to episodes where the boom of life occurs following significant freshwater input. It must also be noted that no two rainfall events are identical. Intensity and frequency of rainfall will have a large bearing on the biology of a salt lake. The underlying physical and chemical properties of a salt lake system remain the main factors that interact with rainfall to determine the ecological function of salt lake systems.

Such parameters provide a better set of baseline conditions that assist in the definition of a salt lake system. If and when impact occurs to the physical and chemical characteristics of a salt lake system, such alterations to the environment can be potentially measured and, hopefully, understood.

Salt lakes have progressed from being a sterile waste, to holding great scientific information and value. Salt lake ecosystems represent unique, discrete, apparently simple systems that can be easily manipulated to elucidate data on structure and function, pattern and process. The interaction between economic and scientific values of salt lakes has been at times, a forced interaction, but has however, begun to yield a wealth of knowledge about the ecosystems and their ability to interact with human-induced impacts.

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# IMPACT OF DISCHARGE OF HYPERSALINE WATER FROM THE CUDDINGWARRA PROSPECT ON THE FRINGING VEGETATION OF LAKE AUSTIN

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## ABSTRACT

*This paper reports on the results of a monitoring program designed to assess the impacts of discharge of hypersaline water into Lake Austin. This water was collected and discharged from mine pits at Cuddingwarra between May 1999 to October 2002. The BACI ('Before – After – Control – Impact) design of the monitoring program revealed that discharge has increased the topsoil pH within the vegetation zone immediately fringing the lake, particularly in areas where discharge waters have been in direct contact with the vegetation. There is strong evidence that the salinity of these soils has also been increased by discharge. Despite changes in the topsoil of fringing vegetation in the vicinity of the discharge points, the monitoring program detected no impact on the vegetation. Possible reasons why no impact on the health, growth and recruitment of plants in the fringing vegetation was detected include: a) lack of statistical power (post-hoc power tests demonstrated that, due to the high variability, around 30-50 sampling points would be required to detect any differences in the degree of change between 'control' and 'impact' zones); b) flooding of lake and fringing vegetation, due to abundant rains in summer and autumn 2000, has masked impacts by diluting and mixing discharge waters; and c) the inherent ability of fringing samphire plants to survive and grow in extreme salt levels has meant they can tolerate an increase in salinity (although there was some evidence that seedlings may be more vulnerable to such an increase in topsoil salt levels). Given Lake Austin is an internal drainage system, the half a million or so tonnes of salt added through discharge should be regarded as a long-term addition to the system. Rather than being more-or-less evenly deposited on the lake surface following evaporation of the 2000 floodwaters, salt was preferentially deposited in the lowest part of the system. These were mainly inlet channels which now contain up to 1m thick deposits of salt. This means the next major in-flows into the lake are likely to carry exceedingly high salt loads. Depending on where this water goes, future impacts on fringing vegetation may occur. This study, due to the fact that monitoring has occurred both before and after discharge, and across drought and flood periods, has given us a far better understanding of the how salt lakes function and change over time, as well as how they respond to added hypersaline water. Some important messages for improved monitoring and management of discharge to salt lakes, now a common practice in the gold mining areas of Western Australia, are discussed.*

## INTRODUCTION

Interception of the water table, groundwater seepage, surface runoff and/or rainfall lead to the need for continual removal of excess water from mine pits and shafts, a procedure often termed dewatering (Farrell and Kratzing, 1996; Water and Rivers Commission, 1999). To allow for the extraction of ore, groundwater levels around an operation need to be kept lower than the floor of the pit by using underground pumps and pumps in the bottom of the pit. The removal of groundwater from the immediate area is termed mine dewatering, and the water product is often termed dewater or mine water. There are several options for dealing with mine water (McQuade and Riley, 1996; Water and Rivers Commission, 1999; Hall 2000). Where the water quality is adequate, mine water can be recycled or recirculated into the processing system. This is a common use for water in arid parts of the State where fresh water is at a premium and is required for the processing of ore. Chemical in-line treatment, where mine water is chemically treated to make it of a quality that is then usable in the processing cycle or at other places where water is needed is another option. Disposal of mine water to purpose-built evaporation basins requires large areas of land and permits for land clearing, as well as ongoing long term maintenance of the scale that is required for tailings and waste rock dumps. Mine water has also been used for local groundwater recharge. This option involves difficult and costly engineering solutions and the environmental consequences of groundwater recharge are not yet fully understood. Some mining operations can provide their mine water to a neighbouring site for reuse. Mine water can be used for irrigation, particularly of mine waste dump rehabilitation projects. Mine water is frequently used for dust suppression on haul roads, even when the water is hypersaline (Bertuch 2002), and finally direct discharge to nearby wetlands is also an option.

With the widespread occurrence of salt lakes in the semi-arid and arid regions of Western Australia, disposal of mine water to such lakes has become common practice (WRC, DME & DEP 1999; Ward 2002). Some recent examples of mine water disposal to salt lakes include: discharge from Kundana Gold Mine to White Flag Lake, 25km WNW of Kalgoorlie (licensed for 480,000 $m^3$/year); Placer Granny Smith Mine to Lake Carey, 20km S of Laverton (3,000,000 $m^3$/year); St Ives Gold Mines to Lake Lefroy, 7km SE of Kambalda (4,500,000 $m^3$/year); and Jubilee Mines NL Cosmos Nickel Mine to Lake Miranda, 30km NW of Leinster (1,300,000 $m^3$/year; Finucane *et al*. 2002).

Any disposal of water to the environment requires a licence upon approval from the Department of Environmental Protection. Licenses are typically issued on the proviso that annual environmental reports are submitted showing results of monitoring of both the discharge water and the receiving environment (Ward 2002). The licensee is obliged to show that mine dewatering discharges are "being managed in such a way as to prevent any environmental impacts", however in the report the licensee is asked to discuss the "impact of alteration of the receiving environment, especially with respect to the impacts on existing ecosystems", implying that some level of impact is inevitable and also acceptable (DEP Licence number 7362/4). At no point, however, is an acceptable level of impact defined. The Water Quality Protection Guidelines for Mining and Mineral Processing – Mine Dewatering (WRC, DME & DEP 1999) includes criteria to help decide whether to accept or reject an application to discharge mine water to an existing water body. These guidelines assume that the receiving environment has surface water, and it is the potential to impact upon surface water quality that is assessed in these guidelines. No such guidelines exist for assessing a possible impact to other characteristics of the receiving environment, e.g. aquatic flora and fauna, and terrestrial flora and fauna.

Before an impact can be evaluated as being acceptable or not, it first must be detected (or rather the alternative hypothesis that there has been no impact must be rejected). Detection of environmental impacts is rarely easy and involves appropriate design of monitoring programs (Underwood 1997). This is particularly the case for salt lakes in arid environments as the high to extreme rainfall variability means dramatic changes to the physical environment and biota are highly likely to occur over time. This paper outlines the design and results of a monitoring program which aimed to detect impacts of mine water discharge into Lake Austin from the Cuddingwarra prospect. In doing so the issue of appropriate design and implementation of monitoring programs to detect impacts from discharge is discussed.

## History & background

A new gold mine was commissioned at Cuddingwarra (located between Cue and Big Bell in the Murchison district of Western Australia) in 1999 to provide supplementary ore to the nearby gold extraction facilities at Big Bell. Constant dewatering of the mine pit has been required at Cuddingwarra due to shallow groundwater. Environmental approval was obtained to discharge this hypersaline water into the northern end of Lake Austin, an extremely large, flat and mostly unvegetated salt lake. The various licences to discharge this water into the lake issued by the then Department of Environmental Protection has allowed up to 6000 kL/day (or 180,000 kL/month) of water between 100,000 to 130,000 mg/L total dissolved solids. Actual discharge commenced in May 1999 and continued at a rate of between 3000-5000 kL /day (averaging 4200 KL/day) until early 2002 (Figure 1) after which discharge volumes declined as mining activities were scaled back. From October 2002 discharge to Lake Austin ceased in favour of disposal to mine pits at Cuddingwarra. Total dissolved solids of the discharge have averaged 112,000 mg/L, with electrical conductivity averaging around 150 mS/cm (Table 1). Monitoring has been a condition of environmental approvals – this has included three surveys by the Centre for Ecosystem Management at ECU. The first in September 1998 was to record baseline (pre-discharge) data and establish monitoring plots and protocols for both fringing vegetation and aquatic biota (Horwitz *et al.* 1999); the second was to monitor any changes some 14 months following commencement of discharge (van Etten *et al.* 2000); and the last, conducted during April 2002, recorded changes some 3 years following commencement of discharge (van Etten & Vellekoop 2002). In addition to these studies two honours projects have been completed, one on aquatic biota of the lake bed (Harkins 2001) and the other on fringing vegetation dynamics and impacts (Vellekoop 2002). This paper concentrates on the detection of impacts on the fringing vegetation and soils of Lake Austin resulting from the discharge.

Due to concerns expressed in the first post-discharge monitoring report (van Etten *et al.* 2000) that discharge was potentially damaging fringing vegetation and preferentially entering adjacent inlet channels, the pipeline was extended in March 2000 from the lake edge some 600 m out onto the lake-bed. This was to encourage discharge flow towards the middle of the lake. In February 2001, floodwaters moved the pipeline several hundred metres so that it again discharged close to the fringing vegetation. The pipeline was secured back into its original location on around August of 2001.

## Rainfall, hydrology and lake levels

Monthly rainfall for Cue, located some 25 km east of the discharge point, is shown in Figure 2 for the period January 1996 to August 2002. This graph illustrates the highly variable distribution of rain in this warm to hot, arid climate. It is quite common for no or negligible amounts of rain to be received in any given month. In contrast, monthly rainfall several times the average is also a regular feature; this occurred in: June and July of 1996; February, April and August of 1997; May, July, August & December of 1998; March & December of 1999; and January, March and April of 2000. Overall, 1700 mm of rain was received between December 1995 and June 2000 which is 37% above the average expected for this period. The period between December 1999 and April 2000, which saw a number of cyclonic, low pressure systems move inland from the north-west coast, was clearly the wettest 5 months of recent times. Since the flood of 2000, above rainfall was received during January-February 2001 and October 2001, with most other months receiving below average rain. Summer and autumn of 2002 were particularly dry. In summary, monitoring has been conducted across both fluvial and drought periods.

Little is known of the hydrology of the lake and no detailed measurement of lake levels has occurred. It is known that the lake is usually dry, but fills in response to large rainfall episodes in the surrounding catchment.

**Table 1:** **Chemical attributes of the discharge water from April 2000 to May 2002 (Data courtesy of Harmony Gold Pty Ltd).**

| *Date* | *PH* | *EC* | *TDS* | *Mg* | *Na* | *K* | *Ca* | *Cl* | $CO_3$ | $HCO_3$ | $SO_4$ | *Pb* | *Cu* | *Zn* | *Mn* | *As* | *Fe* | *Cd* | *Si* | *F* | $NO_3$ | $NO_2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *mS/cm* | *mg/L* | | | | | | | | | | | | | | | | | | | |
| 14-4-00 | 6.85 | 126 | 181000 | 265 | 29000 | 950 | | 54000 | | | 16000 | | | | | | | | | | | |
| 5-7-00 | 7.20 | 126 | 120000 | 4100 | 33000 | 970 | 740 | 59000 | <1 | 24 | 16000 | <0.001 | 0.1 | 0.11 | 0.51 | | 2.2 | <0.001 | 9 | | 100 | |
| 7-1-01 | 7.20 | 118 | 108000 | 6200 | 28000 | 710 | 640 | 51000 | <1 | 250 | | <0.001 | 0.13 | 0.07 | 0.7 | <0.001 | 0.08 | | 4 | 0.2 | 120 | <0.1 |
| 14-1-01 | 7.25 | 116 | 106000 | 4000 | 31000 | 750 | 830 | 51000 | <1 | 250 | 18000 | <0.001 | 0.02 | <0.01 | 0.44 | <0.001 | <0.01 | <0.001 | 15 | 0.2 | | |
| 1-2-01 | 7.50 | 120 | 110000 | 4200 | 33000 | 770 | 890 | 51000 | <1 | 250 | 12000 | <0.001 | <0.01 | 0.07 | 0.33 | <0.001 | 0.3 | <0.001 | 15 | 0.2 | 68 | <0.1 |
| 19-4-01 | 7.10 | 120 | 110000 | 3800 | 28000 | 750 | 820 | 52000 | <1 | 250 | 1000 | <0.001 | 0.03 | 0.05 | 0.47 | <0.001 | 0.36 | <0.001 | 15 | 0.2 | 91 | <0.1 |
| 16-8-01 | 7.15 | 122 | 120000 | 3800 | 33000 | 510 | 860 | 47000 | <1 | 240 | 12000 | <0.001 | 0.06 | 0.06 | 0.61 | <0.001 | 0.12 | <0.001 | 14 | | 85 | <0.1 |
| 13-11-01 | 7.00 | 104 | 104000 | 3600 | 25000 | 460 | 720 | 50000 | <1 | 200 | 6300 | <0.001 | 0.1 | 0.3 | 0.1 | <0.001 | 0.1 | 0.03 | 20 | 0.2 | 38 | <0.1 |
| 14-2-02 | 7.20 | 112 | 119000 | 3800 | 29000 | 670 | 770 | 48000 | <1 | 220 | 13000 | <0.001 | <0.1 | 0.7 | 0.6 | <0.001 | <0.1 | <0.001 | <20 | <0.1 | 62 | <0.1 |
| 22-5-02 | 6.70 | 128 | 98000 | 4730 | 36000 | 1020 | 903 | | <2 | 201 | | <0.050 | 0.07 | 0.073 | | | 0.59 | <0.050 | 9.3 | | | |

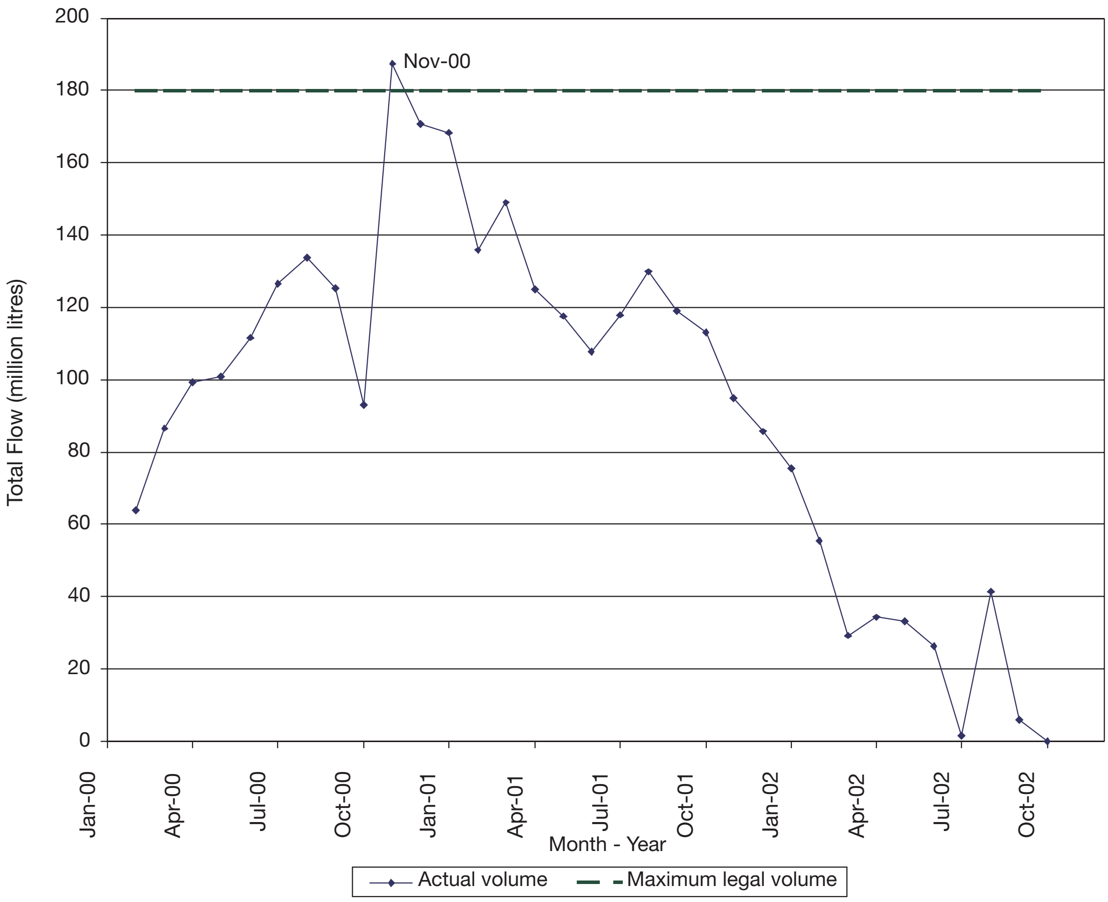
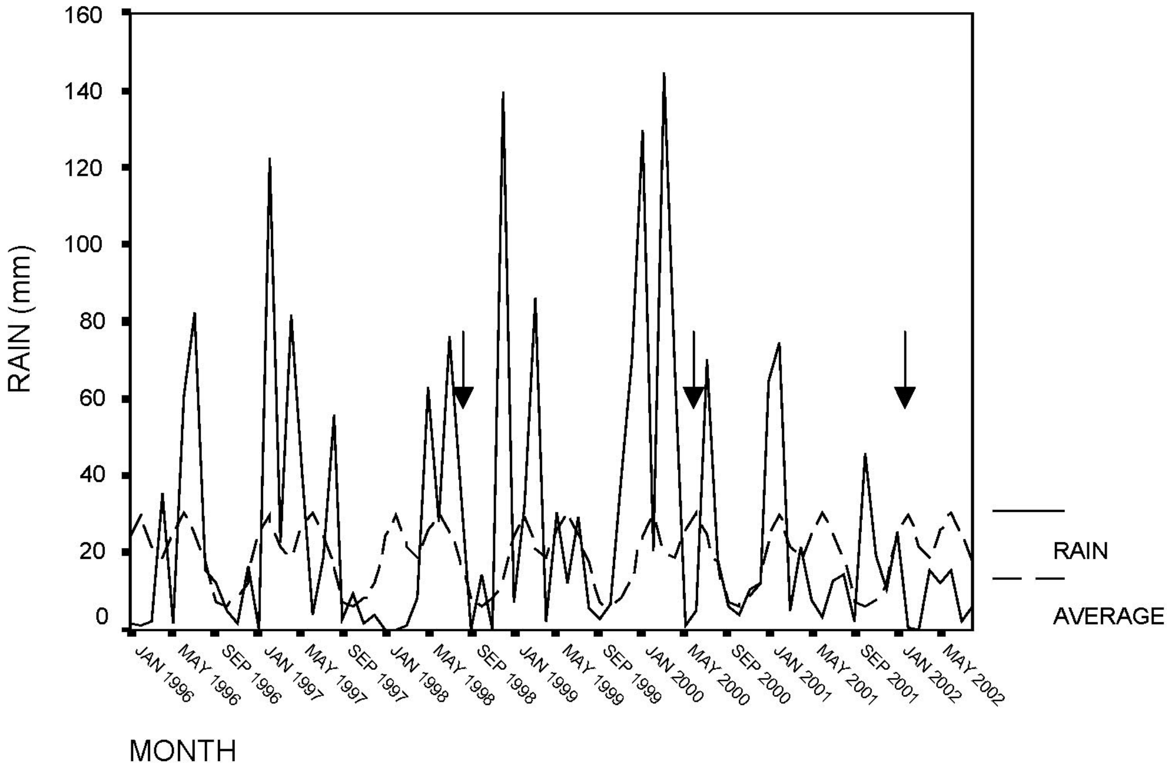



*Figure 1:* *Monthly discharge volumes from the Cuddingwarra mines to Lake Austin from February 2000 to October 2002. Actual monthly volumes shown in solid line with maximum monthly limit in broken line.*

*Figure 2: Monthly rainfall for Cue from January 1996 to August 2002 (solid line). Monthly averages are also shown (broken line). Arrows indicate monitoring dates.*



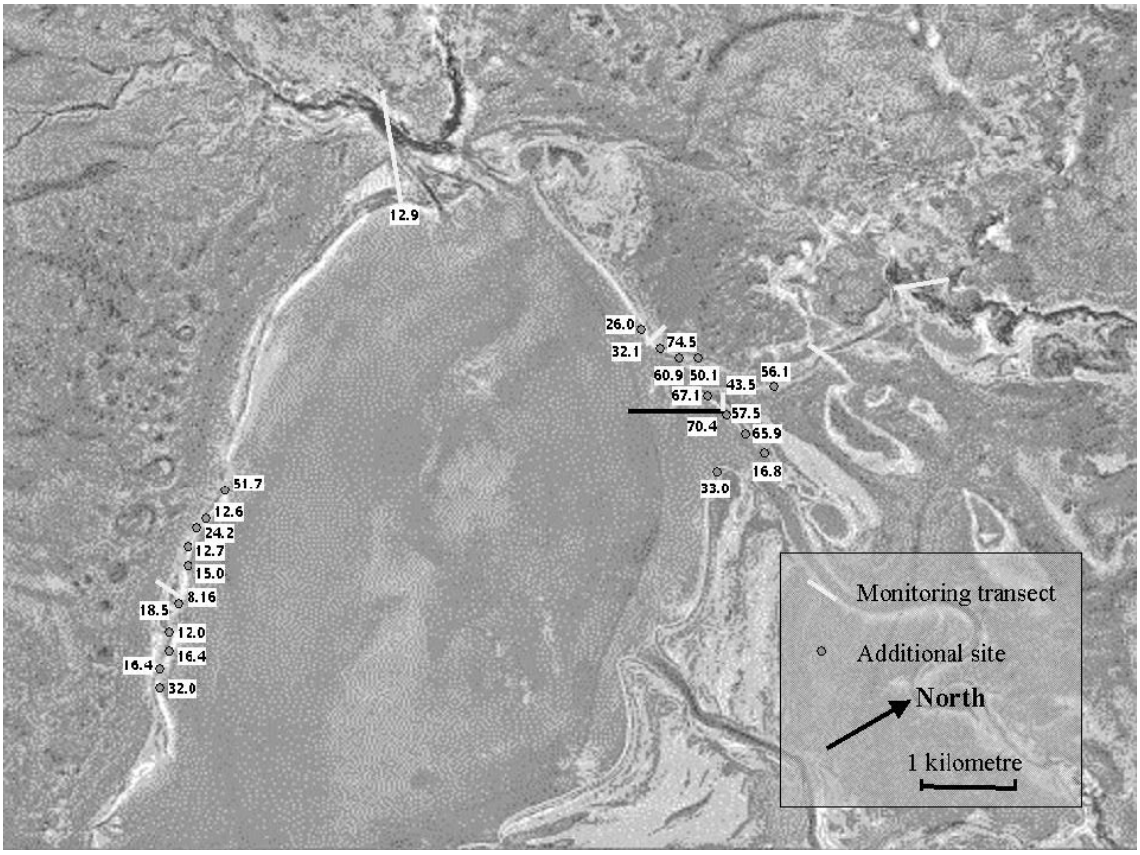

To what degree water entering the lake is derived from surface run-off via drainage lines, as opposed to surface expression of rising groundwater, is unknown. The Lake Austin catchment is known to be endorheic – that is it represents an internal drainage system with Lake Austin, being at the lowest point in the catchment, the ultimate source of much of the surface drainage and groundwater discharge (Curry *et al.* 1994). The size of the catchment is approximately 13,750 $km^2$.

At the time of the initial (baseline) survey in September 1998, the lake contained a reasonable amount of water, contributed by above average rainfall during winter of that year, but was not near full. Lake levels remained below fringing salt-marsh vegetation. The substantial summer-autumn rains of 1999/2000 contributed to extremely high lake levels which inundated much of the lower parts of the fringing vegetation around the lake and inlet channels. At the time of the June 2000 survey, the edges of fringing vegetation were still flooded in many places although the floodwaters had receded from their peak of April that year by several centimetres (A. Wilkeis, pers. comm.). Lake levels have gradually receded since the flood of 2000 through evaporation with below average rainfall since the flood meaning little recharge of lake water. During March 2001, there were some discrete ponds of water remaining on the lake bed, but at the time of the final monitoring trip (April 2002), water remained only in the deeper drainage lines entering the lake and in the area immediately around the discharge point. Monitoring has therefore occurred across a marked pluvial – drought transition and any concomitant changes in vegetation and physical environment need to be incorporated into any assessment of impacts arising from discharge.

## METHODS

During September 1998 (before commencement of discharge), 33 permanent monitoring sites were established and measured along seven transects placed more or less perpendicular to the shore-line from lake bed to dune systems above fringing salt-marsh. Four of these transects were located close to the discharge point, two leading from the lake-bed, and two across the major inlet channel which enters the lake near the discharge point. These were referred to as 'discharge' sites, as they were deemed likely to be impacted by discharge waters at the time of baseline survey. The other three transects were located some distance from the mine discharge point, one across an inlet channel several kilometres to the north-east of the discharge point, and the other two on the other side of the lake (over 10 km in distance). These were known as 'non-discharge' sites and were designed to act as controls (the adequacy of these sites as 'controls' and the monitoring design as a whole are critically evaluated in the discussion). Transect locations are shown in Figure 3, together with extra sampling points conducted in April and May 2002.

*Figure 3: Location of discharge pipe (black line) and permanent monitoring transects (white lines) (NB one 'control' transect not shown as it is located some 5 km to the south). Also shown are topsoil EC values (mS/cm) at extra sampling sites established May 2002 in fringing* Halosarcia frimbriata *community.*




Along each transect, sites were located each time there was a noticeable change in dominant species. At each site, a jarrah or metal picket was hammered into the ground on the transect line and its location calculated using a GPS with distance and compass angle between each site also recorded to enable relocation of monitoring plots. At each monitoring site, a 10 x 5m plot was measured out by placing a line 5m either side of the jarrah picket (ie transverse to the direction of the transect) and then 5 m along the direction of the transect. Within each plot the percentage cover and abundance (ie no. of individual plants) of all species of trees and tall to medium sized shrubs was measured. Three randomly placed 1m$^2$ quadrats within the plot were used to estimate the cover and abundance of low shrubs and herbaceous species. Three specimens of each of the dominant trees and shrubs within each plot were selected for monitoring and tagged with an aluminium label tied around one of the main branches. Each of these plants was then measured in terms of height, crown/shrub width (along the direction of the transect) and the percentage of the plant volume which was living and healthy. The location of each of the plants was recorded onto maps of each plot to enable them to be relocated. At least one photograph was taken of each monitoring plot.

At each 20m along transects, the slope angle was measured with a clinometer to enable a topographic profile to be constructed. At each monitoring plot, the pH was measured using a CSIRO field kit and, at three to five random points, soil samples were taken of the surface soil (top 1cm) and the topsoil (between 1-4cm depth). These samples were consolidated for each of the two layers. In the lab, the conductivity and pH of the soils was determined using appropriate probes placed into a 1:5 soil to deionised water solution. The particle size distribution of these soils was also determined following sieving.

Sites were re-measured in June 2000 and April 2002. This included the measurement of vegetation characteristics, soil parameters and tagged plants within permanent plots. For each plant and soil variable, a two-way ANOVA was performed with factors being time (3 monitoring visits) and zone (discharge vs. non-discharge groups of sites). Significant interactions between time and zone demonstrate an impact due to discharge (1997). Change in condition of each variable as a proportion of baseline (September 1998) was calculated, as well as change between 2000 and 2002. Statistical tests (one way ANOVA) to compare the average change in the impact zone to that in the control zone were then performed. Significant differences, it was argued, indicated either positive or negative impact due to discharge.

The underlying assumption here is that the discharge of large volumes of hypersaline water leads to greater water volumes and water/soil salinity in the area immediately surrounding the discharge point than elsewhere. Discharge water has been observed to persist close to the drainage point when the lake is dry or contains small amounts of water; it has also been observed to move up the adjacent major inlet channel under certain wind directions. Data was tested for normality and homogeneity of variances, with appropriate corrections made if these were not demonstrated.

## RESULTS

### Changes in species composition

#### Spatial changes

Classification and ordination of study sites demonstrated that five reasonably distinct plant communities are found in the northern part of Lake Austin. These are:

1. *Acacia sclerosperma – Eremophila miniata* woodland on sandy dune systems;
2. Mixed chenopod low shrubland on raised banks;
3. *Halosarcia pruinosa – Sclerostegia tenuis* saltmarsh on low lying saline plains adjacent to inlet channels;
4. *Halosarcia halocnemoides* saltmarsh on crests and upper slopes of fringing banks;
5. *Halosarcia fimbriata* saltmarsh on lower slopes of fringing banks.

With the exception of community 3 which occurred on highly alkaline clays on flats either side of drainage lines entering the lake, the other communities formed reasonably distinct zones parallel to the shoreline of the lake. Community 5 occurs in the lowest lying areas of the lake shoreline and lower slopes of the small bank which fringes most of the lake. This community was extensively flooded during early 2000 and has highly saline (EC of 10-20 mS/cm) and very fine clay topsoil. This community gives way to community 4 on the slopes and crests of the banks where soils are appreciably sandier and less saline (EC < 1 mS/cm), with community 2 and 1 on higher ground. In summary, the pattern and gradient analyses demonstrate that subtle changes in micro-relief in areas fringing the lake and inlet channels have a marked influence on the species composition and distribution of communities. The lowest lying areas are prone to regular waterlogging and infrequent flooding by saline waters; these sites have exceedingly high soil salinities and a flora presumably adapted to surviving these extremes. However areas which are slightly higher than (i.e. raised by even 10-20 cm) have different species, particularly in terms of the dominant samphires. This is most likely because the extremes in terms of salinity and waterlogging are considerably lower.

Low lying community 5 is the most likely to come into direct contact with discharge waters due to its low-lying nature and susceptibility to flooding; analysis therefore concentrated on this community and its dominant species *Halosarcia fimbriata*, although communities 3 and 4 were also analysed for impacts given their proximity to the lakebed and floodwaters.

The dominant species of fringing communities are samphires - species of *Halosarcia, Sclerostegia, Tecticornia* and other salt-tolerant succulents of the tribe *Salicornieae* within the family Chenopodeaceae. These species are notoriously difficult to identify due to such things as: 1) lack of characters on which to base classification and identification; 2) small size and general unavailability of flowering and fruiting parts; 3) phenotypic plasticity, especially in response to rainfall in the months previous to sampling; 4) extensive hydridisation between species; 5) variation within species (with many subspecies, varieties and forms recognised); 6) difficulty in pressing and preserving specimens; and 7) lack of taxonomic work for some of the species groups. These genera are, not surprisingly, considered to be taxonomically difficult. This warranted a taxonomic review of species and confirmation of identifications by Paul Wilson of the WA Herbarium (now retired but regarded as the world authority on the *Salicornieae*).

#### Temporal change

Major changes in the richness and composition of plant species occurred across three years of monitoring period. Most of this change has been in terms of annuals and short-lived perennials, rather than woody perennials which have remained highly consistent. Daisies (family Asteraceae) dominated the short-lived flora during September 1988, whereas grasses (family Poaceae) were the most common component in June 2000. This is to be expected as September 1988 followed good winter rains, whereas the sampling in 2000 followed extremely high summer and autumn rains (Figure 1). Compositional differences in the short-lived flora in response to amount and season of rainfall are well known for arid areas. The below average rainfall of 2001-2 resulted in little or no annual flora present in monitoring plots in April 2002, which contrasts with previous visits. Many short-lived perennials, which were present on previous monitoring visits, were also no longer evident at sites. Although species changes across the study area were profound, when looking within the five plant communities, no differences in species richness and composition were found between discharge and non-discharge sites.

**Table 2: Results of two-way ANOVA showing F values, observed power in parentheses, and levels of probability of a type I error ( *** denotes p<0.001, ** denotes p<0.01, * denotes p< 0.05). # denotes p<0.05 for Levene's test of equality of error variances.**

| Parameter | | Time *F* value | Zone (*F* value) | Time X Zone Interaction (*F* value) |
|---|---|---|---|---|
| *H. fimbriata* | Height | 0.5 (.13) | 0.7 (.13) | 0.3 (.54) |
| | Width | 0.1 (.06) | 2.6 (.35) | 0.1 (.61) |
| | Health | 5.5 (.80) ** | 0.1 (.06) | 0.1 (.06) |
| | Cover | 0.8 (.17) | 0.04 (.05) | 0.03 (.05) |
| | Abundance | 0.3 (.09) | 1.1 (.18) | 0.5 (.12) |
| *H. halocnemoides* (form a) | Height # | 0.04 (.05) | 0.6 (.12) | 0.01 (.05) |
| | Width | 0.3 (.09) | 2.7 (.35) | 0.1 (.06) |
| | Health | 12.6 (.99) *** | 2.4 (.32) | 1.5 (.29) |
| | Cover | 0.02 (.05) | 0.8 (.14) | 0.4 (.11) |
| | Abundance | 0.1 (.06) | 5.5 (.61)* | 0.5 (.12) |
| *H. pruinosa* (form a) | Height # | 0.5 (.11) | 2.4 (.28) | 0.6 (.13) |
| | Width # | 0.05 (.06) | 1.1 (.15) | 0.1 (.06) |
| | Health | 0.05 (.05) | 3.4 (.38) | 0.02 (.05) |
| | Cover | 0.2 (.07) | 6.8 (.64)* | 0.06 (.06) |
| | Abundance | 0.04 (.05) | 9.0 (.76)* | 0.1 (.06) |
| Soil electrical conductivity | All sites # | 3.6 (.65)* | 0.1 (.07) | 0.25 (.05) |
| | Fringing sites | 4.3 (.70)* | 1.1 (.17) | 0.7 (.16) |
| Soil pH | All sites # | 16.6 (1.0)*** | 5.9 (.67)* | 2.9 (.56) |
| | Fringing sites | 4.4 (.70)* | 4.3 (.50) | 4.3 (.68)* |

## Analysis of BACI design

The standard statistical analysis for Before – After – Control – Impact (BACI) experiments are two-way ANOVA with time ('before' vs 'after') and zone ('impact' vs 'control') being the two factors (Underwood 1999). Statistically significant interactions between time and zone are of interest here as they disprove beyond a reasonable doubt (here less than 5% chance) that there has been no impact due to an experimentally imposed treatment, and that therefore we should accept an impact due to treatment has occurred over time. In our case, time refers to the time of each monitoring study, zone refers to either the discharge area or areas distant from it, and the treatment is the discharge.

With one exception, there were no statistically significant interactions between time and zone (Table 2), demonstrating that almost none of the changes in vegetation and soil parameters measured over time could be attributable to discharge. The exception was for soil pH in fringing vegetation communities which was significantly different between discharge and non-discharge zones over time. Several parameters not surprisingly showed significant differences over time alone (such as health of *H. fimbriata* and *H. halocnemoides* (form 'a'), and soil pH and conductivity; Table 2), whilst others showed significant differences between zone only (eg abundance of *H. halocnemoides* (form 'a'), cover and abundance of *H. pruinosa* and soil pH; Table 2).

To explore actual trends and degrees of change, the mean change in soil and vegetation parameters over time are compared between discharge zone and non-discharge zone in the next three sections.

## Change in vegetation structure

No significant difference was found in the change to cover and abundance of perennial species between 'discharge' and 'non-discharge' sites for both periods 1998-2002 and 2000-2002. This is despite the fact that mean cover increased by around 5% (relative to initial values) across both periods at discharge sites compared to a drop of 3-8% in non-discharge sites (Figure 4). Very high site to site variation in the degree of change at least partly explains the lack of statistically significant results. There were also no significant differences between 'discharge' and 'non-discharge' sites in the areas immediately fringing the lake and inlet channels. These fringing areas were almost completely inundated for several months in the first half of 2000. This flooding resulted in a decline in cover of perennial species at both discharge and non-discharge zones, although to a far greater degree at non-discharge sites (1-2% compared to 22-28%) although again this difference was not significant (p=~0.4). This decline in cover was in some ways compensated for by an increase in the abundance of perennial plants in these areas following inundation with the number of plants increasing by 57% in discharge zone compared to 18% in non-discharge zone across the monitoring period (t=0.41; p=0.62).

## Change in plant condition

In terms of individual plants, adequate replication was available for only three *Halosarcia* taxa. These three species dominated each of the three distinct saltmarsh communities (no.s 3 to 5 as described above) of Lake Austin and are outlined in turn.

*H. fimbriata* dominates the areas immediately fringing the lake and lower reaches of the inlet channels and other low lying areas. These areas have extremely high soil salinities (10-80 mS/cm) and were generally inundated for several months in 2000. This species seems to be very slow growing and have, in absolute terms, grown only 4-5 cm in height and less than 1 cm in width, on average, across almost four years

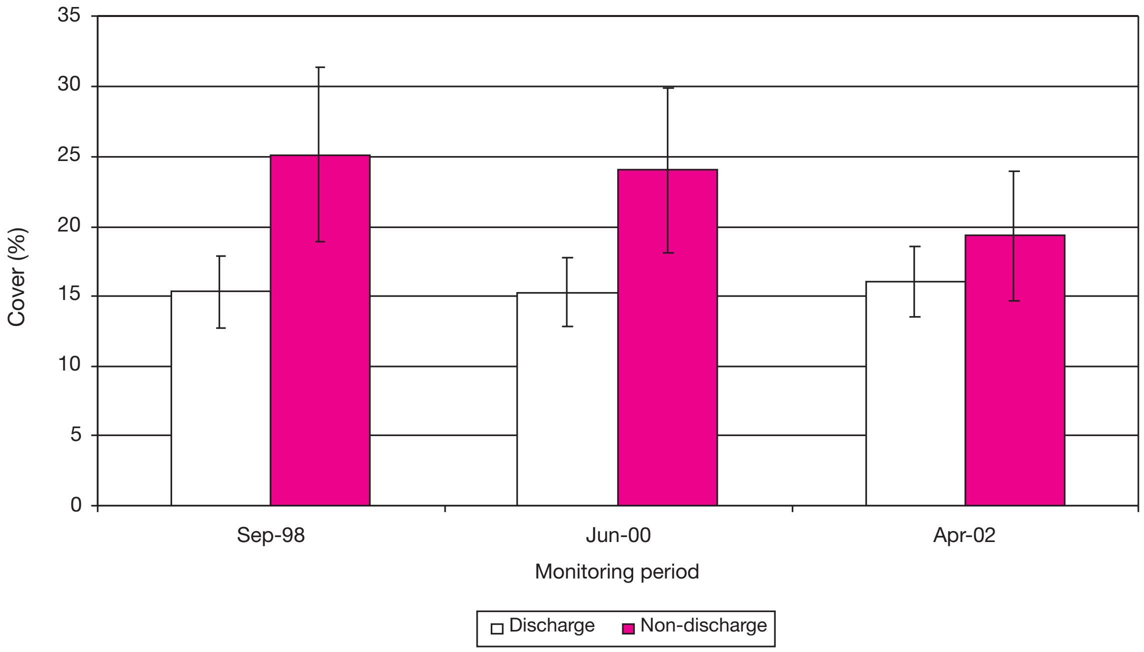



*Figure 4: Mean and standard error of perennial species cover over all sites. The change in cover between the discharge and non-discharge sites was not significantly different over time.*

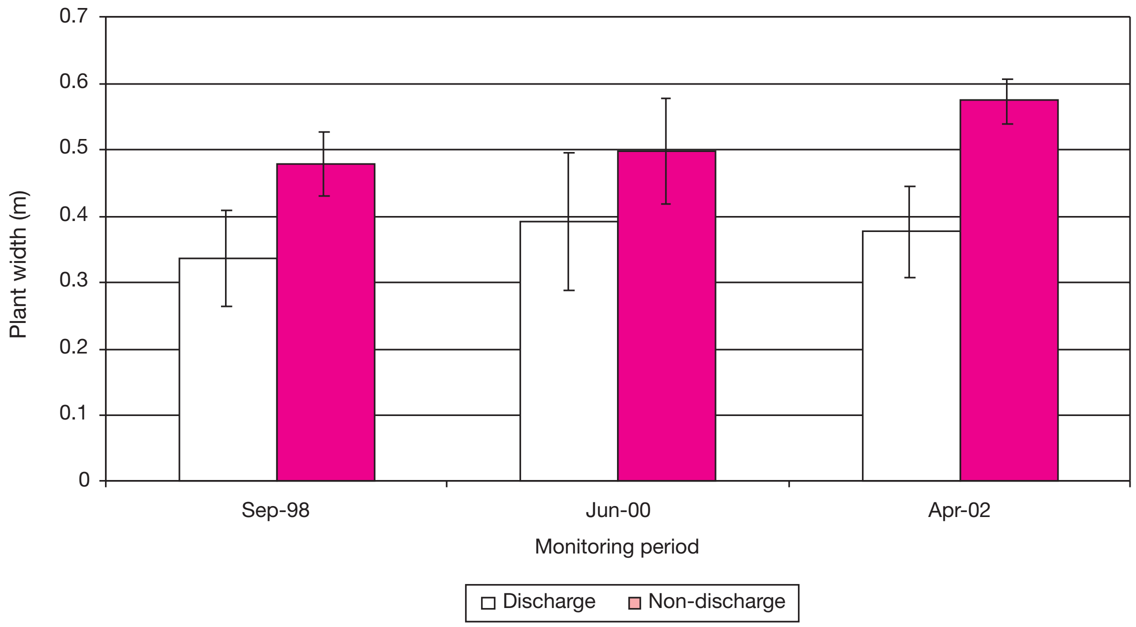



*Figure 5: Mean and standard error of absolute values of* H. fimbriata *width at 'fringing' sites. The change in width between the discharge and non-discharge sites was significantly different over the period 2000-2002 (p=.048).*

of monitoring. Relative to its initial height however this species has declined in height by around 10% on average with most of this decline occurring following the inundation in 2000. In contrast plants have, on average, increased their width by around 7% from their initial size, again mostly following inundation. Health of plants has declined overall by around 30% across both monitoring periods. Most of this change can be attributed to death and damage of growing tips following flooding (perhaps due to environmental stress and/or the smothering of plants with *Ruppia* and macro-algae) and subsequent lateral regrowth of plants. Growth however varied widely from site to site and from plant to plant. No significant differences were found in the growth and change of health of this species between discharge and non-discharge zones. However when comparing these zones in terms of sites immediately fringing the lake only, across the period 2000-2002, the mean relative growth in width within the non-discharge zone (+15.4%) was significantly greater (p=0.048) than in the discharge zone where a mean decline of 4.1% was recorded (Figure 6). The average cover of *H. fimbriata* has declined across both zones, particular following inundation, whereas the abundance of individual plants has generally increased, particularly in the discharge zone. This reflects death and dieback of plants following flooding and subsequent recruitment of new individuals. No significant difference in the change in cover and abundance across monitoring periods was detected between discharge and non-discharge zones, even when restricting the analysis to fringing lake sites only. The response in terms of recruitment and death was highly patchy across the study area, which no doubt contributed to the high standard errors measured for these parameters.

*H. halocnemoides* (form 'a') was mainly found as single-stemmed plant around 1 m high atop of the low banks fringing the lake and inlet channels. These banks mainly had coarse sandy soils of moderate salinity and were not flooded in 2000. These mostly large plants grew only by 3 cm in height on average (but highly variable) despite the above average rainfall received across much of the monitoring period. Growth was greater in the non-discharge zones compared to the discharge zone, with the mean percentage change in width of plants in the non-discharge zones (9%) significantly less than in the non-discharge zone (47%). No such difference was found for the 2000-2002 period, which suggests that the differences detected mainly relate to the period before inundation. The health of this species has declined across all monitoring periods, whilst cover has increased slightly on average in the discharge zone but decreased in the non-discharge zone (differences however are not significant).

The third taxon compared is *H. pruinosa* (form 'a'). This taxon dominates the low-lying clay flats (with their highly alkaline soils) adjacent to inlet channels. It has declined in size, health and cover from 1998 to 2002 and 2000 to 2002. No significant differences in the mean level of decline were detected between plants located in discharge zone compared to plants distant from it.

## Changes in soil parameters

The pH of the topsoil decreased following discharge to a greater degree (in both relative and absolute terms) in the non-discharge zone compared to the discharge zone (Figure

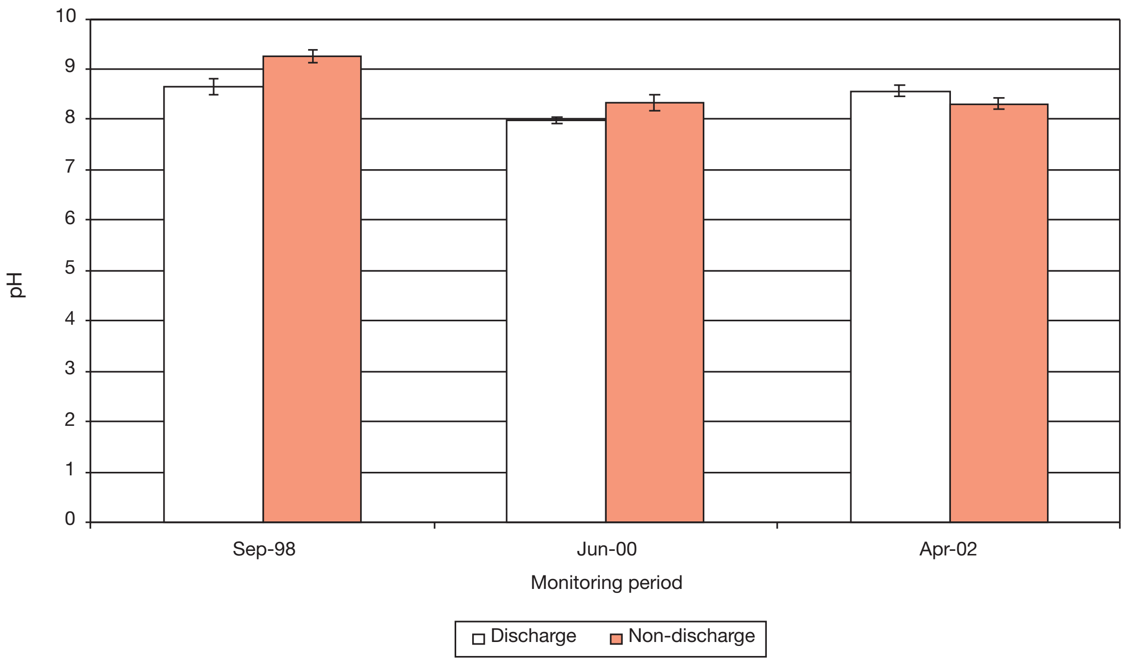



*Figure 6: Mean absolute values and standard error of soil pH. The change in pH between the discharge and non-discharge sites was significantly different over 1998-2002 and 2000-2002 (p=.006 & p=.001 respectively).*

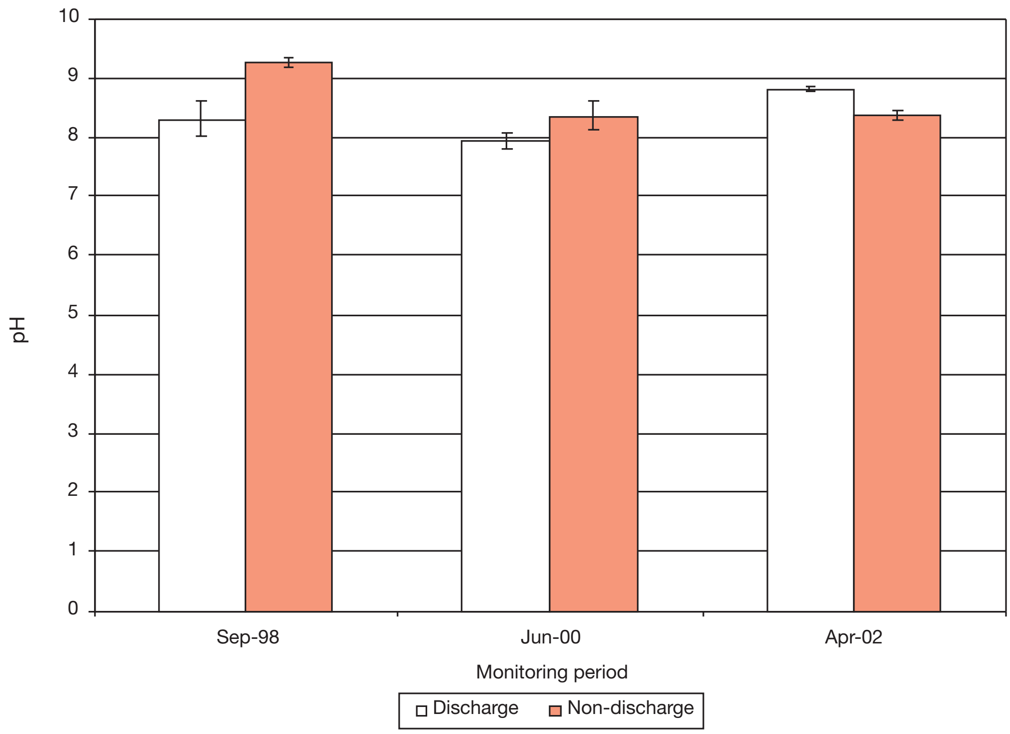



*Figure 7:* *Mean absolute values and standard error of soil pH at 'fringing' sites. The change in pH between the discharge and non-discharge sites was significantly different over 2000-2002 (p=.001).*

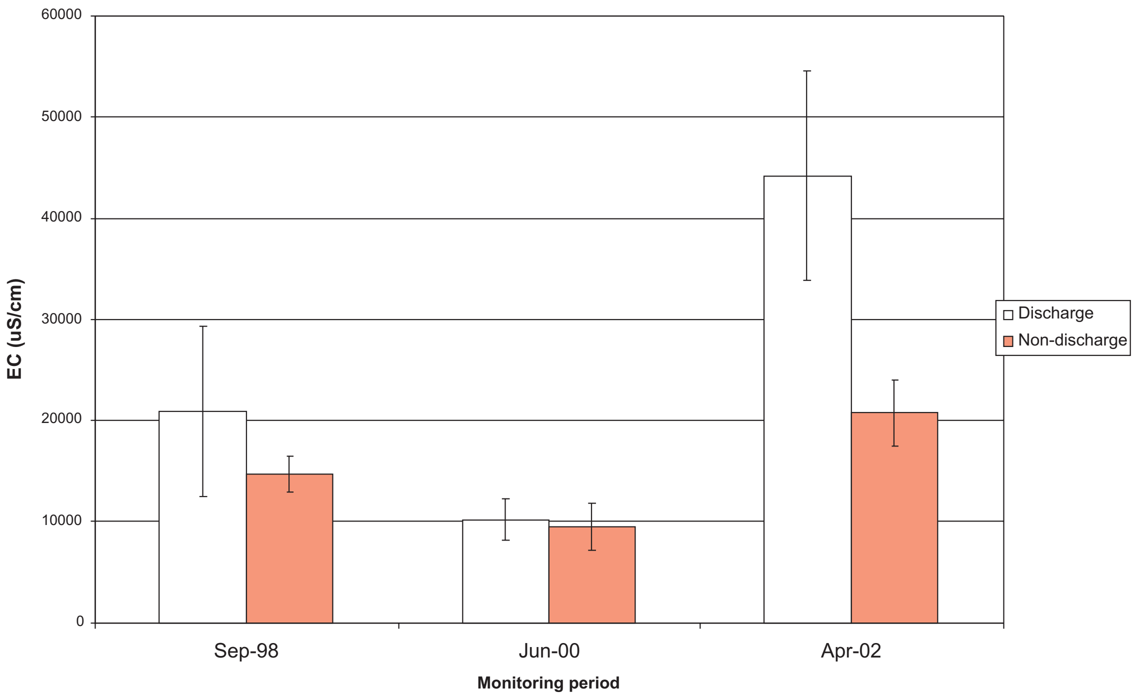



*Figure 8:* *Mean value of soil electrical conductivity at the three monitoring periods for fringing vegetation sites only. Standard errors are indicated on bars.*

6). Between 1998 and 2002, the pH declined by around 2% on average in the discharge zone, whilst in the non-discharge zone it was almost 11%; this difference was statistically significant ($t=2.9$; $p = 0.06$). Between 2000 and 2002, the pH actually increased in the discharge zone by 5% whilst it declined by almost 3% in the non-discharge zone; again this difference was significant ($t= 3.7$; $p=0.001$).

The trend in electrical conductivity (EC) over time is similar but far more pronounced than that of pH. Indeed the two factors are highly correlated to one another ($r=0.76$; $p<0.001$). However site-to-site variability in the change in EC was very high and no significant differences in the average change between discharge and non-discharge zones were found. In terms of average level of change across all sites, there was a three times increase in EC from 1998-2002, whereas it increased by almost six times in the non-discharge zone. There is no doubt that massive changes in EC recorded at two sites outside the fringing vegetation contributed to the large overall increase away from the discharge zone. Indeed when looking at fringing vegetation only, there was a 117% increase in the discharge zone on average compared to an increase of 42% in the discharge zone over the same period (Figure 8). EC values were lowest at June 2000 when much of the fringing vegetation was inundated or recently flooded. Since that time evaporation of waters has led to several fold increases in EC in both discharge and non-discharge zones. No significant difference in the degree of this change from 2000 to 2002 was found despite the discharge zone increasing to a far greater degree on average (Figure 8). Extra sampling in the fringing vegetation during May 2002 demonstrated that the EC of topsoil in the non-discharge zone was generally lower and more consistent spatially compared with that of the discharge zone (Figure 2). EC values varied widely in the fringing vegetation of the discharge zone, but were clearly higher at sampling points immediately around the discharge point (Figure 2).

Moisture of the topsoil declined from September 1998 to April 2002; this is not surprising given the substantial lower rainfall in the months preceding sampling in April 2002. The mean change in moisture content (relative to initial values) was significantly lower in the discharge zone compared to the non-discharge zone. Similarly, the decline in course particles (>2 mm) in the topsoil was significantly greater in the discharge zone (at $p=0.050$) than in the non-discharge areas.

## DISCUSSION

### Impacts due to discharge

The monitoring approach established by the Centre for Ecosystem Management was specifically designed to detect impacts (if any occurred) arising from discharge of hypersaline water into Lake Austin from the Cuddingwarra mine. Baseline (i.e. pre-impact) data was collected at several sites both from near the discharge and in a similar area around 10 km away which was envisaged would be away from the influence of the discharge waters. Two 'post-impact' monitoring studies were done, the latest, in April 2002, occurred some 3 years following discharge commencement. The design therefore followed widely accepted BACI design principles for detecting impact. Despite the best of intentions when the design was established before commencement of discharge, two events occurred during the discharge phase that would make it less likely that impact would occur in the vegetation surrounding the lake. The first of these was the extension of the pipeline some 600 m from the lake edge which effectively moved the discharge away from the fringing vegetation (at least most of time). The second was the flooding event of 2000 which substantially decreased and homogenised salt levels in the water around the discharge point for a period of at least several months. Despite the decreased likelihood of impacts being detected, as previously argued, investigation of any impacts were still warranted.

An impact of discharge was detected in soil properties of the lake edge. Since the recession of floodwaters from June 2000, the topsoil pH of the fringing vegetation has increased by 10% in the area close to the discharge point which was significantly more so than in areas distant from it (0.2% increase). Salinity of the topsoil in these areas has shown a similar trend and although differences were not statistically significant, it is obvious that certain sites close to the discharge point have increased substantially in salinity, and, overall, topsoil salinity is currently much higher in areas close to discharge than in areas remote from it. As pH is strongly related to salinity levels of the soil, it is reasonable to conclude that the hypersaline levels in the discharge water has increased salt and pH levels in the topsoil of the fringing vegetation. How then has this occurred? Firstly, since the recession of floodwaters, it is possible that discharge water has spread up to fringing vegetation nearest to the discharge pipe, particularly at times of high discharge volumes. Indeed observations of salt scalds on the surface of the lake at April 2002, both on the ground and from the air, support this contention. In addition the movement of the pipe by incoming floodwaters from the inlet channel in early 2001 moved the pipe to a position quite close to fringing vegetation. The second possibility is that accumulation of salt which occurred in the fringing vegetation prior to the pipe extension in March 2000 is still persisting to at least some degree. Although it would be expected that this added salt would have been brought into solution when flooded, perhaps deeper stored salt would have not and has since risen in response to evaporative rise.

There is little evidence that this enhanced salt loading of fringing soils close to the discharge point has led to an impact on the vegetation of this area. Although the change in width of the dominant fringing species *Halosarcia* *fimbriata* was significantly less in the discharge zone compared to the non-discharge zone over the period 2000-2002, the fact the probability level of this being true is close to the 95% confidence limit, and the fact that other parameters and other time periods measured for this species did not reveal significant differences, suggests caution in attributing decline in this species to discharge. *H. halocnemoides* (form 'a'), which dominates the small levee banks surrounding much of the lake, grew significantly less in areas close to discharge compared to areas distant from this for the period September 1998- June 2000. Given this species has not been in direct contact with discharge water, it is difficult to attribute discharge as the reason for the difference. Salt spray is one possibility, but it is more likely that some other difference in disturbance (such as grazing intensity) or in the physical environment (such as depth to groundwater) across zones may be occurring. Non-discharge sites were located on a different pastoral station to that of the discharge sites.

There are a number of possible reasons why impact on the fringing vegetation was not conclusively demonstrated despite the increases in soil salinity around the discharge point. The first is that, as salt tolerant plants, *Halosarcia* and *Sclerostegia* spp. may be withstanding the effects of increased soil salinity and pH. The fringing species *H. fimbriata* typically grows in soil where the surface EC is some 10-20 mS/cm, with values of up to 50 mS/cm recorded before commencement of discharge. These levels of soil salinity are typically 2 to 3 orders of magnitude higher than other salt marsh communities on slightly higher ground. This species is therefore in a league of its own in terms of salinity tolerance and it is not unexpected that it may be able to withstand and grow at elevated levels of salt (the highest recorded EC in April 2002 was 75 mS/cm). A range of annual plant species have been found in the fringing community on previous visits (Horwitz *et al.* 1999; van Etten *et al.* 2000), but were absent in April 2002 due to lack of preceding rains. These species may be more sensitive to increased salt levels and it is recommended that monitoring following substantial rainfall episodes be conducted to gauge the impact on these species.

Although no impact on adult plants were detected, it is possible that the effects of increased salt levels may arise sometime in the future, particularly on other stages of the life-cycle. It is likely that *Halosarcia* spp. are more sensitive to salt at the seed germination and seedling stages. Vellekoop (2002) demonstrated, using glasshouse flooding experiments, that *H. fimbriata* requires a period of flooding with fresh to brackish water to stimulate germination from the soil store and for recruitment of new individuals. This was supported by field observations which showed ample seedling recruitment, primarily of *H. fimbriata*, as the floodwaters of 2000 receded. Despite being extremely patchy, no difference in seedling recruitment was found between discharge and non-discharge zones, as measured from both the field and flooding experiments, demonstrating that enhanced salt levels at points close to the discharge have yet to impact on the potential for seedling recruitment. Observations of seedling survivorship as at April/May 2002 however show that, where recruitment of *H. fimbriata* on the shoreline has been substantial, more seedlings were dead than alive at sites of enhanced soil salinity (i.e. >30 mS/cm) near the discharge point, whereas in areas of lower salinity further away from the discharge point, the opposite trend occurred (difference in ratio of dead to alive seedling abundance was significant using Mann-Whitney U-test; $z=-2.2$; $p=0.03$). Enhanced salt levels seem therefore to be impacting on the survivorship of the seedlings. The study by Vellekoop (2002) also showed that recruitment only occurs when floodwater salinity is less than around 60 mS/cm. As discharge water is around 120 mS/cm in salinity, this suggests that direct inundation by discharge water or where salt from discharge waters have raised salinity levels of lake water, recruitment is unlikely to occur. Fortunately, for extensive areas of fringing vegetation to be inundated, the lake needs to be full, an uncommon phenomena only occurring after sustained high rainfall. Salinity levels at these times are typically around 30 mS/cm (van Etten *et al.* 2000) and the massive volumes of water in the lake mean discharge waters are effectively diluted and dispersed.

Lack of statistical power is another reason why impacts may not have been detected in this study. Post-hoc power tests routinely showed that there was a high probability that significant differences could not be detected, assuming of course they exist (eg Table 2). This was generally due to sampling intensity not being great enough to counter the high variability in many of the parameters measured. In particular, the degree of change in vegetation characteristics and soil parameters like EC demonstrated huge spatial variability, even within plant communities. Power tests (Table 2) reveal that the sampling effort required to detect impacts on fringing communities, if they indeed exist, is in the order of 50-150 sites (depending on the parameter). This contrasts with the 10 monitoring sites established in the fringing community. It is extremely difficult to estimate, pre-impact, the sampling effort required, especially given that a pilot study was not feasible. The findings however have implications for future BACI type monitoring of salt-lakes subject to saline discharge, at Lake Austin and elsewhere.

In summary, the monitoring program conducted over the last four years has revealed that, in areas close to the discharge point, the salinity and pH of the topsoil have been raised, presumably because discharge waters have at times been in contact with or close to fringing vegetation of these areas. This enhanced salt level seems to be having a detrimental impact on the survivorship of seedlings, but otherwise no impacts were detected on soil seed store, recruitment potential, health and size of the main fringing species, *H. fimbriata*. Impacts may occur some time in the future however as Lake Austin is widely believed to be an enclosed drainage system. The half a million tonnes or so of extra salt deposited in the lake system through discharge should in many ways be regarded as a long-term addition to the system. As it did during the floods of 2000, much of this extra salt becomes dissolved during flood events and, given the huge volumes of water at these times, is diluted to a level where it makes only a marginal contribution to total water salinity. However, in contrast to what was anticipated, the deposition of salt as the floodwaters evaporate and recede is not even across the lake-bed. Waters drain to the lowest points in the system which, somewhat counter-intuitively, were observed mainly to be inlet channels. It is only then that waters become saturated with salt and deposition occurs. The fact that inlet channels now contain deposits of crystalline salt up to one metre in depth means that the first large flows into the lake following the end of drought periods are likely to be very high in salinity. The build up of salt in drainage lines is also likely to be a concern for aquatic biota and fringing vegetation in these areas.

## Dynamics of fringing vegetation

The fact that monitoring has occurred over both a flood and drought period has been fortuitous in that it has enabled measurements and observations of profound changes in the vegetation. Arid environments of inland Australia are known for their exceptional variability, particular in the temporal variability in rainfall, which, in turn, drives dramatic changes in the physical environment and the biota. Rainfall episodes substantial enough to flood the fringing vegetation around inland salt lakes like Lake Austin only occur once every decade or so on average. The monitoring around Lake Austin has shown that flooding resulted in substantial death and damage to perennial shrubs (particularly *Halosarcia fimbriata*) due most likely to a combination of several weeks/months of inundation and smothering by macroalgae and *Ruppia* (an aquatic monocot), with smaller plants and those closer to the lakebed impacted upon to a greater degree due to greater length and depth of inundation. Seed germination and recruitment of new *Halosarcia* individuals was substantial although patchy as floodwaters receded, an event not observed in the fringing vegetation on previous visits. The majority of these seedlings were surviving (although again deaths were patchy) some two years after flooding. Growth rates of seedlings differed substantially with differences observed to be linked to subtle difference in microtopography. On slightly higher ground within the fringing vegetation, groups of seedlings were 10 to 20 cm high, whereas on lower parts, seedlings less than 5 cm in size (which, co-incidentally, often showed symptoms of water-stress) were common. The height plants obtain before their next inundation is likely to play an important role in their ability to survive flood, whenever it arrives. Plants on the slightly lower slopes closer to the lake bed are less likely to survive than on higher parts of the slopes or on slight mounds due to difference in growth rates as well as in the frequency, depth and period of inundation they are likely to experience. This therefore would tend to control the position and, possibly, the density of the edge of the fringing vegetation, which would be expected to fluctuate spatially in response to the flooding regime. Substantial number of years (say 10+) between flooding events could result in an extension of the fringing vegetation toward the lake bed as plants have a chance to get to a reasonable size between floods and disperse seed further afield. By the same principle, a retraction in the edge is possible when flooding frequency is increased.

Within non-flooded saltmarsh communities on higher ground, the flood – drought transition saw a change from modest perennial species growth and high annual/short-lived species richness to a decline in the size of perennial plant species and a virtual absence of annual/short-lived species. This reflects typical temporal patterns seen in (terrestrial) arid lands in response to rainfall fluctuations.

## Implications for Management

Many lessons have been learnt whilst conducting and reporting on the monitoring program at Lake Austin. These lessons are summarised here as they should help improve both the management of and monitoring protocol for mine water disposal to salt lakes elsewhere. This is important given disposal of mine water into salt lakes is likely to remain a popular option over at least the short term.

Firstly, the design of monitoring program should subscribe, as best as practically possible, to BACI experimental design principles. Ideally this will include adequate replication both before and after the discharge, in both time and space. Spatial replication, as suggested by this study, needs to be relatively high (in the order of 30-50 sites) to enable statistical tests to be powerful enough to detect impacts as results here suggests that the response of fringing vegetation and soils to discharge water is highly variable. Therefore the emphasis should be to sample a small number of key variables extensively over many sites rather than intensive measurement of many variables at fewer sites.

Establishing control sites, albeit an integral component of such monitoring designs, is problematic for large salt lakes. Without a control, as has been the case with some salt lake monitoring, all you can show is that the system has changed. Such change, of course, is inevitable and, in an arid salt lake system, likely to be dramatic. In the absence of similar salt lakes close by, controls need to be established in similar vegetation/soil distant from the direct influence of discharge. The main problem encountered with this approach is that flooding episodes will disperse and homogenise the discharge water over most or all of the lake; however it can be argued that the discharge will also be diluted at such times to a point where its effect will be indistinguishable from a typical flood. Another problem is that 'control' and 'impact' sites may differ in ways other than discharge (such soil, grazing intensity, aspect etc.). This can be countered by spreading sites around the lake and testing for any likely differences.

Lastly, this research has demonstrated the benefits of keeping the discharge some distance from fringing vegetation. The enhancement of soil pH and salinity identified here is likely to have been the result of discharge water coming into direct contact with the fringing vegetation. Extending and maintaining discharge pipelines towards the middle of salt lakes is therefore a major management recommendation.

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# EXPLORATION ENVIRONMENTAL MANAGEMENT PLANS (EEMPS)

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## INTRODUCTION

The Environment Branch (Mining), as part of the Minerals and Petroleum Services Group of DoIR, delivers regulatory services to the Western Australian mining industry, under the provision of the Mining Act 1978.

Our goal is to promote effective environmental management practices and good rehabilitation outcomes, through:

- environmental assessment and approval of new mining activities (eg assessment of Notice of Intent (NOI) for productive mining and Ground Disturbance Approval Application (GDAA) for exploration)
- environmental performance and compliance monitoring of existing mining activities (such as reviewing Annual Environmental Reports, auditing and inspections) and
- development of appropriate guidelines to assist industry in preparing and implementing mine closure plans.

### Exploration approval

In regard to exploration activities, there is a standard condition on all exploration and mining leases, requiring "written approval" from the DoIR for the use of "scrapers, graders, bulldozers, backhoes or other mechanised equipment for surface disturbance or the excavation of costean". This written approval currently is obtained through the submission of a GDAA.

Each year DoIR has been processing in excess of 1,000 GDAAs and 70 to 80% of the applications were from the Goldfields region. The large number of the GDAAs received per year is a reflection of the nature of the GDAA process. This process is primarily designed for small exploration programs consisting of defined drilling locations or covering a small number of leases (typically 5 to 10 leases), and over a brief timeframe (usually within 12 months). The GDAA is also used for an exploratory drilling program prior to the development of a resource definition exploration program.

### The EEMP process

The EEMP concept came about in 2002 in recognition of the need for a more strategic approach to environmental approval of exploration activities. Together with the GDAA process, the EEMP will enable more flexibility to exploration companies in implementing their exploration programs. A company may chose to obtain approval for an exploration program by submitting either a series of GDAAs or just an EEMP.

The EEMP is particularly useful and effective when a company has a defined exploration program covering a large number of tenements. Through the EEMP process, a project area can be defined (in terms of mineral field or administrative boundaries) together with an assessment of the environmental impacts and an environmental management plan for the exploration activities in the project area over the life of the program.

The EEMP process can assist exploration companies in:

- better exploration planning and budgeting
- reducing the amount of paperwork caused by multiple GDAAs
- better allocation of resources to rehabilitation work and research
- better management of ground disturbances and environmental outcomes
- more cost effectiveness of the rehabilitation (and exploration program)
- facilitating the land clearing permit (purpose permit) through the same process
- reducing approval time through technical certification of the EEMPs and EAERs.

The EEMP approval can be valid for up to 5 years (the same timeframe as the purpose permit) with a requirement for Exploration Annual Environmental Reports (EAER) to be submitted to DoIR. The EAERs will allow the company to review its environmental performance in the last 12 months and to plan for exploration program in the next 12 months. The EAERs will be used by DoIR to monitor the environmental performance and rehabilitation efforts.

An environmental bond may be required as a condition of the EEMP approval or may be imposed later as part of the EAER assessment.

An EEMP document should contain the following information:

- Summary (to include a consolidated list of environmental management commitments)
- Background information (to include project overview, location, ownership, history and land uses)
- Existing environment (to include the physical and biological environment)
- Project description (to include survey, infrastructures, transport, drilling programs)
- Assessment of potential environmental impacts and management of the impacts (to include management measures and procedures, monitoring, workforce induction and training)
- Assessment and management of social impacts (to include stakeholders consultation process and aboriginal heritage).

An EAER document should contain the following information:

- Project background
- Updated information on existing environment
- Details of completed exploration (last 12 months)
- Proposed/planned exploration (next 12 months)
- Rehabilitation progress and future targets
- Environmental monitoring and updated management measures.

Both the EEMP and EAER must have written endorsement of a senior manager (or a senior executive) accountable for the exploration project before approval can be given.

To date, four EEMPs have been submitted and three of those have been approved, as a trial implementation of the process.

The DoIR, together with industry representatives, are developing guidelines to explain the EEMP process and how to get approval under this process. We expect the guidelines to be available to industry before Christmas 2004.

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# ENVIRONMENTAL ASPECTS OF NATIVE TITLE CO-EXISTENCE AND ENVIRONMENTAL MANAGEMENT

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## ENVIRONMENTAL RAMIFICATIONS OF NATIVE TITLE DECISIONS

*As native title claims become native title decisions, courts are recognising native title rights that have environmental aspects, such as a right to use water. In many cases, these native title rights 'co-exist' with non-native title rights such as the rights under mining tenements. How best can native title holders and miners 'get along' in the new era of co-existence? What roles do environmental managers have?*

## INTRODUCTION

This paper argues that mining environmental managers are likely to have a role in native title negotiations. However, environmental managers need not be alarmed about being burdened with a substantial new area of work, as the role is not likely to be onerous.

Some native title rights have environmental aspects. Mining companies and others will need to negotiate with native title holders to minimise the impact of mining operations on those native title rights. Environmental managers will have a role in assessing, and explaining, how a proposed mining operation will impact on native title rights.

Native title negotiations are still likely to be carried out by specialist native title negotiators. It is unlikely that environmental managers will find themselves pushed centrally into this role. However, environmental considerations will, more and more, have a role to play in native title negotiations.

### Native title decisions

Most people are aware that native title claims are slowly being converted into finalised native title decisions by the Federal Court. There are about eight native title decisions in Western Australia which have been finalised. The large Wongatha claim, covering parts of the Goldfields, will probably be decided by the end of this year.

## WHICH NATIVE TITLE RIGHTS ARE SUBJECT TO ENVIRONMENTAL IMPACTS?

When the Federal Court finalises a native title claim, it specifies the native title rights which exist. Native title rights are not just about rights to visit and protect sacred sites, although these rights are also being recognised in native title decisions.

Some of the native title rights recognised by the Court have environmental aspects:

- a right to take water for drinking and domestic use;
- a right to hunt and forage;
- a right to fish in the waters;
- a right to collect and forage for bush medicine and bush food;
- a right to take fauna (including goanna, kangaroo, emu, turkey, echidna, porcupine);
- a right to take flora;
- a right to take black, yellow, white and red ochre[1].

It can readily be seen that the environmental impact of a large scale mining project could hamper these kinds of native title rights.

It is important to keep in mind that native title rights vary from group to group among Aboriginal people. There is not a uniform scope of native title throughout Australia. It is necessary to consider the native title rights which exist in a particular area.

How does native title law deal with the impact of mining activities on the kinds of native title rights listed above – rights which involve use of the land's resources? Before turning to address this question, it will be helpful to explain some important aspects of native title law.

## AN OVERVIEW OF RELEVANT NATIVE TITLE PRINCIPLES

### Why worry about native title?

The reason that regard must be had to native title rights is that they survive the grant of a mining tenement. Historically, Aboriginal heritage (such as sacred sites) was the only concern for tenement operators. Now that it is clear that native title rights can and do survive the grant of mining tenements, there is much more to consider than Aboriginal heritage.

The grant of a mining tenement in Western Australia does not extinguish the kinds of native title rights listed above.[2]

[1]THESE EXAMPLES ARE TAKEN FROM *DANIEL V WESTERN AUSTRALIA* [2003] FCA 666 AT PARAGRAPH 510.
[2]THE EXTENT OF EXTINGUISHMENT OF NATIVE TITLE RIGHTS DEPENDS ON THE TYPE AND DATE OF THE TENEMENT. TENEMENTS GRANTED FROM 1 JANUARY 1994 GENERALLY DO NOT EXTINGUISH ANY NATIVE TITLE RIGHTS. TENEMENTS GRANTED BEFORE 1 JANUARY 1994 EXTINGUISH SOME NATIVE TITLE RIGHTS (PARTICULARLY, ANY NATIVE TITLE RIGHTS WHICH ALLOW NATIVE TITLE HOLDERS TO EXCLUDE OTHERS, OR ALLOW NATIVE TITLE HOLDERS TO DICTATE THE USE TO WHICH LAND CAN BE PUT).

Typically, grants of mining tenements only 'partially extinguish' native title rights. The grant of a mining tenement before the operation of the *Native Title Act*[3] would, for example, extinguish any exclusive native title rights. However, rights to use the land and its resources (rights like the ones listed above) typically survive the grant of mining tenements.

For grants of new mining tenements[4], the 'non-extinguishment principle' applies[5]. This means native title is not extinguished by the grant of the tenement.

### How do native title rights interract with rights under mining tenements?

It was explained above that some native title rights survive the grant of mining tenements.

The grant of a mining tenement also creates rights in the miner. For example, the grant of a mining lease allows the grantee, to the exclusion of all others, to mine for any minerals in or under the land land leased. [6]

So how do these two sets of rights (the native title rights and the tenement rights) interrelate? What if they clash? For example, what if a miner wants to develop a mine in such a way that it would prevent native title holders exercising their use rights?

Native title law provides that the miner's ability to carry out operations under a valid mining tenement 'prevails' over any native title rights, but does not extinguish the native title rights. [7]

This does not this mean that a mining operator can simply ignore native title rights. Where there is a clash between native title rights and other rights, both parties must exercise their rights reasonably. [8]

[3] THE EXTINGUISHING EFFECT OF TENEMENTS GRANTED BEFORE 1 JANUARY 1994 (THE START DATE OF THE *NATIVE TITLE ACT 1993*) IS NOT EXPRESSLY DEALT WITH BY THE NATIVE TITLE ACT. THE EXTINGUISHING EFFECT OF THESE TENEMENTS HAS BEEN CLARIFIED BY CASE LAW INCLUDING THE HIGH COURT DECISION IN *WESTERN AUSTRALIA V WARD* (2002) 76 ALJR 1098 (SEE PARAGRAPHS 309 AND 340).
[4] SINCE 1 JANUARY 1994.
[5] SECTION 24MD(3)(A) OF THE *NATIVE TITLE ACT 1993*.
[6] SECTION 85(3), MINING ACT 1978; *WA V WARD* (HIGH COURT) AT PARAGRAPHS 285 TO 296.
[7] SEE SECTION 44H OF THE *NATIVE TITLE ACT* (ESPECIALLY IN RELATION TO TENEMENTS GRANTED FROM 1 JANUARY 1994).
[8] IN THE NATIVE TITLE DETERMINATION ARISING FROM *NEOWARRA V WESTERN AUSTRALIA* [2003] FCA 1402 THE RELATIONSHIP BETWEEN NATIVE TITLE RIGHTS AND THE 'PREVAILING' TENEMENTS WAS EXPRESSED IN THE FOLLOWING WAY (NOTE THAT MINING TENEMENTS ARE REFERRED TO, FOR THE PURPOSES OF THE DETERMINATION, AS 'INTERESTS' WHICH 'REQUIRE OR PERMIT THE DOING OF AN ACTIVITY' (THAT IS, MINING)):

> '[T]HE REQUIREMENT OR PERMISSION AND THE DOING OF THE ACTIVITY PREVAIL OVER THE NATIVE TITLE RIGHTS AND INTERESTS AND ANY EXERCISE OF THOSE RIGHTS AND INTERESTS;
>
> THE EXISTENCE AND EXERCISE OF THE NATIVE TITLE RIGHTS AND INTERESTS *DO NOT PREVENT* THE DOING OF THE ACTIVITY;
>
> BOTH THE RIGHTS UNDER THE OTHER INTEREST [THE MINING TENEMENT] AND THE NATIVE TITLE RIGHTS AND INTEREST *MUST BE EXERCISED REASONABLY…*' (EMPHASIS ADDED)

When making decisions about native title, Courts do not provide specific, detailed guidance on how native title rights are to be treated by the exercise of non-native title rights. So, for example, Courts will say that the non-native title rights 'prevail' over native title rights, but will not provide guidance on what is to happen in particular factual circumstances. A Court might recognise that a native title right to hunt exists, and might also recognise that a miner has a valid mining lease. The Court will declare that the miner's rights 'prevail' over the native title rights but will not go further and say exactly how the relationship between the rights is to be managed in a practical, 'on-the-ground' sense. Courts go no further than to say that each set of rights must be exercised 'reasonably'.

## THE 'REASONABLE' EXERCISE OF RIGHTS

It is because of the requirement on mining companies to exercise their rights reasonably, where there might be an impact on native title rights, that negotiations about environmental impacts become relevant.

### The importance of early negotiations

It will usually be better to negotiate with native title holders about the effect of mining activities on their native title rights, *prior* to carrying out the mining activities. This is because:

- prior negotiations will build trust and respect between the parties;
- prior agreement reduces the risk of litigation. For example, if a miner harms a native title right, and the native title holders consider that the miner has not exercised its rights 'reasonably', the native title holders could bring costly and time-consuming injunction proceedings to prevent the continuation of the mining activity.

### Some examples

It is worth considering some examples of how the environmental impacts of mining activities could harm native title rights.

**Scenario 1:** A group of native title holders has a native title right to forage for bush medicine plants. There is only once source of a particular medicinal plant within the native title group's traditional lands. The source of this plant is near a mine, and the miner is proposing to construct a road nearby. Under its mining tenement, the mining operator has a right to construct the road, and this right 'prevails' over the native title rights (including the right to gather the traditional plants). However, the miner must exercise its rights reasonably.

Negotiations prior to construction of the road would reveal the existence of the medicinal plants (if not already known to the miner). Environmental studies may reveal that dust from the road could harm the plants. The solution might be to seal the road or relocate it a short distance away. The involvement of environmental expertise at an early stage might prevent the impact of the road on the native title rights, and lead to a successful resolution. The miner would clearly have exercised its rights 'reasonably'.

**Scenario 2:** The native title group has a right to use water for domestic purposes. The native title holders have a community a small distance from a mining project. The miner proposes to construct a large new tailings dam adjacent to the mine. The native title holders are concerned that tailings will leach from the dam and poison the creek from which they obtain drinking water for their community.[9]

Early negotiations would reveal the native title holders' concerns. Such concerns may be based on fear and uncertainty, rather than scientific fact. By involving environmental expertise in the negotiations, it may be possible to satisfy the native title holders that there is no risk of contamination to their water source.

## When do native title negotiations occur?

The comments above relate mainly to negotiations with native title groups before the construction or development of an actual project, such as a mine. These are the negotiations which are most likely to concern environmental impacts, because there is an actual physical development project being considered. The precise physical location of the project, and details of its impact, can be discussed in negotiations.

However, environmental managers should be aware that negotiations with native tile groups also occur prior to the grant of mining tenements. The *Native Title Act* requires negotiations to be held between mining lease applicants and native title groups prior to the grant of the tenement. This is the 'right to negotiate' which is so often spoken about. The 'right to negotiate' requires the mining company to negotiate with native title holders about the effect that the grant of the tenement will have on their native title rights and interests.

[9] WATER IS OF PARTICULAR IMPORTANCE TO MOST ABORIGINAL GROUPS. WATER SOURCES ARE OFTEN ASSOCIATED WITH IMPORTANT MYTHOLOGICAL ANCESTRAL CREATION BEINGS OR 'DREAMING' FIGURES. WATER SOURCES ALSO DICTATED THE LIVING PATTERNS OF ABORIGINAL GROUPS IN TRADITIONAL TIMES. WATER REMAINS CENTRAL TO ABORIGINAL BELIEFS, LAND RELATIONSHIPS AND IDENTITY.

Negotiations prior to the grant of a tenement often will not be about a specific defined project (especially if it is an exploration or prospecting licence), so the negotiations are of a different nature. If a specific, defined project is contemplated prior to the grant of a tenement (such as is sometimes the case with mining leases, general purpose leases or miscellaneous licences) then it is possible that environmental impacts will be 'on the agenda' in the negotiations.

To recap, native title negotiations mainly occur at two points in the mining process:

- prior to the grant of a mining tenement. For tenements such as mining leases, native title holders have the benefit of the 'right to negotiate';
- after a tenement is granted, where on-ground activities are proposed to be conducted (such as the construction of a mine, the development of mining infrastructure, or a drilling program).

At both of these stages, native title rights can be affected.

## Ongoing negotiations

It is recommended that consultation with native title groups not be limited to these two stages of a mining project. It is beneficial if relationships of trust can be developed, through ongoing liaison and information sharing. Many mining operators set up regular quarterly or half-yearly meetings with affected Aboriginal groups, to provide information on the project and consider the views of Aboriginal people.

Again, environmental managers can have a role to play in such ongoing negotiations and information sharing. As projects are developed, environmental impacts can change. Typically, Aboriginal people will have a keen interest in the environmental impacts of a proposal and will want as much information as possible about it.

## Delivering the message

It goes without saying that environmental impact information should be presented to Aboriginal people in a way that is meaningful to them. For example, if English is not the first language, make sure clear, simple, direct language is used.

Just as importantly, try to engage with Aboriginal people, rather than just deliver information to them. Many Aboriginal people have expressed disappointment at being presented with a *fait accompli*, with no real opportunity for their input.

There may be circumstances in which it is more appropriate to allow aboriginal groups to carry out their own environmental studies. Aboriginal concepts of environment differ from non-aboriginal view points. In some cases, the best way to approach the resolution of an environmental issue might be for the mining company to fund an aboriginal group to have environmental studies, from an aboriginal environmental perspective.

## SUMMARY AND CONCLUSIONS

This paper predicts that environmental managers will become increasingly involved in native title negotiations. The role of environmental managers is likely to be greatest where the proposed project (such as a mine) is being presented to native title groups for their consideration.

Mining companies have a right to develop their projects once the relevant mining tenements are granted. In exercising this right, a mining company must have regard to any native title rights which survive the grant of the tenement. This requirement arises because the native title holders, and the mining operator, must exercise their rights reasonably. Where the exercise of those rights come into conflict, it will be desirable to negotiate a solution prior to commencement of the project.

Environmental impacts can change over the life of the project, so ongoing negotiations will also be important. Ongoing negotiations are an important aspect of the mining operator exercising its rights 'reasonably', as required under native title law.

Environmental managers need not be alarmed that these developments will greatly increase the scope of their work, or require them to have a detailed understanding of native title law. It is likely that native title negotiations will continue to be conducted by specialist negotiators, who will call on environmental expertise as and when required.

# RECENT CHANGES IN ENVIRONMENTAL LAW

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## ABSTRACT

*The paper reviews threats and opportunities to mining industry operations arising from the EP Amendment Act 2003 and other recent developments in environmental law in WA. This paper focuses on the changes most relevant to the mining industry. These include environmental harm, changes to licences, clearing permits, notification of offences, notices, third party actions, financial assurances, limitations period and director's liability.*

## INTRODUCTION

This paper comments on recent amendments to the Environmental Protection Amendment Act 2003 (**EP Amendment Act 2003**). The amendments arise from a substantial review of the EP Act conducted over the last 10 years.

The EP Amendment Act 2003 has been partially proclaimed with effect from 19 November 2003. The amendments yet to be proclaimed relate to environmental harm, advertising of licence applications and clearing. These amendments have been delayed to allow for the passing of relevant regulations (such as the clearing regulations).

This paper is not a comprehensive review of all the amendments to the Act. Further, some matters listed as threats may, for some operations be opportunities and vice versa. Specific legal advice on the implications of the amendments should be sought in light of individual circumstances.

## ISSUES

### Amendment of licences and works approvals

Licence holders can now apply for an amendment to licence conditions at any time. The amendments proposed by the licence holder may be approved at the discretion of the CEO. Therefore, if a condition on a licence is either no longer applicable, or, the condition is not able to be complied with, the condition may be amended by the CEO.

Licence holders could consider applying to the CEO to amend the licence as either an additional or alternative approach to the statutory appeal process against licence conditions when the licence is first issued. When considering licence applications or amendments the applicant or holder may wish to apply for a term longer than the usual 1 year. As the licence may be amended, any unworkable conditions may be removed (at the discretion of the CEO) during the term of the licence rather than waiting for expiry.

Licence holders should be aware that there is no statutory right of appeal against the refusal of the CEO to amend the licence. A further risk is that, in pursuing an amendment to a particular licence provision(s), the DoE is likely to review the entire licence and the holder may have further undesirable conditions imposed.

### Strategic proposals

A new class of environmental impact assessment proposals known as "strategic proposals" has been incorporated. Only proponents will be able to refer strategic proposals to the EPA. A strategic proposal is one which may not, by itself, have a significant effect on the environment but which identifies:

- a future proposal that will be a significant proposal; or
- future proposals which are likely, if implemented, to have a significant effect on the environment (s.37B and s.38).

Proponents may have entire proposals strategically assessed without the need for referral of each stage of a proposal that may have had a significant effect on the environment.

EPA Report may include other information

Section 44 is expanded to allow the EPA to include extra information (other than strictly environmental information) in its environmental impact assessment bulletins (s.44(2a)).

This may limit circumstances where Supreme Court challenges to Ministerial decisions may arise based on a report by the EPA that includes matters outside the discretion of the EPA to consider.

### Changes to proposals after assessment

Section 45C gives the Minister the power to approve a change to the proposal without the need to refer the proposal for assessment to the EPA. The Minister is not permitted to give an approval where the Minister considers the change to the proposal might have a significant detrimental effect on the environment that was not contemplated at all or is different in magnitude to that contemplated in the original proposal. Such a change will require full assessment by the EPA.

The words "significant detrimental effect" allow the Minister broad discretion to amend a proposal.

## Principles

A number of principles have been listed as objects of the EP Act (s.4A). Decisions made under the EP Act by the CEO and EPA should consider the principles of the Act. The courts will also have reference to these principles when reviewing an administrative decision made under the Act. Depending on the administrative decision being made and the circumstances of the recipient of the decision, the application of the principles may be considered as a threat or an opportunity.

That is, the application of the principles may be used in a decision to refuse to grant an authorisation (e.g. application of precautionary principle) or may benefit a proponent in having matters assessed by the EPA during the EIA process which relate to pricing mechanisms.

The principles are:

- precautionary principle;
- intergenerational equity;
- conservation of biodiversity and ecological integrity;
- improved valuation, pricing and incentive mechanisms; and
- waste minimisation.

## Bilateral agreements

The EPA is authorised to have regard to bilateral agreements entered into under the Environment Protection and Biodiversity Conservation Act 1999 (Cth). The EPA is permitted to prepare guidelines under any relevant agreement, to require a proponent to do anything to give effect to an agreement and to make its report in a manner that satisfies the agreement.

This will enable proponents to have streamlined assessment for projects that trigger the need for environmental assessment by both State and Commonwealth agencies, although separate approvals will still be required.

## Environmental harm

The new offence of unauthorised environmental harm will broaden the scope of pollution offences to cover any form of detriment to the environment. The definition of environmental harm expands the threshold of liability to include “potential” harm to the environment. This amendment, coupled with the newly created Environmental Enforcement Unit will lead to increased prosecution activity.

The offence and defence aspects of environmental harm are awaiting proclamation and do not yet have the force of law. However, requirements to report offences and definitional amendments have been made and are therefore relevant now.

### *The offence*

Environmental harm of itself is not an offence. The offence is to either cause or allow to be caused material environmental harm or serious environmental harm.

Threshold amounts are prescribed for the offences of material environmental harm and serious environmental harm. The threshold amounts are $20,000 and $100,000 respectively.

The threshold amount does not have to be exceeded in any case to constitute either material or serious environmental harm. For example, where no monetary loss arises, material environmental harm may still occur where the harm is neither trivial nor negligible.

It is likely there will be many instances where the damage costs used to calculate whether the threshold amount has been met will either exceed, or have the potential to exceed, the prescribed amount.

### *Penalties*

Serious environmental harm with intent or criminal negligence is a Tier 1 offence with a penalty of up to $1,000,000 for companies and $500,000 for individuals and up to 5 years gaol.

The penalty for material environmental harm is up to $500,000 for companies and $250,000 for an individual.

### *Defence*

The existing “due diligence and reasonable precautions” defences provided in sections 74(1) and 74(1a) remain, although they have been amended to provide for both emission and environmental harm offences.

Two other defence provisions have been added.

Section 74A provides a new defence for causing pollution or an emission, or for causing serious environmental harm or material environmental harm. The person charged must prove that the pollution, emission or harm occurred in accordance with an approval or other nominated authorisations or exemptions under the EP Act (including a works approval or licence).

Section 74B provides a specific defence for serious or material environmental harm. The defence requires some form of authorisation or approval or exemption under another written law or one of a number of specified soil and land related approvals.

## Director's liability

A director will be deemed liable for an offence committed by the company (and may be prosecuted for that offence) unless the director can establish one of three defences under the Act. Those defences may broadly be described as:

- no knowledge or reasonable expectation of knowledge of the commission of the offence;
- that, if in a position of influence, the person had used all due diligence and reasonable precautions to prevent the offence from occurring; or
- the body corporate had a defence to the charge (eg. authorised discharge).

A director may be charged for an offence of the company without the company being charged, although the prosecution will have to make out its case against the company for the charge against the director to stand.

The removal of the limitation period for Tier 1 offences described in detail below means that a director may be liable for an offence committed by the company for any period.

## Limitation period for offences

A prosecution for a Tier 1 offence may be brought at any time. The Act previously provided for a limitation of 24 months from the time the matter of complaint arose.

Prosecution for other offences under the Act must be brought within 24 months of either the matter of complaint arising or when the matter is brought to the attention of an officer authorised to bring a prosecution. There is potential for "non tier 1" offences to have an open ended time for bringing the prosecution while the DoE remains unaware of the circumstances which gave rise to a breach of the Act.

## Third party action

In addition to the right of the DoE to prosecute, section 73B provides for a third party cause of action in tort against an organisation for damages for failure to comply with an environmental protection notice, vegetation conservation notice, or a prevention notice.

## Financial assurances

A proponent may be required to provide a financial assurance (bond) as a condition of a project approval, other authorisation, or notice issued under the EP Act. Although the CEO and Minister are required to have regard to bonds imposed under the legislation, separate "bonds" may apply to various aspects of a project which are enforced by separate regulators.

The CEO has the discretion to impose (with the Minister's consent) the financial assurance on a reasonable estimate of the total likely costs and expenses involved in addressing any financial matters the subject of the notice. If the financial assurance is insufficient, the CEO may recover additional costs.

## Clearing

A new offence of unauthorised clearing will apply, once proclaimed. It will be an offence to clear native vegetation otherwise than in accordance with a clearing permit (subject to a range of exemptions).

Section 51C provides the offence of unauthorised clearing. The offence is a Tier 1 offence with penalties up to $500,000 for a corporation and $250,000 for an individual. It is an offence to clear unless it is done in accordance with a clearing permit or is an exempt matter under Schedule 6 of the Act or the Regulations (which are to be drafted) and that clearing does not occur in an environmentally sensitive area.

The exemptions listed in Schedule 6 of the Act are too numerous to mention. Clearing Regulations currently being drafted provide further exemption.

The permits that may be obtained may generally be described as area permits (which are granted to clear an area at a particular time) and purpose permits (which allow clearing of different areas from time to time).

Section 51R provides, as with the liability for directors, a reversal of the onus of proof. An occupier of a property will be deemed to have caused, and the owner of the property deemed to have allowed, the clearing in relation to the offence of unauthorised clearing unless the owner or occupier proves otherwise.

The CEO is able to apply for a clearing injunction before the Supreme Court to stop clearing that is not authorised. The Court may grant an injunction whether or not it is proved that a person intends to engage in any improper conduct.

## Emissions onto premises

Emissions onto premises are now dealt with. Previously, the DoE generally did not pursue matters until the impact occurred outside the boundary of the premises. The amendments confirm that the DoE may now regulate and enforce impacts (or potential impacts) within the boundary of the premises.

## Notices

The range of management tools available to the DoE has increased with the introduction of an Environmental Protection Notice. This replaces the Pollution Abatement Notice and is more flexible in its ability to control environmental outcomes, including those contained on premises.

Other notices include:

- closure notices (section 68A)
- vegetation conservation notice (Section 70)
- environmental protection directions (Section 71)
- prevention notices (Section 73A).

#### *Closure notices*

The DoE will have the power to issue closure notices for operations nearing the cessation of activities. A closure notice may require a company to prepare a closure management plan, carry out investigations and require on-going monitoring. Independent audits of actions taken under a closure plan can also be required. The key "threat" here is increased scrutiny of closure operations from a regulator other than DoIR.

A closure notice may be the subject of a financial assurance.

The closure notice may be issued either during or after the lapsing of the relevant authorisation.

#### *Environmental protection directions*

Section 71 provides for environmental protection directions which were in existence under the previous Act. Given the expansion of thresholds for environmental offences under the Act and the new offences of environmental harm, there will likely be an expansion of use of this power.

#### *Vegetation conservation notices*

Section 70 provides for vegetation conservation notices which may require a person to repair any damage caused by clearing and re-establish vegetation to the state it was in prior to clearing.

### Licences

The scope of conditions that may be imposed on a licence has been expanded.

For example, conditions may require the provision of audit compliance reports to the CEO. Draft regulations are being considered by the DoE to require annual compliance statements to be made in relation to a licence. This power may be used to require verification audit reports for some aspects of the relevant operations.

### Notification of offences

Section 72 under the previous Act required notification to the CEO of any discharge of waste that caused or was likely to cause pollution. As the definition of pollution was limited, notification requirements were at times not triggered. Although the environmental harm offence provisions have not been implemented yet, the requirement to report incidents that may constitute environmental harm is in force. The requirement to report will be triggered in more instances given that the definition of environmental harm will in most instances be wider than that of pollution.

### Environmental impact assessment

A number of amendments have been made to the Part IV EIA process which may depending on the circumstances be classified as "threats". For example, it will be an offence to implement a proposal before the Minister for the Environment determines that it may be implemented. The maximum penalty for a corporation is $125,000, with a daily penalty of $25,000.

It will also be an offence to fail to comply with a notice from the DoE requiring reports and information about the implementation of a proposal and compliance with conditions of implementation. The maximum penalty is $250,000 for corporations.

In addition to the Minister's power to enforce non-compliance with conditions of a Part IV approval, the DoE will have the authority to monitor and enforce compliance with Ministerial conditions (s.48). The enforcement actions may include environmental protection notices, prosecution or directions.

The EPA will have a specific power to terminate an assessment of a proposal if:

- the proponent agrees to that termination;
- the proponent fails to take an action directed by the EPA in a timeframe which the EPA considers reasonable; or
- another decision-making body has refused to approve the proposal.

### Environmental Protection Policies

The amendments now provide that an EPP may apply to the whole of the State. This may limit the circumstances in which individual licence holders can negotiate with licensing officers appropriate licence limits where standards or emission limits are prescribed in a particular EPP (given that licences cannot be inconsistent with an EPP).

### Section 5 exemption removed

The exemption from the application of the Act (to the extent of inconsistency) for operations that operated pursuant to a State Agreement has been removed. Therefore, the EP Act has primacy over any other legislative mechanism, unless a specific exemption has been obtained under section 6 of the EP Act.

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# PROCEEDINGS 2004

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# Day Two

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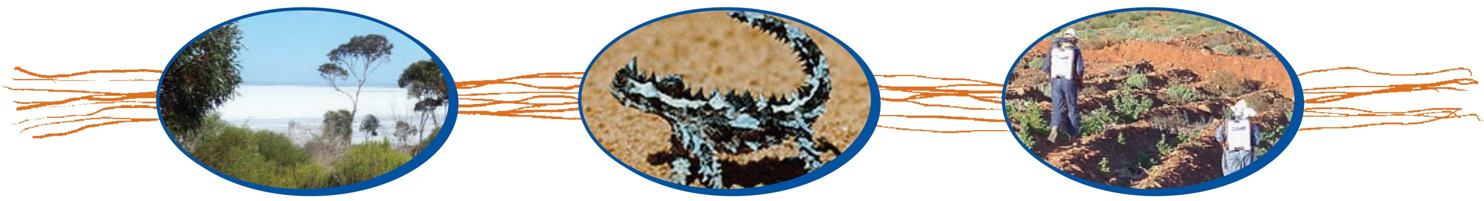

# REVEGETATION STRATEGIES FOR SUSTAINABLE END-USE OF ARSENIC RICH MINE TAILINGS IN THE VICTORIAN GOLDFIELDS

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## ABSTRACT

*Mine tailings storage at vein-gold deposits, such as in Stawell, the largest active mine in the Victorian Goldfields, often result in features that are neither physically nor chemically stable. One of the major environmental issues, which are of concern, is the elevated level of arsenic in tailings (> 2000 mg kg$^{-1}$). The objective of the study is to develop cost-effective revegetation protocols for sulphide-bearing gold mine tailings that result in land of acceptable economic and/or environmental value, which can create an economic asset to the former mining community once the mine has ceased to operate.*

*Trials are being conducted to assess the performance of a partially "open" geochemical system with the purpose of limiting acid and metal release to environmentally acceptable levels, rather than the unrealistic goal of infinite encapsulation. Formation of a permanent and self-sustaining vegetation cover on such a dam would minimize surface erosion and reduce the transfer of oxygen and water to the sulphidic tailings. Surface covers that are being investigated include thin covers (< 500 mm) of waste rock with combinations of topsoil and/or biosolid amendments.*

*A major aim of the project is to determine the performance of potential tree and pasture crops when growing on rehabilitated gold tailings of the vein-gold type, and to assess the viability of a mixed agri-business on a large rehabilitated sulphidic tailing dam. Candidate species include eucalypts for eucalyptus oil; firewood and/or pulpwood, and native grass species for pasture cover and the formation of seed orchards.*

*This report describes the growth responses of candidate plant species of* Eucalyptus *and native grasses in relation to various substrate variables such as salinity, physical constraints and arsenic mobility.*

## INTRODUCTION

A major field study is being conducted at the Stawell Gold Mine, approximately 250 km northwest of Melbourne, Victoria (Fig. 1). It is the largest operating gold mine in the state with a million ounces having been mined in the last 11 years. Current mining activity is located in the underground development which follows the Magdala lode system down plunge, to a depth of 1025 m. The mine and processing plant are approximately 1.5 km west of the town of Stawell. The local climate is temperate (mean January daily maximum temperature: 27.4˚C, mean July daily minimum: 4˚C) with maximum rainfall occurring between May and September (mean annual rainfall 576mm: Bureau of Meteorology 2003).

The underground ore body contains ca. 15 %vol or more of sulphidic minerals. After gold extraction the tailings are stored in a tailings dam. At the projected time of mine closure, this facility will contain >10 million m$^3$ of sulphidic tailings. The sulphide mineralogy includes pyrite [$FeS_2$], pyrrhotite [$Fe_{1-x}S$], and arsenopyrite [FeAsS]. Most tailings have significant acid-neutralising capacity owing to the presence of carbonates such as ankerite [$Ca(Fe,Mg)(CO_3)_2$] and other acid-buffering minerals.

Minesite rehabilitation is defined as the return of a disturbed site to a form and productivity level that conforms to a defined end land use that may not be necessarily be the original use (Bell 1996). Trials are being conducted to assess the performance of a partially "open" geochemical system with the purpose of limiting acid and metal release to environmentally acceptable levels, rather than the unrealistic goal of infinite encapsulation. Surface covers that are being investigated include thin covers (< 500 mm) of waste rock with combinations of topsoil or biosolid amendments. This project is investigating revegetation strategies based on viable agri-business or other land-use that adds worth to the tailings facility, and are both environmentally sound and ecologically sustainable.

This report describes the growth responses of candidate *Eucalyptus*, and native grass species *Microlaena stipoides* and *Austrodanthonia caespitosa* in relation to various substrate variables such as salinity, physical constraints and arsenic mobility.


*Figure 1: Location of Stawell gold mine*

## MATERIAL AND METHODS

Glasshouse trials determined the growth of seedlings of a suite of native plant species in various tailings/cover materials with application of different combinations of ameliorants. These include fertiliser, organic amendments and inert waste rock. Chemical analyses were performed on substrates and plant material at different stages of the experiment.

Field scale experiments (total area 0.5 ha) are evaluating *in situ* plant performance. Three large blocks with 10 different substrate covers were planted with the candidate tree species and sown with grasses. Individual trial plots incorporated covers of various combinations of ameliorants: crushed oxide waste rock, topsoil and municipal sewage sludge (biosolids).

## RESULTS AND DISCUSSION

### Substrate characterization

Elemental analysis of tailings and amendments used in the glasshouse trials reflected the relative concentration present in the mixtures of tailings and amendment materials (Table 1). Total Mn and As concentrations were elevated reflecting the mineralogy of the orebody and waste rock however, DTPA extracts of trace metals were not elevated. Extracted metals give an indication of what may be bioavailable to plants. The presence of high concentrations of reactive iron could render these two elements inaccessible and unavailable. Biosolids from the Stawell sewage farm contained the trace elements of interest at slightly elevated levels e.g As, Cu, Zn, however, these were not above the investigable ecological investigation levels (Imray and Langley 2001). Reactive and extractable Fe was high in tailings and biosolids.

Seedlings of *Eucalyptus cladocalyx* and *E. polybractea* were grown for 150 days. Biomass production was enhanced in both eucalypt species by the addition of either organic (biosolids) or inorganic (NPK fertilizer) nutrient amendments (Fig. 2). Dry plant matter production was less than 0.5 g /pot for both species in the absence of nutrients. Tailings amended only with inorganic fertilizer produced comparable amounts of biomass for both species as standard potting mix and fertiliser or oxide plus inorganic fertiliser or biosolid amendments. *E. cladocalyx* produced the double the biomass of the other nutrient amendments when the high biosolid treatment was applied (292 dry tons $ha^{-1}$).

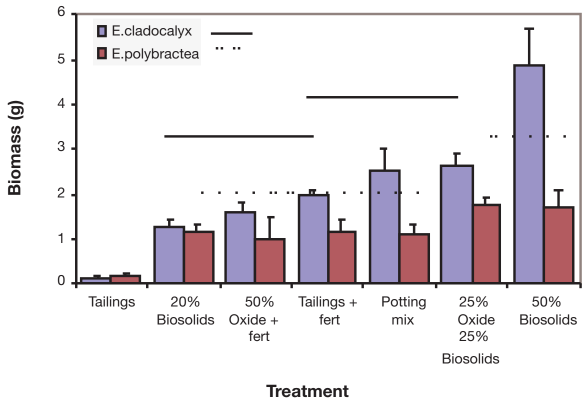



*Figure 2:* Eucalyptus cladocalyx *and* E. polybractea *shoot biomass after 150 days. Values under each line are not significantly different.*

**Table 1: Chemical analysis of substrates used in glasshouse trials.**

| Analysis | Units | Sulphidic tailings | Oxide waste rock | Biosolids | Analysis | Units | Sulphidic tailings | Oxide waste rock | Biosolids |
|---|---|---|---|---|---|---|---|---|---|
| $NO_3$ | Mg $kg^{-1}$ | 9.7 | 2.0 | 77.0 | Cl | mg $kg^{-1}$ | 460 | 896 | 336 |
| $NH_4$ | Mg $kg^{-1}$ | 7.7 | 2.3 | 207.3 | Co | mg $kg^{-1}$ | 11.37 | 39.0 | 3.4 |
| Total N | % | 0.1 | 0.0 | 1.7 | Ni | mg $kg^{-1}$ | 42 | 56 | 22 |
| P Colwell | Mg $kg^{-1}$ | 20 | 17 | 683 | Cu | mg $kg^{-1}$ | 136.8 | 110 | 1138 |
| Total P | Mg $kg^{-1}$ | 1161 | 211 | 3963 | Zn | mg $kg^{-1}$ | 144 | 840 | 1502 |
| K Colwell | Mg $kg^{-1}$ | 104 | 166 | 246 | As | mg $kg^{-1}$ | 3355 | 560 | 33 |
| S | Mg $kg^{-1}$ | 914 | 83 | 2217 | Pb | mg $kg^{-1}$ | 13 | 700 | 122 |
| Organic C | % | 1.4 | 0.2 | 11.2 | Cr | mg $kg^{-1}$ | 44 | 102 | 294 |
| Reactive Fe | Mg $kg^{-1}$ | 3713 | 175 | 2831 | Exch Ca | meq/100g | 4.1 | 0.3 | 9.2 |
| Cu-DTPA | Mg $kg^{-1}$ | 2.9 | 0.2 | 315 | Exch Mg | meq/100g | 0.5 | 2.2 | 2.4 |
| Zn-DTPA | Mg $kg^{-1}$ | 3.2 | 0.8 | 753.1 | Exch Na | meq/100g | 2.6 | 3.6 | 2.3 |
| Mn-DTPA | Mg $kg^{-1}$ | 44.5 | 1.2 | 27.4 | Exch K | meq/100g | 0.3 | 0.4 | 0.6 |
| Fe-DTPA | Mg $kg^{-1}$ | 50.5 | 2.3 | 227.2 | EC | dS/m | 1.2 | 0.7 | 2.3 |
| | | | | | pH $H_2O$ 1:5w/v | | 8.2 | 7.8 | 4.0 |

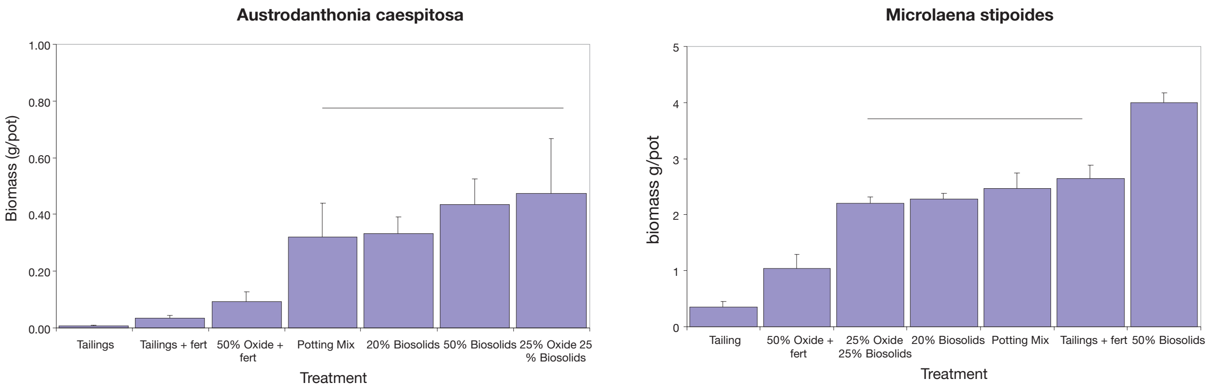



*Figure 3:* Microlaena *(a) and* Austrodanthonia *(b) shoot biomass after 100 days. Values under each line are not significantly different.*

**Table 2. Elemental analysis of *Microlaena* and *Eucalyptus* shoots and roots in different treatments. Values in each row followed by the same letter are not significantly different (n = 3 at P < 0.05)**

| *Microlaena* shoots Elemental analysis υg/g | Potting mix | Tailings | Tailings fertiliser | 50% biosolids | 50% oxide | 50% oxide + fertiliser |
|---|---|---|---|---|---|---|
| Arsenic | 3.2a | 5.6a | 12.4ab | 56.8b | 20.4ab | 13.8ab |
| Chromium | 0.2a | 0.2a | 0.2a | 1.1b | 0.4a | 0.2a |
| Cobalt | 0.3 | 1.0 | 1.5 | 1.2 | 1.1 | 1.0 |
| Copper | 26.6a | 16.7a | 39.1a | 88.1b | 38.0a | 22.2a |
| Lead | 13.7 | 10.2 | 10.8 | 11.8 | 9.5 | 8.3 |
| Manganese | 253.2a | 526.6b | 1091.5b | 622.0b | 821.6b | 741.9b |
| Nickel | 6.5 | 6.9 | 9.4 | 8.1 | 7.1 | 7.6 |
| Zinc | 336.0b | 65.2a | 114.5a | 265.6ab | 132.3a | 102.4a |
| *Microlaena* roots Elemental analysis υg/g | | | | | | |
| Arsenic | 5.5a | 30.7b | 154.4c | 110.3bc | 32.6b | 50.0b |
| Chromium | 0.2a | 0.2a | 2.1b | 3.5b | 0.4a | 0.4a |
| Cobalt | 0.8a | 12.1bc | 21.1c | 2.1b | 11.0bc | 9.9bc |
| Copper | 34.7a | 40.8a | 55.6a | 230.2b | 35.6b | 27.4b |
| Lead | 7.9a | 13.0b | 15.9b | 21.2b | 15.0b | 14.9b |
| Manganese | 115.0a | 3819.2c | 4536.7c | 537.6b | 4072.0c | 2862.9c |
| Nickel | 4.6a | 26.6c | 30.8c | 9.3b | 20.8c | 21.6c |
| Zinc | 187.1b | 136.4b | 105.6b | 389.1c | 115.0b | 87.0a |
| *Eucalyptus cladocalyx* shoots Elemental analysis υg/g | Potting mix | Tailings | Tailings + fertiliser | 50% biosolids | 50% oxide | 50% oxide + fertiliser |
| Arsenic | 6.5a | 7.6a | 20.6b | 8.6a | 7.7a | 4.3a |
| Chromium | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| Cobalt | 0.4 | 0.3 | 0.8 | 0.3 | 0.3 | 0.6 |
| Copper | 14.2 | 11.6 | 14.0 | 16.2 | 13.5 | 11.5 |
| Lead | 6.4 | 5.9 | 6.3 | 5.6 | 5.3 | 5.1 |
| Manganese | 468.7a | 354.0a | 1127.9b | 1533.8b | 1376.4b | 1817.1b |
| Nickel | 4.8 | 2.3 | 3.9 | 2.5 | 3.6 | 4.3 |
| Zinc | 90.9ab | 55.4a | 92.3ab | 113.2b | 73.0ab | 64.8ab |
| *Eucalyptus cladocalyx* roots Elemental analysis υg/g | | | | | | |
| Arsenic | 9.1a | 66.5b | 110.9c | 92.4c | 56.2b | 60.8b |
| Chromium | 0.2 | 0.4 | 0.5 | 0.7 | 0.4 | 0.4 |
| Cobalt | 1.0a | 10.7b | 24.3b | 6.8b | 17.8b | 22.1b |
| Copper | 19.4a | 30.0b | 48.1b | 112.4c | 61.8b | 58.2b |
| Lead | 5.7 | 10.8 | 12.6 | 9.1 | 7.5 | 7.3 |
| Manganese | 516.0a | 1541.8c | 2827.1c | 899.3b | 1684.4c | 1302.6c |
| Nickel | 3.9a | 10.7b | 33.1c | 14.6b | 16.2b | 19.5b |
| Zinc | 149.1a | 157.6a | 137.9a | 388.4b | 203.0ab | 167.1a |

Shoot biomass for *Microlaena* and *Austrodanthonia* (Fig. 3) was enhanced by incorporating large amounts of biosolids. The highest rate of biosolid application, 50% (w/w) biosolids (equivalent to 292 dry tons/ha) produced significantly greater *Microlaena* dry shoot matter than all other treatments. Herbage production in this treatment was 1 - 1.5 times greater than the next best treatments which were potting mix, tailings with medium levels of biosolids application (25%) or tailings with fertilise. Addition of inorganic fertiliser or biosolids increased biomass production by 6-7 times compared with unamended tailings. High oxide incorporation rates (50%) with fertiliser increased biomass by 4.5 times.

Maximum biomass production in *Microlaena* was 3.99 g/pot compared to 0.47 g/pot in *Austrodanthonia*. The greatest amount of herbage in *Austrodanthonia caespitosa* was produced high biosolids amendment, potting mix and 20% oxide + fertiliser. All other amendments also produced significantly greater herbage than tailings alone.

## Concentration of heavy metals and arsenic in shoots and roots

Plant tissue from two of the species were analysed for trace metal uptake using ICP-MS. The concentration of arsenic (Table 2) was elevated in the leaves of *Microlaena* grown in biosolid amended tailings and in *E. cladocalyx* leaf tissue in tailings amended with inorganic fertiliser. Biosolids amendments increased the uptake of Zn in both species and Cu concentrations in *Microlaena* only.

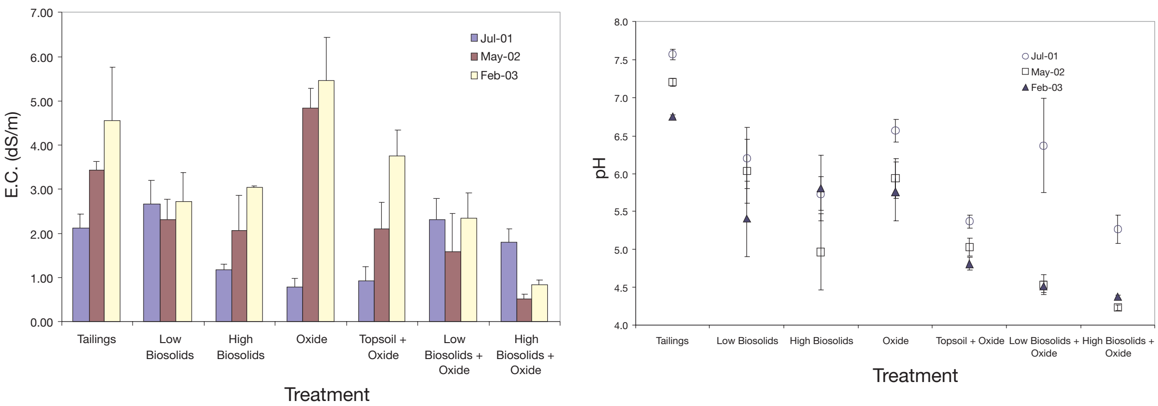
## Field Experiments

Chemical changes in the tailings cover were monitored over two summers. Soil sampling of the experimental plots was regularly performed and pH and electrical conductivity measured. After two summers, the pH of tailings ranged from 6.4 - 6.7, and oxide covers pH 5.8 were still slightly acidic (Fig. 4). The surface of exposed tailings was observed to have changed in colour from dark grey to light red in different sections of the experimental plots. Biosolid amended tailings or oxide cover were acidic (pH 4 - 6). Unamended oxide cover had electrical conductivity levels which could only be tolerated by very saline tolerant plant species. Biosolid incorporation into oxide material reduced salinity levels by increasing water infiltration and reducing capillary movement of saline tailings water (Fig. 4).

We have observed that establishment of pasture species (predominatly exotic) was successful in all the biosolid amended treatments, either biosolids directly on tailings or amended oxide. Vegetative cover was greater than 70% in these treatments. Topsoil-amended oxide had 23 - 25% vegetation cover with most of being represented by the exotic pasture species. The contribution by native grasses to the pasture biomass was minimal. Cultivation of the topsoil into the oxide would improve the soil structure and increase water collection. Initial observations of vegetation on the biosolid-amended plots suggest that productivity is comparable to improved pasture systems in the district. The pasture cover has persisted into the second growing season without any apparent decline.

Recent excavation of root profiles through the test plots have showed that shrinkage and desiccation cracks have formed in the covered tailings. These form preferential pathways for water to percolate through as well as allowing proliferation of plant roots to the deeper levels of the tailings. The formation of oxidized cutans or skins was also pronounced where there was extensive cracking of the tailings. Geochemical analysis of these boundary layers is currently identifying components of the secondary minerals formed through the oxidization process. The pH of deeper un-oxidised tailings were consistently > pH 7 and were oxidization had occurred it was pH 6.5 - 7. This indicates that there is significant acid neutralizing capacity in the tailings. Proliferation of cracks enhance washing of the secondary minerals eg. gypsum down the profile away from the root zone.

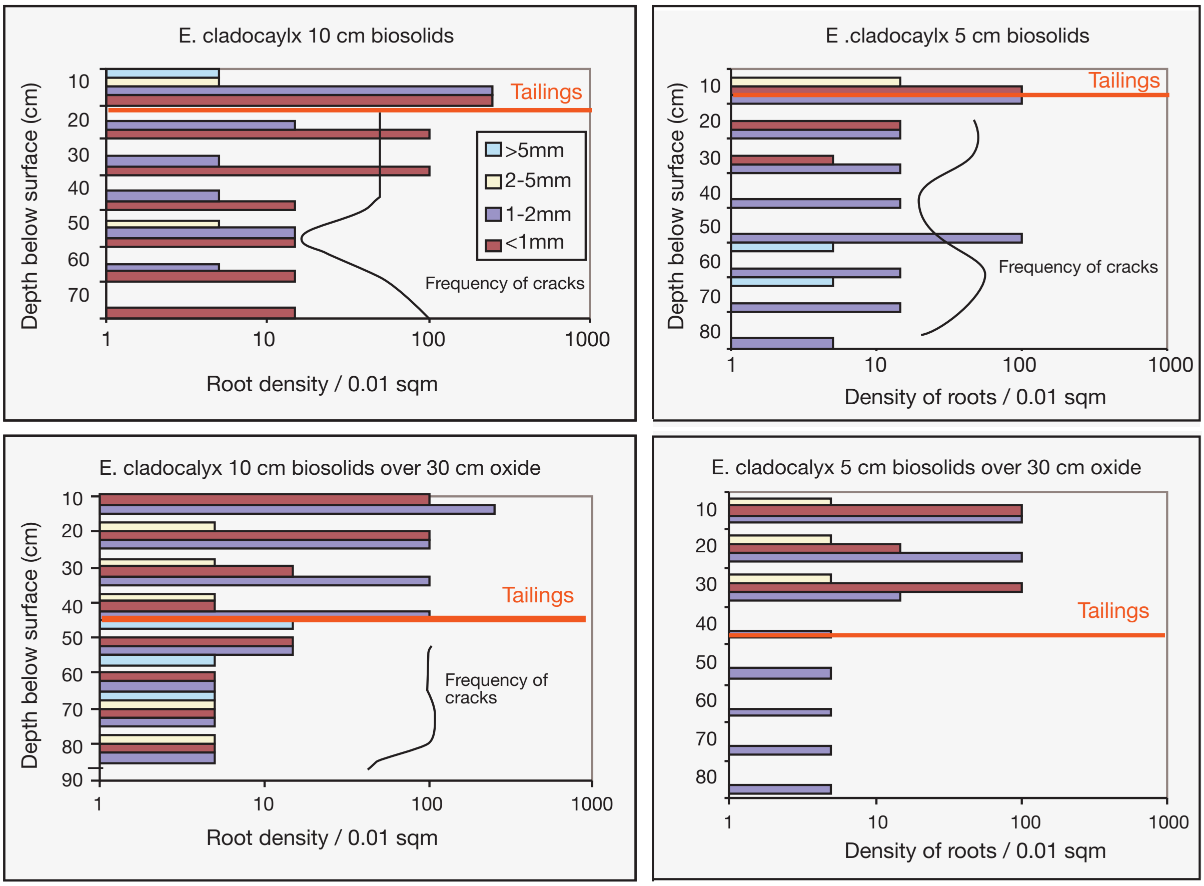
*Figure 4: Change in electrical conductivity and pH of surface treatment on sulphidic tailings.*



The average density of different size classes of roots at different depths underneath *E. cladocalyx* seedlings is illustrated in Figure 5. This species is deep rooted and the fastest growing of the eucalypts in the trial and would show greater stress responses from limiting factors after 2.5 years. Proliferation of roots in the deeper reaches of the profile appears to be strongly related to the presence of cracks in the tailings. Preferential pathways are created for water to percolate through. Formation of fine and very fine roots was greatest in the upper layers. These are predominantly roots of pasture species, however eucalypt roots were evident in the deeper cracks down to almost 1 m depth.

Tree species have been able to persist and grow successfully over two drought years. Plant growth has also encouraged weathering of the upper profile and also created conditions which reduce release of arsenic. Biosolids amendments have enhanced the biological activity of soil flora as well as the improved soil structure which has encouraged weathering.

*Figure 5:* *Depth distribution of* E. cladocalyx *roots. Data are abundance of different size classes of roots in different abundance classes 1- 10, 10 - 25, 25 - 200, > 200 for very fine < 1mm and ,1 - 2 mm, fine roots and for medium and, 2 - 5 mm, and coarse roots > 5 mm. Density scale is a logarithmic scale.*



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# UPTAKE OF ARSENIC BY NATIVE PLANTS GROWING ON GOLD TAILINGS IN WESTERN AUSTRALIAN RANGELANDS*

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## ABSTRACT

*The natural concentration of arsenic in soils may range from 1-40 mg/kg, whereas soils overlying sulphide ore deposits in Western Australia may contain several hundred mg arsenic per kg. The greater concentration of arsenic exists within the orebodies and their immediate surrounds, and values in the thousands of mg/kg are often recorded. As a result, high arsenic levels are often found in gold tailings milled from these orebodies. Environmental considerations require that local native species are established on tailings storage facilities (TSF). Uptake of arsenic by these plants is a concern, but there is little information available to allow the potential risks to be assessed in an Australian context.*

*A glasshouse experiment was conducted using arsenic–rich gold tailings as the growth medium. The aim was to determine if native plants accumulate arsenic, and their growth response in the tailings. A complementary field survey assessed accumulation of metals in native plant species growing on historic and more recent TSF's in the Western Australian rangelands. In the glasshouse experiment, survival and growth of native species was far greater on low-arsenic material than on the arsenic-rich tailings. All the plants that survived in the tailings took up arsenic with concentrations ranging from 6 to 66 mg/kg, depending on plant species and the level of phosphorus application.*

*In the field, there were substantial interspecific differences in the concentration of arsenic in leaf material, for plants growing in arsenic-rich materials. For example, Atriplex species accumulated relatively little arsenic, even at high soil concentrations. By contrast, another chenopod, Maireana pyramidata, appeared to consistently take up larger quantities. Species of other genera appeared to fall in a range between these two. In preliminary comparisons of washed and unwashed Atriplex plants, it appeared that considerable quantities of arsenic may be also found on leaf surfaces. If confirmed, then arsenic that wildlife may ingest by eating leaves and shoots may be 50% greater than measured in this survey.*

*In 2 out of 14 species grown in the glasshouse experiment in these arsenic-rich gold tailings, arsenic concentrations exceeded the ANZECC maximum tolerable dietary intake level for livestock (50 mg inorganic arsenic per kg of diet). In the field study, arsenic in leaf material of Maireana pyramidata also exceeded the toxicity limit. Eight out of 14 species grown in the glasshouse experiment, and plants from two genera sampled in the field, contained in excess of 20 mg/kg of arsenic.*

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## INTRODUCTION

Arsenic is a naturally occurring, potentially toxic element in sediments and waters of the earths crust (O'Neill, 1995). Arsenic speciation in the environment is of critical importance for its toxicity. Inorganic arsenic compounds are more toxic than organic arsenic compounds to mammals. The reduced species of inorganic arsenic, As(III), is reported to be 25 to 60 times more toxic than the oxidized species, As(V). Furthermore, As(III) is intrinsically more mobile in the soil environment (Smith *et al.*, 1998). The toxicity of arsenic to plants is a function of the species of arsenic present and the amount of water soluble arsenic that is available for plant uptake. The availability of arsenic for plant uptake is affected by soil parameters such as pH, redox status, organic matter content, clay content, the occurrence of iron and aluminium, and the phosphorus content of soils (De Koe, 1991; Parametrix, 1995; Smith *et al.*, 1998).

Wastes generated by the mining of gold and other base metals often contain elevated concentrations of arsenic (Bech *et al.*, 1997; Bruce *et al.*, 2001; De Koe, 1991; Smith *et al*, 1998). In Western Australia, high arsenic values are often found in the tailings-solids derived from gold deposits. The arsenic is usually derived from arsenopyrite (FeAsS) in the ore (O'Neill, 1995). Environmental considerations and regulatory commitments require that local native species are established on tailings storage facilities (TSF). Uptake of arsenic by these plants is a concern, but there is little information available to allow the potential risks to be assessed in an Australian context.

A considerable variation in plant response to arsenic has been demonstrated between species of crop plants, especially in capacity for arsenic uptake and tolerance of arsenic in plant tissue (Fergusson, 1990; Peterson *et al.*, 1981). Plants that can survive in arsenic rich soil/tailings, and especially if they accumulate arsenic in leaves and shoots, have the potential to impact on grazing animals.

The phytotoxic effects of arsenic may result in a sudden decrease in water mobility, as suggested by root plasmolysis and discolouration (yellow-browning) followed by necrosis of leaf tips and margins (Fergusson, 1990). Symptoms can also include growth reduction, violet coloration (increased anthocyanin accumulation) and leaf wilting (Kabata-Pendias & Pendias, 1984). Seed germination can also be arrested (Fergusson, 1990). The movement of arsenic within plants is restricted, and the relative order of arsenic concentrations is usually roots>vegetative tissue>seeds and fruit, with old leaves likely to contain more arsenic than the young ones (Fergusson, 1990; Smith *et al.*, 1998).

Although there are suggested differences in tolerance to arsenic among species, the maximum tolerable dietary intake of arsenic for livestock is 50 mg of inorganic forms per kg of diet or 100 mg of organic forms, per kg of diet (ANZECC & ARMCANZ, 2000). North American literature refers to a suggested limit of 20 mg arsenic per kg of plant-containing feedstuff for domestic livestock, and reports adverse effects in mammals at levels of 50 mg of inorganic arsenic forms per kg of feed (Koch *et al.*, 2000). Therefore, for plants containing arsenic greater than 20 mg/kg dry weight of leaves and stems, possible effects on wildlife cannot be excluded.

In this study, a glasshouse experiment was conducted using arsenic-rich tailings as the primary growth medium. The aim was to ascertain the tolerance of native plants to arsenic contained in tailings, and to determine if plants accumulate arsenic when grown on the mine residue. In addition, a field survey was carried out to gain an understanding of the issue of bioaccumulation of arsenic by arid land native plant species growing on historic and more recent tailings storage facilities in the Western Australian rangelands.

## METHODS

### Glasshouse experiment

In this experiment, we examined the effect of increasing additions of phosphorus on plant growth and arsenic uptake, with 14 native species growing on arsenic-rich tailings material (Table 1). The tailings material had been collected from 12 areas across a gold mine tailings facility near Leinster, Western Australia, and spread evenly into eight 50 kg containers. Plant growth in the tailings was compared to that in low-arsenic lateritic waste material, which was collected from one area on the mine.

Three samples of the tailings and one sample of the laterite waste material were analyzed for plant available nutrients using standard techniques (Page *et al.*, 1995) (Table 2). The tailings and laterite were also analysed for total arsenic using an Inductively Coupled Plasma – Mass Spectrometer (ICP-MS) (Quaghebeur *et al.*, 2003).

For the pot experiment, tailings were placed into a cement mixer and mixed for 10 minutes to create a homogeneous sample. The laterite waste was passed through a 2 mm sieve to remove rocks and gravel. Pots were lined with plastic bags and each pot was filled with 1.6 kg of material. The pots were 25 cm deep, with a surface area of 49 $cm^2$. Eighty-four pots were filled with tailings and 14 were filled with laterite waste.

Fertilizer treatments were applied to the pots prior to planting (Table 3). The g/kg of fertilizer for the glasshouse situation was converted from kg/ha in the field situation using a general conversion factor of 2 million kg of soil per hectare. A higher rate of Agrich® was applied to the laterite than to the tailings, because the laterite contained lower levels of nitrate than the tailings (Table 3).

**Table 1: Species selected for planting in laterite and arsenic-rich tailings in a glasshouse experiment**

| FAMILY | SPECIES | COMMON NAME |
|---|---|---|
| AMARANTHACEAE | *Ptilotus obovatus* | Cotton Bush |
| CHENOPODIACEAE | *Atriplex nummularia* | Old Man Saltbush |
| | *Atriplex vesicaria* | Bladder Saltbush |
| | *Atriplex semilunaris* | Annual Saltbush |
| | *Maireana brevifolia* | Small Leafed Bluebush |
| | *Maireana georgei* | George's Bluebush |
| | *Maireana tomentosa* | Felty Bluebush |
| | *Maireana villosa* | |
| MIMOSACEAE | *Acacia acuminata* | Fine Leaf Jam |
| | *Acacia ligulata* | Umbrella Wattle |
| SAPINDACEAE | *Dodonea viscosa* | Sticky Hopbush |
| | *Dodonea lobulata* | Bead Hopbush |
| PITTOSPORACEAE | *Pittosporum phylliraeoides* | Native Willow |
| CAESALPINIACEAE | *Senna planitiicola* | Arsenic Bush |

**Table 2: Analyses on laterite and tailings material used in the glasshouse experiment (mean ± SE, n=3)**

| Analysis | Tailings | Laterite* |
|---|---|---|
| Total Arsenic (mg/kg) | 2980 ± 80 | 11 ±1 |
| Nitrate Nitrogen (mg/kg) | 45 ± 1 | 26 |
| Ammonium Nitrogen (mg/kg) | 1.3 ± 0.3 | 1 |
| Extractable Phosphorus (mg/kg)[1] | 14 ± 1 | 3 |
| Extractable Potassium (mg/kg)[1] | 1000 ± 10 | 173 |
| Extractable Sulphur (mg/kg)[2] | 527 ± 2 | 5,200 |
| Organic Carbon (g/kg) | 2.3 ± 0.005 | 2.5 |
| Conductivity (1:5 $H_2O$) (dS/m) | 1.09 ± 0.08 | 3.58 |
| pH (1:5 $CaCl_2$) | 8.1 ± 0.1 | 7.6 |
| pH (1:5 $H_2O$) | 8.5 ± 0.06 | 7.8 |
| Exch. Calcium (cmol(+)/kg) | 2.37 ± 0.2 | 12.6 |
| Exch. Magnesium (cmol(+)/kg) | 0.30 ± 0.03 | 4.99 |
| Exch. Sodium (cmol(+)/kg) | 2.81 ± 0.1 | 5.18 |
| Exch. Potassium (cmol(+)/kg) | 0.28 ± 0.02 | 0.36 |
| Texture[3] | Light Clay | Medium Clay with gravels |

*For all analyses except Total Arsenic, only 1 rep was analyzed.

[1]Colwell (1963), [2]Anderson *et al*. (1992), [3]McDonald *et al*. (1998).

**Table 3: Fertilizer treatments applied to tailings and laterite in the glasshouse experiment (kg/ha)**

| Fertilizer | ---------- | Tailings | ---------- | Laterite waste |
|---|---|---|---|---|
| | $P_1$ | $P_2$ | $P_3$ | |
| Agrich® (11.5%N, 11.4%P) | 50 | 50 | 50 | 100 |
| Double Phos (18%P) | 0 | 50 | 100 | 50 |

The Agrich® and Double Phosphate fertilizers were dissolved separately in water and added. For the tailings, each species was grown in two replicate pots at each phosphorus level.

Before planting, pots containing laterite and tailings were brought to field capacity, and were maintained at these water contents throughout growth. The field capacities of the tailings and laterite waste material were determined by subjecting saturated soil samples to 10 kPa suction for 5 days (Page *et al.,* 1995).

To ensure adequate plant numbers, seed was pre-germinated and planted into the pots when the radicle was 2 mm in length. The pots were then sealed to prevent moisture loss and maintain a high level of humidity for early growth. The pots were arranged in the glasshouse in a randomized block design. Once the seedlings had fully emerged, the bags were opened and a layer of plastic beads (1 cm deep) was placed on the soil surface to reduce evaporation and the generation of dust.

Plant deaths and discoloration in plant leaves was recorded at 3, 5, 7, and 9 weeks of growth. After 5 days, all seedlings of *Maireana brevifolia* had died in pots containing tailings, and this species was replanted. Plants were harvested 9 weeks after planting. Fresh and dry weights of shoots were recorded. The shoots were digested in concentrated nitric acid and analyzed for total arsenic using the hydride generation method on ICP-MS (Quaghebeur *et al.,* 2003). The tailings material was also analysed for arsenic speciation using ICP-MS.

## Field study

### Sampling

Plants and soils were sampled at 18 sites in early March 2002. Sampling sites included tailings storage facilities (TSF) and unconfined tailings on active mine sites, as well as at old abandoned mines. Both capped and uncapped tailings materials were sampled. Capping is achieved by spreading local soils or mine wastes over the tailings. The sampling route through the Western Australian goldfields was via Cue, Meekatharra, Wiluna, Leonora, Kalgoorlie, and Southern Cross.

At each sampling site, two plots (2 replications) with good plant growth were chosen, and up to four species were sampled in each plot. The plots were chosen by selecting areas where groups of the same species of plants were growing in a localized area. Each plot was approximately 25 to 50 m in diameter and plots were separated by 50 m or more. The number of species sampled depended upon the number of species common to both plots. Within each plot, soils were sampled at two depths (10 cm and 50 cm) at two separate positions. Soil samples from each depth were bulked giving 2 soil samples per plot, and four soil samples per sampling site. At some sites a capping layer over the tailings material extended to a depth greater than 50 cm. In such instances, soil samples were taken at depths of 10 cm, 35 cm, and 70 cm (tailings), which resulted in 6 soil samples for those sampling sites. Soil samples were collected with a hand auger and spade and placed in plastic snap-lock bags. Approximately 300-500 g was taken for each soil sample. Soils were air dried at 40˚C prior to analysis.

Plant species were identified and then sampled separately. Leaf samples were taken from plants of similar size, from the largest plants present at the site. The oldest green leaves were sampled and placed in plastic snap-lock bags. Approximately 100 g were taken for each leaf sample. At the end of each day, the plant material was washed 5 times in tap water and once in deionized water to minimize contamination of the samples by soil particles. The samples were then placed in paper bags for transportation to the laboratory. Plants were dried in a drying oven at 65˚C prior to analysis.

### Soil and plant analysis

Preliminary measurements of arsenic concentrations in soil were carried out in the field using a specially-adapted kit. This field kit provided immediate estimates of arsenic concentration, and allowed the choice of sampling sites with relatively high arsenic concentrations. The kit was adapted by Mieke Quaghebeur (PhD student – The University of Western Australia) from an arsenic kit that was designed to determine arsenic concentrations in water. This kit is still under development.

Soils from the 18 field sites were sieved to 2 mm and digested in nitric acid. Total concentrations of arsenic were then measured using ICP-MS (Quaghebeur *et al.*, 2003). In addition, 'plant-available' arsenic was extracted from soil using the $NH_4HCO_3$ – DTPA method (Amacher, 1996) and measured using ICP-MS (Quaghebeur *et al.*, 2003). Measurements of pH and EC were carried out on the tailings and capping layers from the field sites using a 1:5 soil:distilled water suspension. Samples of leaf material collected at the field sites were ground to create an homogeneous sample. The sample was then digested in nitric acid and analyzed for total arsenic using ICP-MS (Quaghebeur *et al.*, 2003).

## RESULTS AND DISCUSSION

### Glasshouse Experiment

The tailings contained a high concentration of total arsenic, while the concentration in the laterite waste was low (Table 2). Plant growth and survival on the laterite material was far better than on the tailings material (Table 4). All 14 species survived on the laterite, while even at the highest rate of phosphorus, only 10 species survived in the tailings material (Table 4). These values emphasize the highly deleterious effects of these metal-rich tailings on plant growth.

Adding phosphorus to the tailings increased average plant growth and survival however, there were no clear relationships for each species between plant biomass and the rate of phosphorus applications to the tailings. The range of dry shoot weights for various plant species on the laterite was 13 to 2311 mg/plant, compared to a range of 0 to 54 mg for the tailings material, depending on phosphorus application rate.

All the plants that survived in the tailings took up arsenic, whereas plants growing in laterite material contained little or no arsenic. The concentration of arsenic in plant tops ranged from 6 to 66 mg/kg dry weight, depending on the plant species and the level of phosphorus application (Table 4). However, there was no consistent relationship between average arsenic concentration in shoots and phosphorus application to the tailings for this diverse selection of native plant species. For example, *Atriplex vesicaria* and *Maireana georgei* appeared to have reduced arsenic uptake when phosphorus application was increased (Table 4). By contrast, arsenic concentration in *Senna planitiicola* increased from 6 to 36 mg/kg d.w. when the equivalent of 100 kg/ha phosphorus was added to the tailings (Table 4). The dry weight of *Senna planitiicola* also decreased with increasing phosphorus application to the tailings, possibly due to arsenic toxicity. Further work is required to characterise the overall effect of phosphate application on native plant uptake of arsenic.

The interaction of arsenic and phosphorus in soil and in plant uptake is complex. In soil, similarly-charged arsenic and phosphorus species compete for sorption sites on the soil components (Peterson *et al.*, 1981). The smaller size of the phosphate ions, compared to the corresponding arsenate ions, and considerably greater concentration of phosphorus in soil, often means that the phosphate binds in preference to arsenate or arsenite. Therefore, phosphorus application to the tailings may have displaced previously bound arsenic, causing an increase in arsenic mobility (i.e. plant availability) (Kabata-Pendias and Pendias, 1984; Smith *et al.*, 1998).

**Table 4:** **Dry weights and arsenic concentration in shoots of plants grown in a glasshouse on laterite and tailings from a gold mine in Western Australia (mean ± standard error (SE), n=2)**

| Species | Soil | Double Phos added (18% P) to tailings (kg/ha) | Shoot dry wt per plant (mg) | | Shoot As (mg/kg d.w.) | |
|---|---|---|---|---|---|---|
| | | | mean | SE | mean | SE |
| *Acacia acuminata* | tailings | 0 | 19 | 5 | 21 | 6 |
| | tailings | 50 | 22 | 3 | 33 | 17 |
| | tailings | 100 | 16 | 3 | 36 | 1 |
| | laterite | - | 95 | - | 0 | - |
| *Acacia ligulata* | tailings | 0 | 6 | - | 66 | - |
| | tailings | 50 | 17 | 4 | 16 | 1 |
| | tailings | 100 | 7 | 0 | 37 | 9 |
| | laterite | - | 68 | - | 0 | - |
| *Atriplex nummularia* | tailings | 0 | 0* | - | - | - |
| | tailings | 50 | 5 | 0 | 17 | 1 |
| | tailings | 100 | 6 | - | 13 | - |
| | laterite | - | 898 | - | 0 | - |
| *Atriplex semilunaris* | tailings | 0 | 0* | - | - | - |
| | tailings | 50 | 0* | - | - | - |
| | tailings | 100 | 0* | - | - | - |
| | laterite | - | 1314 | - | 0 | - |
| *Atriplex vesicaria* | tailings | 0 | 11 | 5 | 42 | 6 |
| | tailings | 50 | 14 | 5 | 31 | 3 |
| | tailings | 100 | 54 | 54 | 8 | 8 |
| | laterite | - | 1147 | - | 0 | - |
| *Dodonaea lobulata* | tailings | 0 | 0* | - | - | - |
| | tailings | 50 | 0* | - | - | - |
| | tailings | 100 | 0* | - | - | - |
| | laterite | - | 65 | - | 1 | - |
| *Dodonaea viscosa* | tailings | 0 | 0* | - | - | - |
| | tailings | 50 | 0* | - | - | - |
| | tailings | 100 | 0* | - | - | - |
| | laterite | - | 13 | - | 1 | - |
| *Maireana brevifolia* | tailings | 0 | 0* | - | - | - |
| | tailings | 50 | 0* | - | - | - |
| | tailings | 100 | 0* | - | - | - |
| | laterite | - | 1011 | - | 0 | - |
| *Maireana georgei* | tailings | 0 | 22 | 0 | 31 | 4 |
| | tailings | 50 | 19 | - | 20 | - |
| | tailings | 100 | 42 | 22 | 20 | 5 |
| | laterite | - | 995 | - | 0 | - |
| *Maireana tomentosa* | tailings | 0 | 8 | 2 | 35 | 7 |
| | tailings | 50 | 16 | - | 43 | - |
| | tailings | 100 | 11 | 4 | 26 | 5 |
| | laterite | - | 667 | - | 0 | - |
| *Maireana villosa* | tailings | 0 | 0* | - | - | - |
| | tailings | 50 | 16 | 16 | 8 | 8 |
| | tailings | 100 | 6 | 6 | 15 | 15 |
| | laterite | - | 2311 | - | 0 | - |
| *Pittosporum phylliraeoides* | tailings | 0 | 9 | 0 | 28 | 1 |
| | tailings | 50 | 10 | 4 | 36 | 18 |
| | tailings | 100 | 15 | 1 | 33 | 19 |
| | laterite | - | 56 | - | 1 | - |
| *Ptilotus obovatus* | tailings | 0 | 0* | - | - | - |
| | tailings | 50 | 2 | 2 | 32 | 32 |
| | tailings | 100 | 6 | 0 | 62 | 34 |
| | laterite | - | 876 | - | 0 | - |
| *Senna planitiicola* | tailings | 0 | 30 | 3 | 6 | 1 |
| | tailings | 50 | 25 | 0 | 9 | 3 |
| | tailings | 100 | 22 | 2 | 36 | 7 |
| | laterite | - | 39 | - | 0 | - |

*INDICATES THAT THE SPECIES DIED.

**Table 5: Extractable arsenic (As), total As, EC, and pH of tailings and capping layers at sites located in the rangelands of Western Australia (mean ± standard error (SE), n=3)**

| Site | ------ Site description ------ | | | Sample depth | Ext. As (mg/kg) | | Total As (mg/kg) | | EC (dS/m) | | pH | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | con. /uncon. | cap. /uncap | reveg. | (cm) | mean | SE | mean | SE | mean | SE | mean | SE |
| 1 | con. | cap. | seeded | 10 | 5.3 | 1.7 | 649 | 153 | 3.1 | 1.1 | 6.1 | 1.4 |
| | | | (~4 y.o.) | 50 | 23 | 9 | 1400 | 520 | 1.7 | 0.1 | 6.6 | 0.8 |
| 2A | con. | cap. | seeded | 10 | 1.8 | 0.1 | 2390 | 1140 | 1.6 | 0.6 | 8.3 | 0.8 |
| | | | (~7 y.o.) | 50 | 10 | 0.7 | 1370 | 47 | 2.4 | 0.8 | 9.2 | 0.0 |
| 2B | con. | uncap. | seeded | 10 | 20 | 0.5 | 1980 | 157 | 1.6 | 0.4 | 9.7 | 0.3 |
| | | | (~7 y.o.) | 50 | 13 | 0.7 | 1080 | 9 | 1.1 | 0.0 | 9.3 | 0.1 |
| 3 | con. | cap. | seeded | 10 | 2.3 | 1.1 | 523 | 72 | 3.7 | 1.2 | 7.6 | 0.2 |
| | | | (~4 y.o.) | 50 | 10 | 0.4 | 708 | 487 | 0.6 | 0.0 | 9.7 | 0.1 |
| 4 | con. | cap. | seeded | 10 | 4.3 | 2.3 | 906 | 121 | 5.3 | 2.1 | 8.2 | 0.3 |
| | | | | 50 | 31 | 8 | 764 | 147 | 8.0 | 4.8 | 8.4 | 0.1 |
| 5 | uncon. | uncap. | unseeded | 10 | 43 | 8 | 1060 | 60 | 1.0 | 0.5 | 8.6 | 0.3 |
| | | | | 50 | 69 | 4 | 1520 | 331 | 2.2 | 0.7 | 8.3 | 0.0 |
| 6 | uncon. | uncap. | unseeded | 10 | 14 | 7 | 4070 | 1710 | 2.6 | 0.2 | 8.4 | 0.0 |
| | | | | 50 | 14 | 6 | 3910 | 2270 | 1.5 | 0.1 | 8.4 | 0.1 |
| 7 | uncon. | uncap. | unseeded | 10 | 81 | 31 | 2110 | 360 | 6.5 | 6.0 | 8.1 | 0.1 |
| | | | | 50 | 26 | 7 | 1450 | 538 | 5.5 | 3.2 | 7.9 | 0.1 |
| 8 | uncon. | uncap. | unseeded | 10 | 83 | 33 | 3080 | 35 | 3.7 | 1.5 | 8.0 | 0.2 |
| | | | | 50 | 86 | 6 | 3450 | 342 | 3.4 | 0.1 | 7.9 | 0.1 |
| 9 | uncon. | uncap. | unseeded | 10 | 24 | 3 | 671 | 32 | 1.9 | 0.8 | 8.4 | 0.1 |
| | | | | 50 | 33 | 5 | 638 | 13 | 2.3 | 0.5 | 8.6 | 0.0 |
| 10 | con. | uncap. | unknown | 10 | 3.1 | 0.0 | 605 | 39 | 6.2 | 1.6 | 8.2 | 0.1 |
| | | | | 50 | 3.5 | 0.3 | 944 | 197 | 4.1 | 0.7 | 8.0 | 0.3 |
| 11 | con. | uncap. | unknown | 10 | 11 | 1.7 | 1410 | 405 | 0.1 | 0.0 | 8.6 | 0.1 |
| | | | | 50 | 27 | 17 | 1790 | 737 | 0.3 | 0.1 | 9.0 | 0.0 |
| 12 | con. | uncap. | unseeded | 10 | 22 | 9 | 1380 | 64 | 1.2 | 0.4 | 8.4 | 0.1 |
| | | | | 50 | 26 | 4 | 1540 | 185 | 10.1 | 7.8 | 8.5 | 0.0 |
| 14 | con. | uncap. | unseeded | 10 | 1.0 | 0.0 | 175 | 34 | 12.8 | 3.7 | 7.8 | 0.4 |
| | | | | 50 | 0.9 | 0.6 | 132 | 72 | 5.0 | 0.0 | 8.1 | 0.1 |
| 17 | con. | cap. | unknown | 10 | 0.6 | 0.1 | 49 | 3 | 0.3 | 0.0 | 8.9 | 0.2 |
| | | | | 35 | 2.7 | 0.5 | 251 | 100 | 3.6 | 0.0 | 8.3 | 0.0 |
| | | | | 70 | 69 | 15 | 1760 | 47 | 4.9 | 0.1 | 8.1 | 0.1 |
| 18 | uncon. | uncap. | unknown | 10 | 1.2 | 0.5 | 377 | 122 | 1.2 | 0.2 | 8.5 | 0.3 |
| | | | | 50 | 1.1 | 0.1 | 409 | 112 | 1.9 | 0.3 | 8.7 | 0.2 |
| 19 | con. | cap. | seeded | 10 | 0.1 | 0.1 | 25 | 8 | 0.2 | 0.1 | 6.3 | 0.1 |
| | | | (~5 y.o.) | 50 | 6.6 | 0.1 | 751 | 1 | 2.7 | 0.4 | 7.6 | 0.0 |
| 20 | con. | cap. | seeded | 10 | 0.2 | 0.1 | 28 | 5 | 11.2 | 1.6 | 8.0 | 0.0 |
| | | | (~8 y.o.) | 50 | 0.4 | 0.1 | 119 | 13 | 4.9 | 0.7 | 8.3 | 0.0 |

confined/unconfined: confined = built structure (generally <20 years old)
unconfined = open structure (historic sites >20 years old)

capped/uncapped: capped = distinct layer of waste rock or topsoil (may be multiple layers)
uncapped = original as deposited tailings surface

revegetation: seeded = seeded with a known mix and known quantities (y.o. = years ago)
unseeded = naturally colonized
unknown = may be seeded or naturally colonized

Arsenic and phosphorus are taken up by the same transporter in the root-cell plasma membrane (Peterson *et al.*, 1981). A small amount of phosphorus is required to stimulate the transporter, thus allowing arsenic to be taken up as well. However, if the amount of available phosphorus is large, there will be competition between phosphorus and arsenic and the result may be decreased arsenic uptake (Kabata-Pendias and Pendias, 1984; Smith *et al.*, 1998). The outcome depends on the characteristics of each plant species, therefore, the overall effect of phosphorus application on plant uptake of arsenic is difficult to predict.

## Field Study

A large range of arsenic concentrations were found in the diverse tailings sites sampled. Total arsenic concentrations in tailings ranged from 119 to 4070 mg/kg, while total arsenic in capping layers ranged from 25 to 2390 mg/kg (Table 5). There was also a large range of EC values, with native plants found growing on tailings material up to 12.5 dS/m (Table 5). The tailings were circum-neutral to strongly alkaline, with the bulk of the soils occurring in the pH range 7.5 to 9 (Table 5). There was no relationship between arsenic levels in soils and EC or pH.

In general, the level of extractable arsenic in tailings tended to be higher with high total arsenic levels, particularly at 50 cm depth (Figure 1). However, there were some very clear exceptions to this trend (Figure 1). The scattering of the data could be due to different properties of the tailings at each site, such as the levels of organic matter and phosphorus, clay content, and the occurrence of iron.

There was a large range of arsenic concentrations in plants growing at the tailings sites (Table 6). For example, *Maireana pyramidata* contained up to 71 mg/kg (Table 6; Figure 2), while others, especially *Atriplex* species had very low levels, even at high concentrations of arsenic in the soil. In particular, *Atriplex nummularia* appeared best at excluding arsenic, with arsenic concentration in the plants always below 6 mg/kg, even when the total arsenic concentration in tailings reached 3800 mg/kg (Tables 5, 6). Arsenic concentrations in leaves of *A. vesicaria* and *A. bunburyana* did not exceed 20mg/kg (Table 6).

In contrast to the *Atriplex* species, *Maireana pyramidata* appeared to contain larger concentrations of arsenic at given low concentrations in the soil (Figure 2). There were no obvious relationships for arsenic concentration in the plants and the soil for the other species sampled. This may be due to the small number of replications available for those species.

At five of the seven capped sites (Sites 1, 3, 17, 19, and 20), the total arsenic concentration in the capping layer was lower than in the tailings below (Table 5). However, the

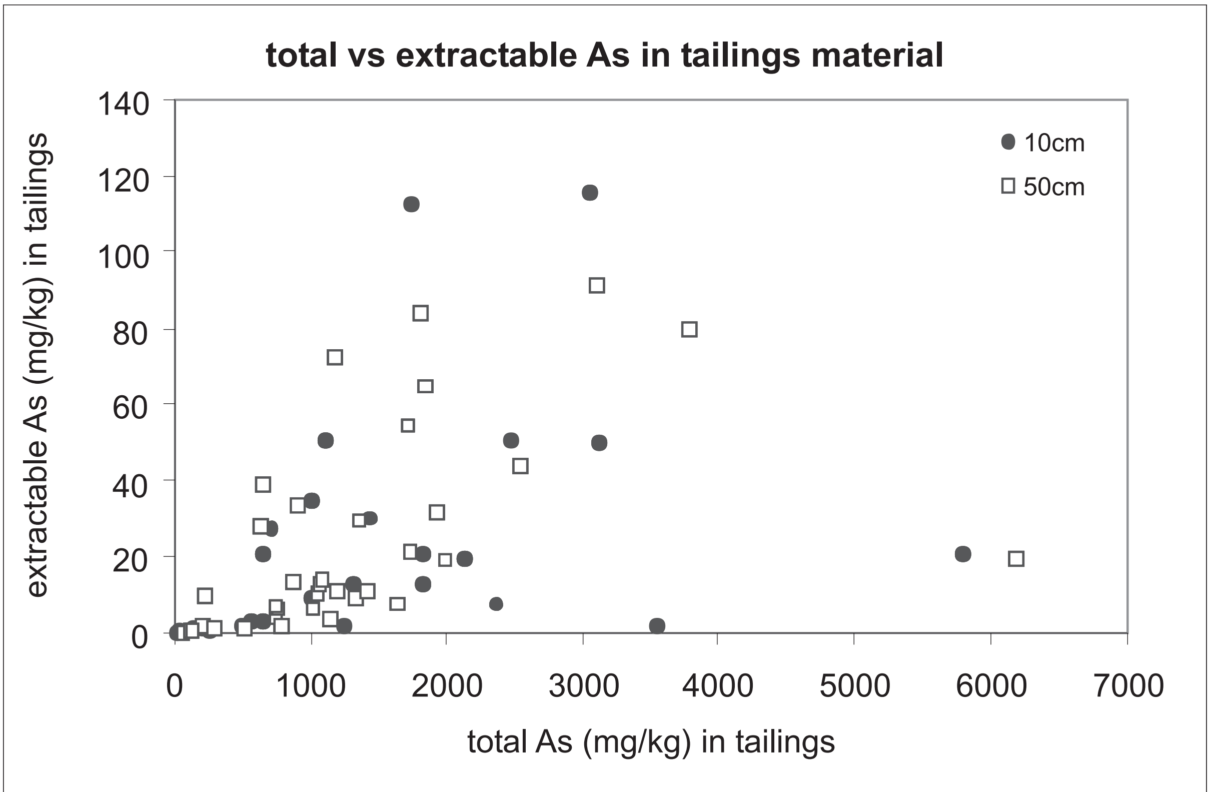


*Figure 1: Total and extractable (plant available) arsenic (As) in tailings at sites located in the rangelands of Western Australia*

**Table 6:** **Arsenic (As) concentration in leaves of plants growing on tailings at sites located in the rangelands of Western Australia**

| Site | Capped/uncapped | Species | Plant As (mg/kg) | |
|---|---|---|---|---|
| | | | mean | SE |
| 1 | Capped | *Atriplex bunburyana* | 1.8 | 1.1 |
| | | *Atriplex nummularia* | 1.6 | 0.8 |
| | | *Maireana pyramidata* | 2.0 | 1.0 |
| | | *Maireana triptera* | 2.7 | 2.3 |
| 2A | Capped | *Atriplex vesicaria* | 12 | 0.6 |
| | | *Maireana polypterygia* | 29 | 20 |
| | | *Maireana pyramidata* | 32 | 9 |
| 2B | Uncapped | *Atriplex vesicaria* | 16 | 1 |
| | | *Maireana polypterygia* | 26 | 5 |
| | | *Maireana pyramidata* | 71 | 2 |
| 3 | Capped | *Atriplex nummularia* | 1.1 | 0.1 |
| | | *Atriplex vesicaria* | 3.5 | 0.3 |
| | | *Maireana pyramidata* | 2.5 | 0.3 |
| | | *Maireana triptera* | 1.3 | 0.1 |
| 4 | Capped | *Acacia pruinocarpa* | 13 | 8 |
| | | *Acacia victoriae* | 4.3 | 1.7 |
| | | *Atriplex nummularia* | 0.8 | 0.6 |
| | | *Maireana pyramidata* | 1.6 | 1.1 |
| 5 | Uncapped | *Atriplex bunburyana* | 8.0 | 0.5 |
| | | *Atriplex vesicaria* | 6.2 | 0.4 |
| | | *Halosarcia syncarpa* | 2.3 | 0.4 |
| | | *Muehlenbeckia sp.* | 13 | 1 |
| 6 | Uncapped | *Atriplex quinii* | 21 | 4 |
| | | *Halosarcia syncarpa* | 5.2 | 0.5 |
| | | *Maireana georgei* | 17 | 3 |
| 7 | Uncapped | *Atriplex bunburyana* | 4.7 | 0.4 |
| 8 | Uncapped | *Atriplex bunburyana* | 8.6 | 0.6 |
| | | *Atriplex nummularia* | 4.5 | 0.9 |
| 9 | Uncapped | *Atriplex bunburyana* | 3.2 | 0.2 |
| | | *Atriplex vesicaria* | 3.1 | 0.2 |
| | | *Halosarcia halocnemoides* | 5.0 | 0.4 |
| | | *Maireana pyramidata* | 2.8 | 1.0 |
| 10 | Uncapped | *Atriplex bunburyana* | 0.9 | 0.1 |
| | | *Atriplex nummularia* | 0.5 | 0.1 |
| | | *Atriplex vesicaria* | 1.0 | 0.2 |
| | | *Eucalyptus salubris* | 0.7 | 0.1 |
| 11 | Uncapped | *Alyogyne hakeifolia* | 13 | - |
| | | *Atriplex stipitate* | 12 | 0.3 |
| | | *Eucalyptus sp.* | 4.0 | 2.3 |
| 12 | Uncapped | *Atriplex bunburyana* | 4.6 | 0.0 |
| | | *Atriplex lentiformis* | 5.9 | 0.4 |
| | | *Atriplex stipitata* | 10 | 1.0 |
| 14 | Uncapped | *Atriplex bunburyana* | 3.4 | 1.7 |
| 17 | Capped | *Atriplex bunburyana* | 1.2 | 0.2 |
| | | *Atriplex vesicaria* | 1.0 | 0.7 |
| | | *Maireana pyramidata* | 0.9 | 0.1 |
| | | *Maireana triptera* | 0.7 | 0.2 |
| 18 | Uncapped | *Atriplex bunburyana* | 3.4 | 1.7 |
| | | *Maireana pyramidata* | 42 | - |
| 19 | Capped | *Acacia aneura* | 9.7 | 0.1 |
| | | *Acacia murrayana* | 24 | 0.5 |
| | | *Maireana pyramidata* | 7.3 | 1.7 |
| | | *Maireana villosa* | 9.0 | 3.1 |
| 20 | Capped | *Atriplex nummularia* | 0.3 | 0.2 |
| | | *Atriplex vesicaria* | 1.5 | - |
| | | *Maireana pyramidata* | 1.2 | 0.0 |

opposite occurred at Sites 2A and 4, where the total arsenic concentrations in the top 10 cm were 2390 and 906 mg/kg respectively, with total arsenic concentrations at 50 cm depth of 1370 and 764 mg/kg respectively. This may be due to capillary rise of water bringing arsenic to the surface over time, or from contamination during or after application of the capping layer. In the case of site 2A, tailings dust was known to be deposited on the capping (H. Lacy, pers. comm., 2002).

Capping layers can provide a habitat for roots of shallow-rooted species to remain in, thus minimizing penetration of roots of such species into the tailings below. This may result in lower arsenic uptake and concentrations in the foliage. As an example, arsenic concentration in leaves of *M. pyramidata* was positively related to total arsenic in the top 10 cm. Therefore, capping layers with low total arsenic appear likely to minimize arsenic uptake by this species. Arsenic concentrations in leaves of *M. pyramidata* plants growing in surface layers with up to 1,000 mg As/kg, generally remained less than 10 mg/kg. There was one exception, where 42 mg As/kg arsenic was recorded in leaves of *M. pyramidata* growing in material with total arsenic around 500 mg/kg. This site consisted of uncapped tailings of pH 8.8 and 1.36 dS/m E.C. Further work is required to ascertain factors determining arsenic uptake in the soil-plant system.

No plant species other than *M. pyramidata* showed any decrease in arsenic uptake as a result of a capping layer. For some species, this conclusion was limited by the small number of replications available. For other species, such as *Atriplex* species it may be because they only take up small amounts of arsenic, independent of the concentration in the soil.

Successful natural colonization and growth of native species on uncapped tailings material with high arsenic concentrations were observed in the field, for example Sites 5 to Sites 14 (Table 6). This was in contrast to very poor plant growth and survival in tailings with similar arsenic levels in the pot experiment. Therefore, it may be that other factors in the tailings were affecting plants in the pot experiment. Alternatively, it may be due to the adaptation of plants to arsenic in the field.

The potential for adverse health effects on biota from the arsenic in tailings needs to be further assessed. The maximum tolerable dietary intake of arsenic for livestock is 50 mg of inorganic forms per kg dry matter of 100 mg of organic forms per kg dry matter (ANZECC & ARMCANZ, 2000). Arsenic concentrations in the plant shoots grown in the glasshouse experiment in raw tailings, with no fertilizers added, ranged from 6 mg/kg dry weight in *Senna planitiicola* to 66 mg/kg dry weight in *Acacia ligulata* (Table 4). It is likely most of that arsenic was in the inorganic form (Quaghebeur *et al.*, 2003). If this is really the case, i.e. - if all the arsenic in *A. ligulata* was in an inorganic form, it would exceed the ANZECC Guideline. In the glasshouse experiment, *Ptilotus obovatus*, with 100 kg/ha phosphorus added to the tailings, also exceeded 50 mg/kg arsenic (Table 4). Hence, out of 14 species tested, 2 exceeded the maximum tolerable concentrations of arsenic from the standpoint of dietary intake by livestock. In the field study, *Maireana pyramidata* (71 mg/kg) (Table 6) also exceeded the 50 mg As/kg toxicity limit.

North American literature refers to a suggested limit of 20 mg/kg arsenic in fodder for domestic livestock, and reports adverse effects in mammals at feeding levels of 50 mg of inorganic arsenic forms per kg of feed (Koch *et al.*, 2000). It is therefore suggested that a figure of 20 mg for inorganic arsenic per kg dry matter may well be a more appropriate limit for native vegetation growing on tailings. If this conservative approach was adopted, this would suggest that *Acacia acuminata, Aca. ligulata, Atriplex vesicaria, Maireana georgei, M. tomentosa, Pittosporum phylliraeoides, Ptilotus obovatus* and *Senna planitiicola* from the glasshouse experiment would contain unacceptable levels of arsenic in plant tissue (Table 4). This represents 8 out of the 10 species that survived in the Lawlers tailings. In the field study, *Maireana polypterygia, M. pyramidata,* and *Acacia murrayana* also exceeded the 20 mg/kg toxicity limit, which represents 2 genera at 4 of the field sites (Table 6).

In addition to the concentration of arsenic in plant material, arsenic in soil needs to be taken into account when considering potential toxicity to grazing animals. The tailings material from the glasshouse experiment contained inorganic arsenate [As(V)], which is the predominant arsenic species in well-aerated soils. As(V) is more toxic than organic arsenate (Smith *et al.*, 1998). Since animals can directly ingest tailings material while grazing, a capping layer would prevent direct access to the tailings. In considering the effect of capping, one should keep in mind that arsenate-salts can accumulate on the surface of capping layers as a result of capillary rise, which is enhanced in arid regions such as the Western Australian goldfields, where evapotranspiration is high and exceeds rainfall.

Other factors that need to be considered when assessing the risk of contaminated tailings to biota are 1) the ingestion of tailings dust adhered to plant material, 2) the ingestion of salt on the soil surface, and 3) animals drinking from contaminated pools of water. During the field study a salt crust was observed on the soil surface at some of the sites, such as Site 1 and Site 8. Surface soil at these sites contained 649 and 3080 mg/kg total arsenic respectively (Table 5). Therefore, ingestion of both the contaminated salt and soil may be a risk for the wildlife.

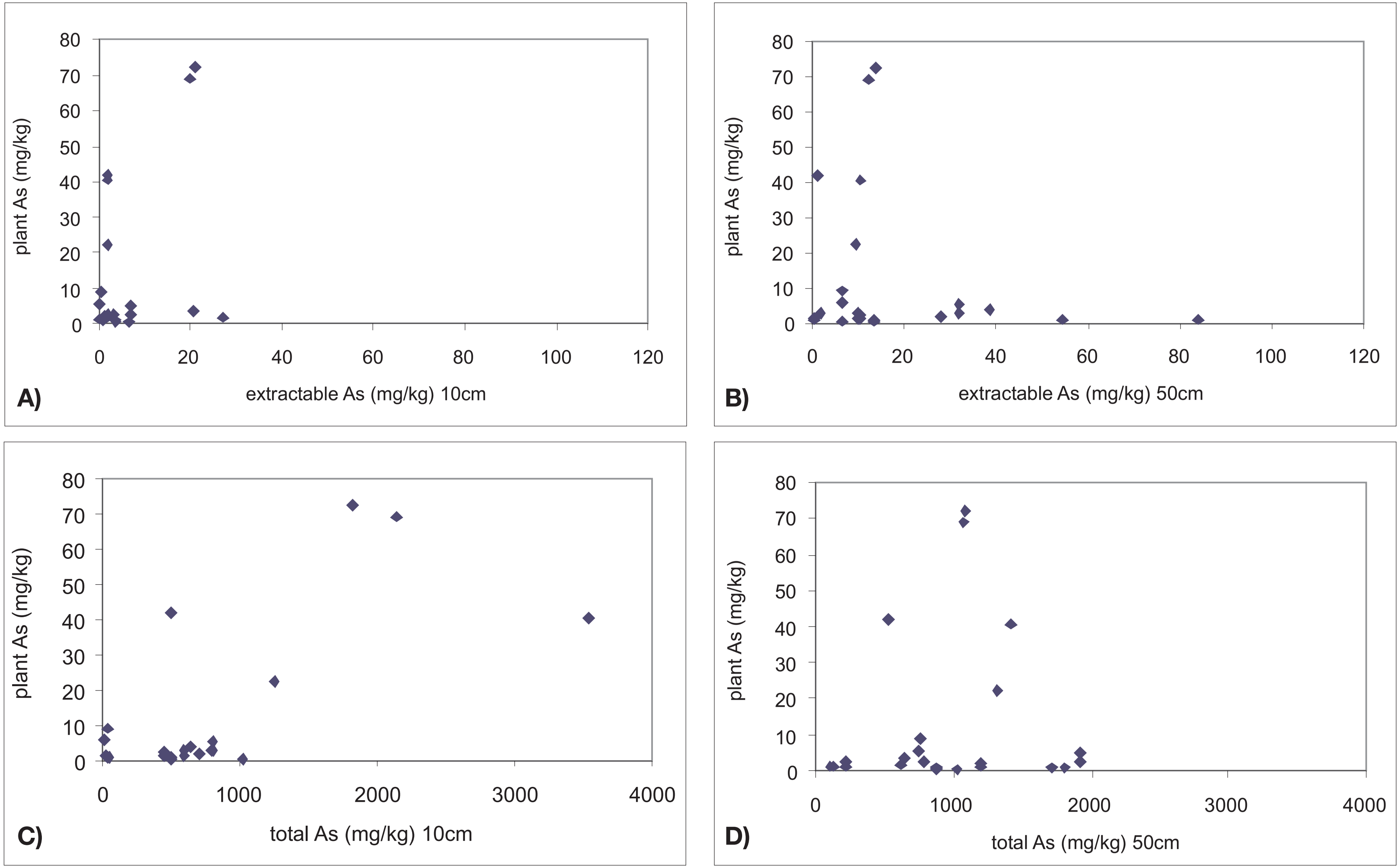


*Figure 2:* *Arsenic (As) concentrations in leaves of* Maireana pyramidata *growing in capped or uncapped tailings, in relation to As in the soil profile A) Extractable As at 10cm depth B) Extractable As at 50cm depth C) Total As at 10cm depth D) Total As at 50cm depth*

Preliminary observations suggest that substantial arsenic may occur on leaf surfaces, in addition to that within the plant. At Site 1, washing of leaf material of *Atriplex* species prior to analysis removed, on average, almost 50% of total arsenic in unwashed material (data not shown). The arsenic on these leaf surfaces may be from dust adhering to the leaves, or associated with salt exudation by these species. At this particular site, there was 649 mg total arsenic per kg in the capping layer, which may be the source of the dust on the leaves. For future research, consideration could be given to routinely analyzing unwashed plant material as this represents the total arsenic likely to be ingested during grazing.

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# COVERS AND THE CLOSURE OF TAILING STORAGE FACILITIES. MAKING THE MOST OF THE INFORMATION AND THE AVAILABLE MATERIALS TO CLOSE TAILINGS STORAGE FACILITIES.

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## ABSTRACT

*Unlike the situation 15 years ago where mine operators spent time debating the point and practicalities of covering upper surfaces of Tailings Storage Facilities, the industry has moved on and a considerable number of facilities are now closed and covered.*

*Considerable experience has been gained and field trials concluded. Sites have been closed and some revegetated for over almost a decade, so that information is available over a period of time in which trends in vegetative growth and maturation, and cover performance, have become well established.*

*The paper will draw on 10 years of field trials and closures from a variety of sites (non saline to hypersaline) that have recently concluded, and the utilization of the results of that work to assist closure planning.*

*With increasing production of tailings produced from primary ores, the industry now needs to contend with tailings that contain sulphides and arsenic forms. The information obtained on cover performance from the last 10 years of work provides a sound basis upon which to develop closure strategies for tailings that are more geochemically challenging than those produced from oxide ores.*

*Closure of TSFs in the future rests very much on linking fundamental processes in soil science, arid-land ecology and mine-waste geochemistry, to proven engineering concepts, so that the built-landforms are physically stable and ecologically sustainable in the longer term. The benefits of undertaking focused programmes of laboratory and field studies (viz. cover-plot trials) to the planning of TSF closures is well illustrated by the research findings presented in this paper.*

## INTRODUCTION

Tailings, a waste product of the Australian mining industry, are generally impounded in engineered, above-ground structures. In more recent times, these structures have commonly been covered with topsoil and weathered-rock materials to isolate the underlying tailings, contribute to overall stability and support revegetation. Various forms of covering materials, and covering strategies, can be used and has been a focus for the clients of Outback Ecology Services (OES) for some twelve years.

Successful rehabilitation of decommissioned tailings impoundments is vital to ensure long-term stability and isolation of the tailing. This is particularly important in arid areas where wind and the dry, hot conditions with episodic inundation are characteristic of the environment and can de-stabilise the structure and provide the trigger to the release of tailings and solutes to the environment.

Tailings disposal and rehabilitation in WA has changed considerably over the past ten years. There has been a general move away from the typical paddock style - square Tailings Storage Facility (TSF), constructed by the upstream method using tailings, to TSFs built with, or encapsulated by, waste rock walls. Occasionally an Integrated Waste Landform is constructed where a waste landform and TSF are integrated into one structure. There is also a considerable swing to the use of mined out areas (pits) for in-pit disposal of tailings, and occasional use of the very stable - large footprint - Centrally Thickened Discharge facilities.

The WA Department of Minerals and Energy guideline (1995) on "The Safe Design and Operating Standards for Tailings Storage" recommended that in terms of decommissioning companies should:

> *"Cover the top surface of the tailings storage with a minimum of 500mm of suitable waste where saline process water has been used, followed by spreading of topsoil and seeding; those storages which use potable quality water during ore processing do not require the top surface to be covered with waste, but should be ripped, seeded, and fertilised to encourage revegetation to reduce the erosion and dusting hazards."*

In general terms basic environmental objectives of rehabilitation should be in accordance with the following criteria related to tailings disposal:

- Disposal of tailings should be non-polluting, both during operation and after de-commissioning,
- The tailings disposal structure should remain stable in the long term with regard to engineering aspects and erosion, and be maintenance free, and
- The final landform produced should be compatible with the surrounding landscape (Clarke 1987).

A variety of tailing impoundment designs and rehabilitation techniques have been investigated in the past, in order to meet these objectives. Basic alternative approaches to rehabilitation are either a completely flooded storage or a dry tailing disposal area, with the surface revegetated, and there are varying degrees in between. In dry tailing storage situations, the typical rehabilitation technique is a cover of soil, fertilizer and revegetation (Miedecke and Brett 1991).

Tailings are often inhospitable to plant growth due to their chemical and physical properties, and difficulties the plant seeds encounter during the germination stage (Barth 1988). There are many characteristics of tailings that render them difficult for plant growth. For instance tailings contain low levels of essential plant nutrients (e.g. nitrogen, phosphorous) and are depauperate in terms of natural organic matter and associated microbial populations (Dean *et al.* 1986; Emerson *et al.* 1992). Tailings often contain high levels of salts (Petersen 1992) and heavy metals which can act as phytotoxicants (Ritcey 1989). The materials have poor physical composition and are often unconsolidated sands, which when mobilised by wind, sand-blast and bury plants (Emerson *et al.* 1992). There is either intense reflection or absorption of solar radiation on the tailings surface causing physiological stress to plants (Emerson *et al.* 1992).

Pickersgill (1994) suggested that for a medium (such as mine tailings) to be fertile for plant growth it must have:

- desirable physical properties (e.g. adequate aeration and water holding capacity, and low resistance to root penetration),
- an adequate supply of essential macronutrients - nitrogen, phosphorous, potassium, calcium, magnesium, sulphur and micronutrients - copper, zinc, iron, manganese, boron, molybdenum, cobalt, and chlorine,
- low concentrations of phytotoxic elements, and
- beneficial microbes without the presence of pathogenic species.

## FIRST GENERATION FIELD TRIALS TO TEST COVERING OPTIONS

Over the past decade and on behalf of its clients OES has undertaken field trials throughout various sites in WA to determine the effectiveness of different forms of covering strategies, both physical and chemical. Quite a few of these sites have since been covered, closed and monitored for some years. In the mid-1990s covering was somewhat at its infancy, and as such, the field trials undertaken at this time were relatively simple, concentrating particularly on the differences between physical and chemical treatments.

The effectiveness of different rehabilitation techniques of tailings was investigated by OES through a staged research program using pot and field based trials. Assessment of tailings for a wide range of chemical properties is a necessary part of a rehabilitation program, so that deficiencies and potential toxic elements can be identified (Table 1).

The field trials were conducted not only to determine the success of plants on uncapped tailings in the natural environment, but also to determine whether the application of physical or chemical treatments influenced plant growth responses.

The field trials were undertaken at four sites in the Arid Shrublands of WA, over a region approximately 500 km in length (Lat 25-29° S). They comprised five physical and four chemical treatments, and commenced in early 1995. Depths of physical cover material averaged between 100 and 250 mm. Two plots received no cover, to act as controls. Fencing of the plots with ringlock, barbed wire and rabbit netting after cover application generally ensured the exclusion of grazing animals.

Analysis of the treatments and plant responses was conducted biannually for 5 years. Two tailing cores were collected from each plot at each site. Cores were sampled at random points into the layers according to the type of treatment/cover present. The sampling interface refers to the area where the cover meets the tailings. Horizontal zones for different depths at each individual plot were bulked, and analysed in terms of moisture content, pH and electrical conductivity.

### The ranges of values found in tailings from four field sites prior to commencement

The salinities of the tailings ranged from 16.55 - 92.70 dS/m ECe. One of the principal findings was that even those tailings from 'potable' water process plants (Site 2) were found to have salinities in excess of 20.2 dS/m ECe i.e. all sites are moderately to extremely saline (Petersen, 1987).

**Table 1: Chemical and nutritional analysis of tailings bulked from surface zone (0-30cm) material on trial commencement at four field sites. Adapted from (Lacy, 1998). N ≥ 3.**

| | Field Trial Sites | | | | |
|---|---|---|---|---|---|
| **Parameter** | **Site 1** | **Site 2** | **Site 3** | **Site 4** | **Range** |
| **pH** | **9.3** | 8.6 | 8.7 | 8.5 | 8.5-9.3 |
| **EC1:5 (dS/m)** | 3.7 | 1.9 | 2.7 | **9.9** | 1.9-9.9 |
| **P (ppm)** | **17** | 12 | 2 | 10 | 2-17 |
| **N (ppm)** | **30** | **30** | 10 | 13 | 10-30 |
| **K (ppm)** | 235 | 334 | **442** | 364 | 235-442 |
| **S (ppm)** | 594 | 520 | 1225 | **1586** | 520-1586 |
| **Fe (ppm)** | 1006 | 1826 | 1538 | **3000** | 1006-3000 |
| **Na (meq/100g)** | 21.3 | 7.9 | 8.4 | **56.5** | 7.9-56.5 |
| **Ca (meq/100g)** | 0.18 | 3.1 | 9.0 | **10.7** | 0.18-10.7 |
| **Mg (meq/100g)** | 0.04 | 0.15 | 0.87 | **6.6** | 0.04-6.6 |
| **SAR (meq/100g)** | **64.2** | 6.2 | 3.8 | 19.2 | 3.8-64.2 |
| **ECe * dS/m** | 16.6 | 20.2 | 28.4 | **92.7** | 16.6-92.7 |

- bold type indicates the highest value for that parameter
- EC (Electrical conductivity). SAR (Sodium Adsorption Ratio)

## First Generation Trials (1995- 1999): Site Descriptions and Findings

**Site 1.** The site was characterised by a extreme SAR, was saline (ECe of 16.5 dS/m), and strongly alkaline. Physical treatments (topsoil, laterite, red oxide, mill scats and white oxide), chemical treatments (gypsum, polycrete, PVA/gypsum and Vermiculite) and a control were compared.

1. The physical treated plots proved to be more hospitable to plant establishment than the control and chemically amended plots. Mean plant density, cover and height were significantly greater in the physically treated plots.
2. Of the chemical parameters tested, electrical conductivity varied most significantly and was related to wetting and drying cycles.
3. The cover materials proved particularly valuable in years of higher rainfall, as they appeared to minimise the increase in tailing conductivity in summer while retaining more moisture in the tailings below.

**Site 2.** The site was saline (ECe of 20.2 dS/m), and alkaline. Physical treatments (topsoil, laterite, red oxide, white oxide, and mil scats), chemical treatments (gypsum, polycrete, PVA/gypsum and Vermiculite) and a control were compared.

1. These tailings proved to be quite benign; neither physical treatments nor chemical amendments were better for rehabilitation in terms of plant growth and soil properties.
2. The most successful treatments in terms of plant growth were clearly identified as topsoil, laterite and PVA/gypsum.

**Site 3.** The site was characterised by a high salinities (ECe of 28.4 dS/m), and clay-rich, extremely dense tailings. Physical treatments (topsoil, laterite, green oxide, green rock, and grey rock), chemical treatments (gypsum, polycrete, PVA/gypsum and Vermiculite) and a control were compared.

1. The physical cover materials proved to be clearly effective at this site. Most significant was the effect of the covers on the electrical conductivity of the tailings, which was significantly lower than in the chemically amended plots.
2. The cover materials proved to be somewhat resistant to capillary rise, and maintained consistent levels of salt in the tailings below.
3. Vegetation was considerably higher on the physically treated plots, as opposed to the lack of vegetation on the chemically amended and control plots.

**Site 4.** This site was characterised with very high salinities (ECe of 92.7dS/m) and slight alkalinity. Five physical treatments (topsoil, laterite, competent rock, green oxide and yellow oxide), four chemical treatments (gypsum, PVA/gypsum, polycrete and vermiculite) and two controls were assessed.

1. Plots amended with physical treatments had significantly lower average conductivities than tailings treated with chemical amendments, suggesting physical covers provided a barrier to evaporation and subsequent rise of salts.
2. Vegetation establishment was advanced on the physical treatments, and was lacking on the chemical treatments and the control, implying that initially, tailings material alone was too hostile an environment for plant establishment and growth.
3. The cover materials provided protective niches for seed germination and plant growth, and minimised capillary rise from tailings.

### Broad conclusions from the first generation trials were;

- The EC was lower at the tailings interface of the physically treated plots, than the control and chemically treated plots at all sites; significant at Sites 2, 3 and 4.
- Strong capillary rise was evident in the control and chemically treated plots during the trial life and to a lesser degree in most physical treatments.
- Moisture content was higher in the tailings beneath the physically treated plots than in the tailings of the control and chemically treated plots, significantly at Sites 1, 2 and 4.
- We suggest that levels of salts contained within the tailings under the physical treatments appear to be decreasing, attributed partly to the fact that they are moving up with capillarity into the capping material, being taken up and utilised by the plants, and partly lost to depth due to leaching.
- Different covers and treatments have been most effective in providing a less hostile environment and sustained plant growth throughout the life of the trial.

## SECOND GENERATION FIELD TRIALS – TO TEST COVERING COMBINATIONS

Towards the end of the 1990's and beginning of 2000, covering of TSFs was considered the conventional method of decommissioning by the WA mining industry. Debates about the possibility of direct rehabilitation of potable water tailings appeared to decline in industry forums. On behalf of clients field trials were undertaken on slightly more complex sites that had higher salinities, and limited types of cover material available. We felt we could build on the fundamental basics of successful covers that had been confirmed with some success over the previous five years work.

The trials were undertaken in the Kalgoorlie/Southern Cross/Kambalda regions, approximately 50-200km apart. Depth of cover ranged between 100-300mm. Plots were fenced to prevent fauna access, and to prevent where possible sand blasting of plots.

We evaluated different concepts and cover treatments, on nickel, mixed nickel /gold and gold tailings. The treatments used were combined physical layer combinations, some with capillary breaks, and with chemical treatments in the tailings beneath the covers. Organic materials such as wood and straw mulch were assessed.

The field trials were undertaken at five sites and commenced in the late 1990/early 2000. Analysis of the treatments and plant responses was conducted biannually for three-four years.

### Second Generation Trials (1999- 2003): Site Descriptions and Findings

**Site 1.** High salinity was a characteristic of this site. Five combination treatments and a control were assessed. Physical/chemical treatments (oxide cover over bentonite E and straw mulch and PVA /gypsum) and a control were compared.

1. EC declined in the tailings beneath and increased in all covers over the trial period for all treatments, including the control
2. Statistically, there was no difference between treatments with regard to plant density or cover. However, vegetation was absent on the control whereas all other treatments established plants albeit very sparsely.

**Table 2: Chemical and nutritional analysis of tailings at the commencement of five field trial sites. Adapted from (Lacy, 1998)**

| | Field Trial Sites | | | | |
|---|---|---|---|---|---|
| **Parameter** | **Site 1** | **Site 2** | **Site 3** | **Site 4** | **Site 5** |
| **pH** | **8.10** | 8.12 | 6.34 | 6.62 | 7.22 |
| **EC 1:5 (dS/m)** | 13.94 | **21.23** | 13.88 | 12.13 | 10.62 |
| **ECe * dS/m** | - | - | **205** | 145 | 32 |
| **P (ppm)** | - | - | 3 | **6** | 2 |
| **$NO_3$(mg/kg))** | - | - | **6** | 1 | 5 |
| **$NH_4$ (mg/kg)** | - | - | **7** | 4 | 1 |
| **K (ppm)** | - | - | 794 | 800 | **1882** |
| **SAR (meq/100g)** | - | - | <0.10 | **1.87** | 0.495 |

• bold type indicates the highest value for that parameter

**Site 2.** Very high salinity and alkaline conditions were characteristic of this site. Eight treatments consisting of different depths and combinations of covers and a control were assessed. Combination treatments (waste rock or bentonite or straw mulch or gypsum/ PVA) and a control were compared.

1. Cover materials appear to be inhibiting the capillary rise of salts to the tailings surface by minimising evaporation and salt movement. The control reported the highest EC of all tailings material. The tailings beneath the bentonite cover reported one of the lowest EC of all the treatments.
2. Vegetation development was poor on all treatments, although treatments of 250mm of waste rock reported the highest plant densities and cover of the trial.
3. Addition of chemical amendments did not significantly improve vegetation development, whereas straw mulch under 250mm rock did.

**Site 3.** This site was characterised with very high ECe (205dS/m). Seven treatments and a control were assessed. Physical treatments (white oxide, gravel subsoils, fine topsoil, wood mulch, Bentonite E), chemical treatments (gypsum and PVA) and a control were compared.

1. The physical covers appear to be the most beneficial cover at this site. Most significant was the reduction in EC in the tailings beneath the cover though a apparent restriction in movement of salt to the surface.
2. The treatment containing topsoil and wood mulch consistently reported one of the lowest ECs and had the highest species diversity, density and cover.

**Site 4.** Physical treatments (gravel, green oxide, topsoil, woodmulch, Bentonite E), chemical treatments (gypsum/ PVA) and a control were compared.

1. 100mm topsoil over 100mm of gravel, and 100mm gravel on gypsum/PVA reported the lowest EC over the trial period, with lessened capillary rise of salts.
2. Vegetation was highest on the topsoil/wood mulch treatment

**Site 5.** Physical treatments (screened waste rock, topsoil, bentonite E), chemical treatments (gypsum, PVA) and a control were compared.

1. All treatments involving physical cover materials created an effective capillary break, with a higher mean moisture content apparent in the tailings under the cover materials, compared to the uncovered treatments
2. EC in the cover materials was lowest on the treatment containing screened waste rock and amended with gypsum and PVA. In contrast, salinity was highest in treatments with an exposed tailings surface.
3. Vegetation was present on all treatments, but plant cover was significantly greater on covered treatments.
4. For the last two years of the trial the covers have maintained a significantly lower (200%) EC than the bare tailings area.

#### Broad conclusions from the second generation trials were;

- Given the right materials we suggest plants can grow and develop on very saline (≤15dS/m EC) tailings, however above that - fewer halophytic species survive.
- Rock mulch cover acts as a capillary break and can facilitate the creation of a growth material A) through leaching of salt lower in the profile. B) Maintaining higher moisture content beneath the rocky mulch layer (vital in drier years) in essence, providing a improved growth horizon for plant roots to exploit.
- Capping can be shallow (200-300mm) on saline tailings if it is an effective capillary break ie rocky mulch material, and subsequent topsoil or other growth medium will remain free of capillary rise if the cover is well designed and installed.
- Appropriate rocky mulch/ with topsoil/growth medium grafting can provide a protected niche like environment for plant establishment and development in certain circumstances.

## COVERING AND CLOSING

### REHABILITATION OPTIONS

We suggest that there are a number of options for tailing rehabilitation, and the treatment(s) employed are largely dependent on the nature of the TSF. This implies that final decommissioning choices will depend on the challenges related to that particular TSF. Initial evaluation should give clues as to the strategy that should be trialed, or if confident, applied on a broad scale. According to Lacy (1998), the following options are available for rehabilitation.

#### 1 Physical Stabilisation

This is the application of a physical mulch layer or barrier to the tailing materials to counter erosive effects of wind, water, and other disturbances. The advantages are its resilience and stability over time and therefore its protection of the local ecosystem. It can also be conducive to plant colonisation and provide a niche for seedling establishment, through provision of inherent stability, favourable microclimate and protective nature.

There are a number of mulches available. Readily available mulches include; oxide waste rock, laterite waste rock, topsoil, competent rock (non-acid forming), mill scats and alluvial mining gravels. Mulches that are generally not readily available include; vermiculite, smelter slag, fly ash, organic products (sewerage sludges, straw, bark, compost, wood chips). Physical barriers (windbreaks) such as fences or artificial barriers may also be used, in an effort to achieve initial stabilisation.

#### 2 Vegetative Stabilisation

This is the establishment of vegetation to create the same effects as a physical barrier, while returning the storage area to a beneficial use by the organisms of the local ecosystem. The vegetation may also improve the qualities of the tailings by biological and physical processes, and at the same time improve the aesthetics of the rehabilitated facility. Concentration of toxic elements and metals within the vegetation may occur, so final use of the facility, or even the environmental risk of using vegetation as part of a cover combination may have to be carefully considered.

#### 3 Chemical Amendments

There are a variety of chemical amendments available, for example; gypsum, polyvinyl alcohol, lime-limestone and fertilisers. These ameliorants alter physical structure or chemical make-up of the tailings to make them conducive to the establishment and survival of plants.

#### 4 Chemical Stabilisation

These are artificial alterations of the tailing surfaces, and are used in circumstances where the surfaces are very unstable. The sealants are sprayed or incorporated into the surface of the tailing to create a hard or non erosive crust, designed to prevent wind and water erosion. Examples of chemical stabilisers include; resinous adhesives, bitumen based compounds, sodium-silicate chemicals (geopolymers), lignosulfonates, cement, and elastomeric polymers.

#### 5 Combinations

It is not unusual to use a combination of these different options during rehabilitation. Hydro-seeding is an example of stabilising processes using a combination of physical, chemical and vegetative stabilisation. To achieve success in rehabilitation in the long run, it is likely that combinations of treatments would be the best option. This would ensure not only increased stability, but also enhanced aesthetics.

### ADDED REQUIREMENTS FOR CONTAINMENT OF PRIMARY ORE TAILINGS

With primary-ores from local gold-mines making up an increasing proportion of ore-blends, the closing of TSFs is now needing to contend with surface-zone tailings that contain trace amounts of arsenopyrite. Such tailings are invariably classified as Non-Acid Forming (NAF), due to an abundance of carbonates over sulphides. The "trace-sulphide/abundant-carbonate" mineralogy of primary-ore-tailings reflects the typical nature of mineralisation within the Greenstone belts (viz. pervasive carbonate alteration of bedrocks containing traces of sulphides).

When subjected to weekly weathering-cycles, the alteration of arsenopyrite at circum-neutral-pH may locally result in porewater-As concentrations within the range 1-10 mg/L, and believed to reflect solubility control by "Fe/Ca-hydroxyarsenate-type" phases (Campbell 2002). However, the flushing of mineral-grain surfaces on a weekly basis could not be any further from the truth for surface-zone tailings in the Goldfields – even where there is no cover of soil/regolith materials.

Project work and in-house research indicate that, in the presence of gypsum, porewater-As concentrations 'of-the-order' 0.1 mg/L are to be expected (i.e. As solubility at circum-neutral-pH is suppressed by gypsum). Due to the major-ion chemistry of the groundwaters employed for milling, and evapo-concentration effects, traces of gypsum are inevitably present in surface-zone tailings. Even in the absence of gypsum, porewater-As concentrations may be well within the sub-mg/L range where sulphides (e.g. pyrite) co-existing with arsenopyrite are sufficiently reactive at circum-neutral-pH. This effect from co-sulphide weathering reflects the stronger Fe/As interactions, compared with Ca/As. In addition, the "flushing-frequency" dependence of sulphide oxidation – and rock-water-air interactions generally – in semi-arid/arid settings (Campbell, unpublished results) means that the formation of protecive-alteration rims on arsenopyrite-grain surfaces is favoured, thereby curtailing As solubility and bioavailability.

Whilst arsenopyrite is thermodynamically unstable at circum-neutral-pH, a host of secondary processes therefore operate in semi-arid/settings that greatly reduce the rate of alteration in the first place, and the dissolution of any alteration products that do form. Such processes are promoted where the surface-zone tailings occur beneath a vegetated store/release-cover of soil/regolith materials that reduces the "flushing-frequency" through buffering of incident rainfall via evapotranspiration. As a guide, where vegetated store/release-covers are characterised by water-holding capacities of 50-100 mm (nominal), "breakthrough/recharge" across the cover/tailings-interface may occur, on average, only on a few occasions each year. A weathering regime of this kind is conducive to slow rates of oxidation, and the formation of protective-alteration rims. Related comments apply to the weathering of process-tailings that are classified as Potentially-Acid Forming (PAF), but are further classified as PAF-[Long-Lag] due to carbonates that buffer near pH=7 during the "lag-phase".

Covering TSFs in the future requires a consideration of *inter alia* (a) the water holding capacity of the soil/regolith materials employed for covering, and (b) the distribution of rainfall in conjunction with the plant-soil-water relations of the rangeland vegetation employed for the rehabilitation works. The drought-tolerating strategies (e.g. laterally extensive, but shallow, rooting zones) that the rangeland vegetation have evolved have important implications to the risk posed by arsenopyrite (and sulphides generally) in the surface-zone tailings below the cover. Such rooting-zone anatomy reflects the opportunistic demands placed on the vegetation, and their need to maximise use of infiltration from even light rainfall, be this simply for survival during drought (c.f. maximum water use for growth when soil moisture availability and soil-temperature both become favourable). Isolated roots of shrubs and grasses indeed penetrate to some metres in the *red earths* (of medium-to-coarse texture) characteristic of the Australian mulga zone, but the role of such deep roots is likely more one of tapping scant reserves of soil moisture for survival during extended drought periods, and so contribute minimally to the water economy of the vegetation overall. It is well known that the rainfall distribution within inland Australia (and other semi-arid/arid zones) worldwide is one where major inputs occur in short, intense bursts conducive to runoff as sheet-flow whereby the soil moisture at depth is only rarely recharged.

Where protective-alteration rims form on arsenopyrite during weathering at circum-neutral-pH, the surface-zone tailings in the immediate vicinity of the store/release-cover may be usefully incorporated into the covering philosophy. In effect, a "duplex-soil" profile may evolve wherein the majority of energy and mass exchanges occur within the placed cover of soil/regolith materials, supplemented during periods of extreme soil-moisture stress by moisture derived from the surface-zone tailings. Although further investigation and research are needed to confirm (or refine) these projections, it is clear that there is scope for a simple, cost-effective, yet technically sound, approach to the design of store/release-covers in the Goldfields of Western Australia (and other strongly-dessicating semi-arid/arid areas where the mismatch between annual rainfall and potential evaporation is so marked).

## CONCLUSION

The use of a physical or chemical treatment over the tailings may act to significantly reduce erosion, and provide a more benign medium for plant growth (Barth 1986). We have found that amendment of tailings with physical/chemical treatment combinations has proved successful and conducive to rehabilitation at a number of study sites, with different physical covers being most effective in reducing the salinity, increasing stored water and sustaining plant growth at different sites.

The field trials conducted by OES on behalf of our clients over the last twelve years, have provided much valuable information to tailor vegetated covers on TSFs for the containment of tailings derived from primary ores. Field experience with the establishment and growth of rangeland-vegetation species, and the linking of this to the physical and geochemical characteristics of the cover materials and tailings, is the key to successful covering and closure of TSFs in the Goldfields.

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# Workshop on Environmental Management

GOLDFIELDS ENVIRONMENTAL MANAGEMENT GROUP

# PROCEEDINGS 2004

May 26, 27, 28

Kalgoorlie - Boulder

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# Day Three

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# SUSTAINABLE MINE CLOSURE

*Bill Biggs*
DEPARTMENT OF INDUSTRY AND RESOURCES

## OUTLINE

### What are we looking for?

A process that brings certainty and confidence to the completion process

- Industry – Government partnership
- Based on agreed sustainability principles
- Develop measurable outcomes for each principle
- Identify risks and opportunities
  - Carry out a comprehensive gap analysis
- Identify control measures
- Develop a set of Key Strategies
  - Actions jointly owned by industry and government
  - Accepted by the community
  - Supported by guidelines, information and support systems
- Develop a set of completion or closure criteria
  - Agreed, demonstrable outcomes that lead to sign off

### The Process

- Currently an idea out for discussion
- Need to develop a set of outcome objectives
  - Get buy in from stakeholders
  - Government
  - Industry
  - Community
  - Assign resources (people) to develop and implement
  - Promote the concept to ensure widespread acceptance
- Need to agree on the principles of sustainability
  - Alignment
  - ICMM principles
  - State Sustainability Strategy
  - Flesh out the lower level elements down to operational level
  - MCA – Operational Framework for Sustainable Development Implementation
  - Supported by tangible examples
  - Outcomes
  - Agreed principles and outcomes by which government sets the rules
  - Industry has clear understanding of what it needs to achieve to gain successful relinquishment

## ICMM

### Principles of Sustainability

1. Corporate Governance
2. Corporate Decision Making
3. Human Rights
4. Risk Management
5. Health and Safety
6. Environment
7. Biodiversity
8. Materials Stewardship
9. Community Development
10. Independent Verification

### Principles of Sustainability in detail

1. Implement and maintain ethical business practices and sound systems of governance
2. Integrate sustainable development considerations within the corporate decision making process
3. Uphold fundamental human rights and respect cultures, customs and values in dealings with employees and others that are affected by our activities
4. Implement risk management strategies that are based on valid data and sound science
5. Seek continual improvement of our health and safety performance
6. Seek continual improvement of our environmental performance
7. Contribute to conservation of biodiversity and integrated approaches to land use planning
8. Facilitate and encourage responsible product design, use, re-use, recycling and disposal of our products
9. Contribute to social, economic and institutional development of the communities in which we operate
10. Implement effective and transparent engagement, communication and verified reporting arrangements with our stakeholders

## ANZMEC/MCA

### Strategic Framework for Mine Closure

#### 6 Key Objectives and Principles

- Stakeholder Involvement
- Planning
- Financial Provision
- Implementation
- Standards
- Relinquishment

### Stakeholder Involvement

#### Objective

*To enable all stakeholders to have their interests considered during the mine closure process*

#### Principles

1. **Identification** of stakeholders and interested parties is an important part of the closure process.
2. **Effective consultation** is an inclusive process which encompasses all parties and should occur throughout the life of the mine.
3. A **targeted communication strategy** should reflect the needs of stakeholder groups and interested parties.
4. **Adequate resources** should be allocated to ensure the effectiveness of the process.
5. Wherever practical, **work with communities** to manage the potential impacts of mine closure.

#### The Miner's Role is to

- Initiate the process
- Provide information and facts
- Facilitate the process
- Be diligent in identifying stakeholders
- Honest and open in dealings
- Develop trust and confidence amongst stakeholders

#### The Regulators Role is to

- Participate in the process
- Provide advice
- Facilitate where necessary
- Ensure all stakeholders are considered and their issues heard
- Arbitrate where necessary

### Planning

#### Objective:

*To ensure the process of closure occurs in an orderly, cost-effective and timely manner.*

#### Principles

1. Mine closure should be **integral** to the whole of mine life plan.
2. A **risk-based approach** to planning should reduce both cost and uncertainty.
3. **Closure plans** should be developed to reflect the status of the project or operation.
4. Closure planning is required to ensure that closure is technically, economically and socially feasible.
5. The dynamic nature of closure planning requires **regular and critical review** to reflect changing circumstances.

#### The Miner's Role is to

- Set corporate standards
- Ensure the standards are achievable
- Plan to meet the standards
- Start planning early
- Assess the risks and plan to manage them
- Collect the necessary information
- Identify specific needs, skills and competencies and employ staff or contractors to provide them
- Ensure plans are updated throughout the life of the project
- Review performance and call for the changes

#### The Regulators Role is to

- Ensure mine closure is addressed in management plans
- Assist in identifying risks
- Verify the information
- Set operating conditions
- Ensure closure plans are updated throughout the life of the project
- Review performance and call for the changes
- Ensure the standards are achievable
- Critically review programs and provide feedback

### Financial Position

#### Objective

*To ensure the cost of closure is adequately represented in company accounts and that the community is not left with a liability.*

### Principles

1. A **cost estimate** for closure should be developed from the closure plan.
2. Closure costs should be **reviewed regularly** to reflect changing circumstances.
3. The **financial provision** for closure should reflect the real cost.
4. **Acceptable accounting standards** should be the basis for the financial provision.
5. **Adequate securities** should protect the community from closure liabilities.

### The Miner's Role is to

- Cost plans, options and contingencies
- Budget for costs and expenditures
- Review the costs and budget regularly
- Monitor performance against budgets
- Manage the changes

### The Regulators Role is to

- Critically review development proposals and closure plans before acceptance
- Review the costs at each inspection
- Assess the outstanding liability to the state
- Adjust the securities accordingly

## Implementation

### Objective

*To ensure that there is clear accountability, and adequate resources, for the implementation of the closure plan.*

### Principles

1. The **accountability** for resourcing and implementing the closure plan should be clearly identified.
2. **Adequate resources** must be provided to assure conformance with the closure plan.
3. The **on-going management** and monitoring requirements after closure should be assessed and adequately provided for.
4. A closure **business plan** provides the basis for implementing the closure plan.
5. The implementation of the closure plan should reflect the status of the operation.

### The Miner's Role is to

- Establish clear lines of responsibility and accountability
- Provide the resources to meet the plans
- Provide ongoing management commitment and support
- Ensure staff understand their roles and responsibilities
- Assess their performance
- Review on a regular basis
- Make the changes

### The Regulators Role is to

- Review environmental management systems
- Audit lines of responsibility and accountability
- Review company environmental policy
- Test that the plans are understood by the company personnel responsible for implementing them
- Assess performance against the agreed standards
- Review on a regular basis using environmental reports, inspections and audits

## Standards

### Objective

*To establish a set of environmental indicators which will demonstrate the successful completion of the closure process.*

### Principles

1. **Legislation** should provide a broad regulatory framework for closure.
2. It is in the interest of all stakeholders to develop **standards** that are both acceptable and achievable.
3. **Completion criteria** are specific to the mine being closed, and should reflect it's unique set of environmental, social and economic circumstances.
4. An agreed set of **indicators** should be developed to demonstrate successful rehabilitation of the site.
5. **Targeted research** will assist both government and industry in making better and more informed decisions.

### The Miner's Role is to

- Identify and work with stakeholders to develop standards
- Seek advice and information
- Collect information and data to support the proposal
- Recruit competent and experienced staff
- Support and encourage appropriate research

- Ensure that staff and contractors know, understand and comply with adequate standards
- Demonstrate that adequate standards are being met
- Use established standards
  - ISO and ASA common standards
  - MCA - Code for Environmental Management
  - ICME - Tailings Management Guidelines
  - UNEP - Cyanide Management Code of Practice

#### The Regulators Role is to

- Participate in the process of developing standards
- Provide advice and information
- Recruit competent and experienced staff
- Review legislation, standards and conditions regularly to ensure they stay relevant
- Support and encourage appropriate research
- Facilitate understanding and processes between agencies
- Reference and utilise established standards where appropriate

### Relinquishment

#### Objective

*To reach a point where the company has met agreed completion criteria to the satisfaction of the responsible authority.*

#### Principles

1. A **responsible authority** should be identified and held accountable to make the final decision on accepting closure.
2. Once the completion criteria have been met, the company may **relinquish** their interest.
3. **Records** of the history of a closed site should be preserved to facilitate future land use planning.

#### The Miner's Role is to

- Identify and meet the agreed standards
- Collect data and information that demonstrates that criteria have been met
- Ensure that all stakeholders have had input
- The agreed needs of stakeholders have been met
- Liaise with government agencies
- Ensure that all facilities to be left have been agreed to
- Ensure there is a record of the history of the operation and the closure process

#### The Regulators Role is to

- Identify who is the lead agency
- Ensure that all agencies understand their role
- Inspect and measure the indicators
- Verify completion standards have been met
- Ensure all the agreed needs of stakeholders have been met
- Ensure that all facilities to be left are agreed to
- Remove conditions
- Retire securities
- Ensure there is a record of the closure process

## WHAT ARE WE LOOKING FOR?

### What we want

- Evidence that you understand the detail
- That you have got the necessary information
- Seeking outcomes that are achievable
- Using proven standards

### What we don't want

- Inadequate information
- Undefined or poorly defined outcomes
- To have to drive the proponent to meet reasonable and acceptable standards

## GOOD PRACTICE

### We are looking for

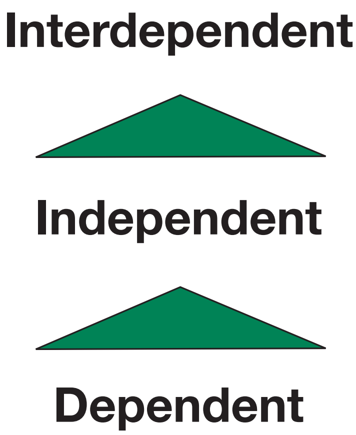
- Environmental practice as a part of core business
- Clear lines of responsibility and accountability for achieving goals and objectives
- Educated and well trained staff helping you achieve your goals and objectives
- Having the right information and data to make good decisions
- Planning for contingencies, identify the risks upfront
- Performance driven contracts
- Effective document control
- Industry and regulators working together
- Community involvement in decision making, sharing the responsibility
- Working to established standards, guidelines and codes of practice
- Pro-active management style, get in front of the game
- Strategic and cooperative research, looking for the answers through industry collaboration

*Best Practice or Good Practice?*

*Best Practice*

*Is when you get it all right*

*Figure 1:* *The Way Forward*




## GOVERNMENT POLICY

**World Commission on Environment and Development** (Bruntland 87)

- Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs

**Council of Australian Governments**

- Development that improves the total quality of life both now and in the future in a way that maintains the ecological processes on which life depends

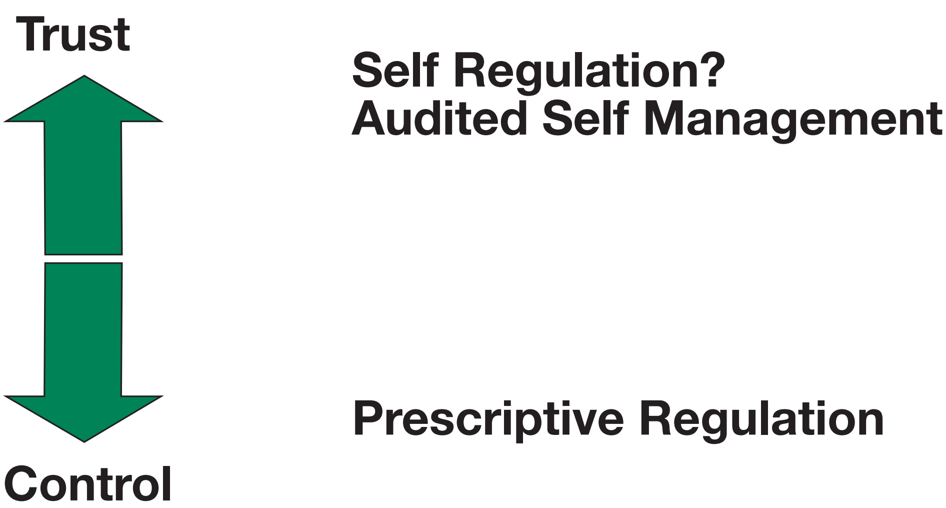
**Western Australia Government**

- The simultaneous achievement of environmental, economic and social goals

**The Department of Industry and Resources**

- Sustainable Prosperity

*Figure 2:* *Regulation or Self Management?*




**Trust + Control = K**

## DOIR - SUSTAINABLE PROSPERITY

*Sustainable Prosperity* means the creation of jobs and prosperity from resources development in ways that;

- Protect our natural environment
- Are safe for workers and the public
- Consider the needs of future generations
- Contribute to a better quality of life for Western Australians

## USEFUL WEBSITES

Department of Industry and Resources

www.doir.wa.gov.au

Department of Environment

www.environ.wa.gov.au

Department Conservation and Land Management

www.naturebase.wa.gov.au

www.calm.wa.gov.au

Water and Rivers Commission

www.wrc.wa.gov.au

Agriculture WA

www.agric.wa.gov.au

WA Government

www.wa.gov.au

Environment Australia

www.environment.gov.au

# MINE - COMMUNITY RELATIONSHIPS THE EXPERIENCE OF STAWELL GOLD MINES (SGM) STAWELL, VICTORIA

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## ABSTRACT

*Stawell Gold Mines (SGM) conducts an underground mining operation located in Western Victoria approximately 230 km north-west of Melbourne. The first recorded phase of mining on the site was from 1853 to 1920 and current mining operations recommenced in 1982. The mine site is located within 1.5 km of the main street of Stawell and a continuing focus on community relationships is a key factor in the ability of the mine to operate.*

*A close association has been developed over the years through regular and formal contact with the Northern Grampians Shire Council, its officers and the Stawell Community. This relationship was tested in 1999 when SGM applied for a permit to commence an open pit mine and the State Government declined to approve the proposal.*

*SGM is a significant member of the Stawell community employing 250 people out of a population of 7,000 and takes great pride in its contribution to the district and the State. The local Gun Club, in cooperation with SGM, has developed a ten trap shotgun facility as a final end use for a small tailings storage facility. In cooperation with Curtin University of Technology and the University of Melbourne a 2.6ha Tailings Experimental Research Facility (TERF) has been constructed to enable experimentation into sustainable end land uses for a >100ha tailings dam which is currently in use.*

*The development of new initiatives is ongoing. The mine and the Community aim to continue to work together enhancing this productive relationship. This process has been formalised by the signing of a Protocol by the Northern Grampians Shire Council and SGM. The interactions of SGM with many disciplines of the scientific community are generating significant research outcomes, and are providing applied training for the coming generation of new graduates.*

*This paper focuses on: Partnerships with the Community and Research Organisations, Innovative and Novel End Uses for Tailings Storage Facilities and Community Engagement*

***Value to business:*** *Operating a mine in close proximity to a significantly sized Community has major benefits to the mine and its personnel; however it brings with it a responsibility to address and meet community standards to maintain a licence to operate.*

*Sustainability must be a key to mine site rehabilitation so that on-going management of the site is in the interests of the long term owners and not a liability*

***Lessons learned:*** *A significant portion of the community is in favour of the mine and appreciates the benefits to employment, economy and the community. They need and ask for information about the operation so they can support the mine when opposition occurs. Opposition groups are small, loud and well organised using modern sources of information (internet) and generalised emotive phrases. Support for the mine must be earned by consistent behaviour.*

***Key take home messages:*** *Communicate frequently and regularly, not just when you want something. Be honest, open and transparent in your dealings with all stakeholders. Be innovative and scientifically rigorous with regular external review and support*

## 1. INTRODUCTION

### 1.1 Location

The Stawell Gold Mine is located in Victoria 230 km NW of Melbourne. It is owned by MPI Gold Pty Ltd. It is operated by Stawell Gold Mines (SGM) a wholly owned subsidiary of MPI Mines Ltd.

Stawell is located in the Northern Grampians Shire and is described on the Shire's web site as follows;

> *"Characterised by the dominant assets of Grampians, Gift, Grapes and Gold, the Northern Grampians boasts a diverse range of activities and attractions. Set against the spectacular backdrop of the Grampians National Park and home to the world's most prestigious professional footrace the Stawell Easter Gift, over 1 million people visit the Northern Grampians each year".*

Whilst this prime location makes SGM one of the best situated mines in Australia, the close proximity to a significant population brings its share of benefits and challenges.

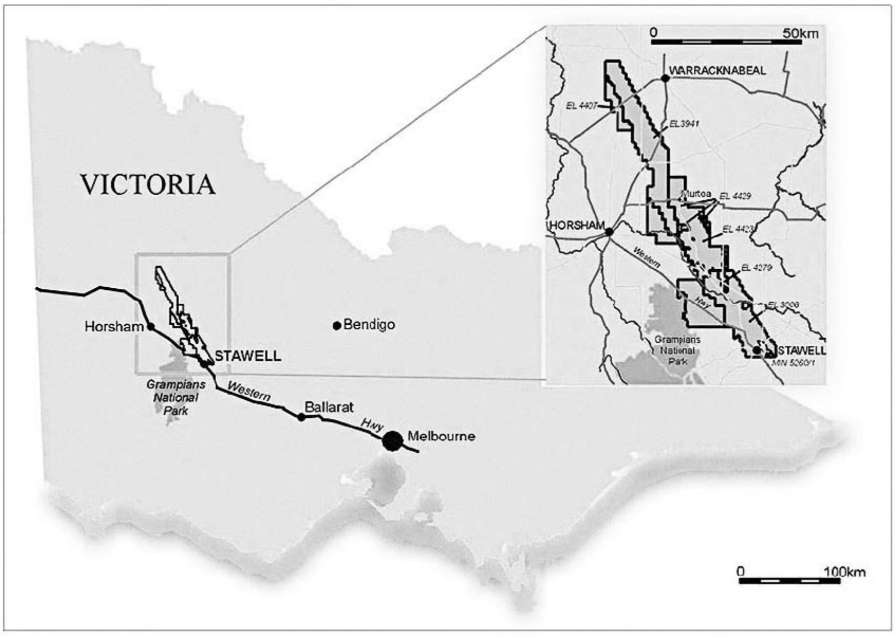


*Figure 1: Location Map*

## 1.2 History

Gold was first discovered at Stawell in 1853, and production from both alluvial sources and high grade quartz reefs totalled an estimated 2,670,000 oz in the 73 years up to 1926 when the last mine closed.

The Stawell Township evolved around the discovery of gold and the town retains many fine buildings funded during the first phase of gold mining. Gold miners are remembered through the Quartz Reef Monument sited where reef gold was first discovered, and the Pioneers Memorial.

The modern producing era began in 1984 when a WMC/Central Norseman Gold joint venture reopened the Stawell Gold Mine. In the nine years under WMC management the mine produced 336,000 oz of gold. MPI and Pittston Mineral Ventures (then 50:50 joint venture partners) acquired the mine in 1992 and to March 2004 output has been increased and a total of 1,042,641oz of gold has been produced.

In February 2004 MPI acquired Pittston's interest and is now the 100% owner of the operation.

Current production comes from the Magdala decline with mining taking place from 300 to 1000m below surface. Since mining re-commenced in 1984 there have been two open cut operations and the Wonga underground mine.

## 1.3 Community

The population of Stawell is approximately 7,000. The mine employs 247 people representing 10% of the working population and is Stawell's largest employer. Most employees live in the town or within a 20km radius. Northern Grampians Shire major businesses include; Stawell Gold Mines, Aunde Australia Pty Ltd, Stawell Regional Health, Frewstal Pty Ltd, Southcorp Wines Pty Ltd. These industries support a significant number of service industries and as a result there are several primary schools, a secondary school and a Campus of Ballarat University. There are numerous sporting and service clubs.

SGM is an integral member of the diverse community that makes up Stawell and like any organisation has its supporters and opponents. Management both local and external have to consider the Community in all its actions and decisions.

# 2. INTERACTION WITH THE COMMUNITY

## 2.1 Locality

The SGM operation is geographically located behind a ridge and is visually hidden from the rest of the town. The portal and milling facilities are located 1.5 kilometres from the main street. The underground mine extends to the north of the portal passing below Big Hill which is a local landmark and tourist lookout and home to the town's reservoirs and water supply. The mine workings have surface expression at three ventilation shafts and an electrical sub-station where power is delivered underground. The milling facilities include crushing, grinding, flotation, cyanidation and gold recovery. The mill tailings are stored in a 100 hectare facility some 4 km from the plant site. The impoundment is a valley style dam built on farmland purchased in the mid eighties. Two completed tailings dams are also located on site. MPI also hold exploration tenements stretching from Stawell 140 km to the north. Four prospects are currently being drilled and two potential resources have been identified.

One of the reasons that the residents know the mine is in operation is the daily production blasts which take place at around 6.00 pm every day (including weekends). Victorian mining regulations require that no blast can exceed a vibration of 10mm/sec and 95% must be less than 5mm/sec. There are around 200 blasts per month, about 25 production (stope) firings and the rest are smaller development blasts. SGM consistently complies with its statutory requirements but in 2003 it received 21 complaints relating to blasting, (one quarter of which were from one person). This represented 55% of recorded complaints. The human body is a very sensitive vibration monitor but it is poorly calibrated.

The other factor that generates complaints is odours. These come from the mine ventilation exhaust and from the carbon re-generation kiln. Odours represent 39% of complaints.

From a different perspective and perhaps less visible to the community, the mine spends approximately $54.8M per year. Approximately 40% is spent within the Stawell region through wages and the purchase of supplies and services.

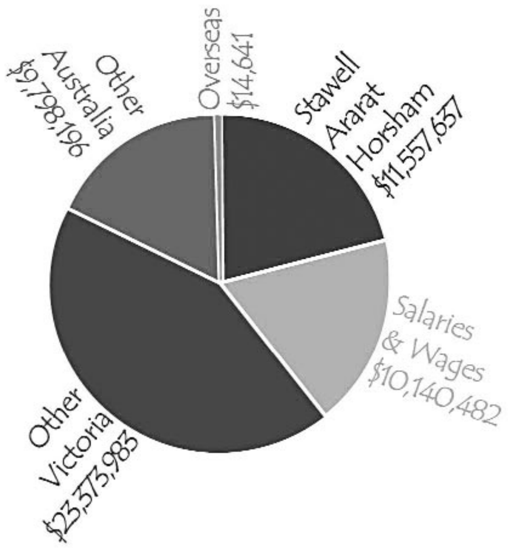


*Figure 2: Distribution of expenditure*

## 2.2 Reflection on Big Hill Project

During the eighties and early nineties the ridge that separated the mine and the town also represented the attitude of management. "We will do our thing behind the hill, please leave us alone and we won't disturb you".

The error in this attitude was brought home in the late nineties through the Big Hill Project. In 1996 the geological team were looking at increasing gold resources. The two obvious places were deeper in the mine and on the surface. The surface efforts resulted in a drilling programme during 1997 and 1998 which delineated around 400,000 oz on Big Hill. The drilling passed without incident with over 200 holes drilled; many in public places and very near residences.

In mid 1998 when SGM applied to commence the Victorian approvals process through the preparation of an Environmental Effects Statement (EES), an anti group was formed; the Big Hill Action Group (BHAG).

An EES Consultative Committee was formed comprising a range of regulatory authorities and members of the Community selected at a fiery public meeting that attracted some 600 people. The committee scoped and tracked the EES preparation for 18 months prior to its release for public comment. A public hearing of nine days duration took place before a panel of three members appointed by the Minister for Planning. In Nov 2000 SGM were informed that the proposal was not acceptable to the Minister.

The proposed project was to produce some 1.7 million tonnes (Mt) of ore and 11 Mt of waste rock over a period of six years from two open pits. The north open pit was to be excavated to its maximum economic depth of 85 m below the crest of Big Hill with the south to be excavated to 100 m below the crest. Each open pit was to be about 450 m long and 200 m wide.

The mining sequence was to commence by removing Big Hill to develop the northern open pit, with mine waste rock forming an emplacement area as an extension to the Big Hill ridge. Big Hill was then to be reformed and re-contoured to a close approximation of its original form using mine waste rock from the southern pit. The Big Hill viewing area was to be replaced and enhanced.

SGM was unprepared for the level of emotion that the project created. The BHAG was driven by half a dozen intelligent and dedicated individuals who recruited a band of some forty to fifty people. As with all protest groups their rhetoric was vivid and unconstrained.

Banner cries included

> *"Fly rock will fall on you when you are shopping in the mall"*
>
> *"Explosions in the pit will vent through old workings launching missiles in all directions"*
>
> *"The dust will kill you"*
>
> *"People will fall into the abandoned southern pit"*
>
> *"You can't trust the Company – They won't monitor the environment and will not do the rehabilitation"*
>
> *"You can't trust the government agencies – they are on the side of the Company"*

Of the 270 public submissions to the panel the majority were against the proposal. Whilst there was much local support most of it was unspoken in public. Some businesses and elderly people felt intimidated.

SGM decided not to take part in a debate in the media. It did not recognise that many in the Community formed their opinions from what they read in the local papers.

SGM did not manage the process well and failed to capitalise on local support. SGM had not developed sufficient community contacts prior to this event through the "leave us to do our business" attitude. Management did not know the Councillors, the Council Officers nor the community decision makers and attitude leaders sufficiently well. It was assumed that the EES process was a technical process, but whilst SGM's technical arguments were sound they lost the political battle.

## 3. REHABILITATION – WORKING WITH AND FOR THE COMMUNITY

### 3.1 Background

SGM has three tailings dams.

| | |
|---|---|
| Reserve Dam | 3.2 ha |
| No 1 Dam | 12 ha |
| No 2 Dam | 80 ha (design 100ha) |

The first two are inactive and the third one is designed to last until 2020.

### 3.2 Stawell Clay target Complex

Working with the Stawell Gun Club the Reserve Dam is part way through being developed into a ten trap Shot Gun Facility. This came about by talking with a wide range of people in the Community at a variety of venues. The local Gun Club were looking for a new site that did not interfere with other people and had plenty of space.

A couple of keen SGM people set about convincing management, Council and the Department of Primary Industry that the scheme could work in harmony with mine activities. After a lot of discussion sufficient approvals and documentation were in place for the Gun Club to commit time, funds and hard work developing their site. From SGM's perspective it means a piece of rehabilitation has been completed with a meaningful end land use that will be maintained by members of the Community. For the Gun Club they have what they need.

Five of these 10 traps are now fully operational and the Minister for Sport & Recreation and Commonwealth Games, The Honourable Justin Madden, officially opened the facility in April 2004. The facility is state of the art and it has recently been suggested it be used for the Commonwealth Games training.

### 3.3 Tailings Experimental Research Facility

The rehabilitation of 100 ha of sulphide bearing tailings is a requirement for the project on closure. The current licence requirement is that rehabilitation is "subject to the satisfaction of the Chief Mines Inspector". Up until early 2004, this was deemed to be a one metre cover. It was obvious a rigorous scientific approach was required to demonstrate that a more appropriate cover may be pertinent to SGM's tailings dam, given the geochemical characterisation of the tailings.

SGM and the University of Melbourne formed a formal Cooperative Research Agreement to allow research into a range of disciplines associated with the mine. Several projects focus on characterisation of tailings material, rehabilitation options and end land use opportunities.

The primary project is a combined effort by the University of Melbourne and Curtin University WA. The project has two main aspects, applied ecology and geochemistry. The aim is to demonstrate what surface treatment is required for successful vegetation cover and anticipated geo-chemical changes over time. To assist the project SGM has constructed two Tailings Experimental Research Facilities. The first, ProtoTERF, was built with fresh tailings adjacent to the existing No2 tailings dam. This was built to allow a sighter on potential plantings that could be useful in the future. The current TERF is a 3.5ha facility built on top of No1 dam to provide an area where research can continue for years to come.

A Curtin University PhD study of geochemical characterisation has, over the past two years, been analysing geochemical characteristics of Magdala sulphidic mine tailings and modelling the tailings' 100 year Acid Mine Drainage (AMD) potential. Acid Based Accounting data shows the tailings to be non-acid generating and furthermore shows the tailings to have significant neutralising capacity. This arises from the high level of carbonates which occur naturally in the orebody. Recent analysis conducted on the Golden Gift orebody also indicates significant neutralising characteristics with the geochemistry of Golden Gift being very similar to that of Magdala.

The use of biosolids to assist rehabilitation has benefits not only to SGM but also the local sewage treatment operators. The Victorian Government are currently pursuing long term management plans for by-products including biosolids. Biosolids produced at Stawell have elevated levels of some elements of environmental concern and, as such, they present a disposal problem to the sewage treatment plant operators. Geochemical characterisation of this material has shown that co-disposal of biosolids with the tailings will not significantly contribute to the metal loading in the tailings, yet will contribute much needed organic matter and nutrients essential for successful plant growth. Utilisation of biosoids for tailings rehabilitation not only assists in achieving our objectives but also decreases liability to the management authority and ultimately the Community.

After the first three years, our rigorous research has begun to prove success. Negotiation for 300mm cover with the Department of Primary Industries has progressed significantly and results have been utilised to amend bond calculation.

The future direction of the project is now diversified to incorporate amelioration of the tailings back towards a more sustainable and balanced medium, capable of sustaining plant growth and developing an ecosystem. SGM has set its standards to, as a minimum, comply with regulatory requirements but more importantly be of benefit to the Community.

## 4. WORKING WITH THE COMMUNITY

Following the learning experience of the last 10 years of operating at Stawell, SGM has modified its approach of working in the Community.

It is a condition of the Mining Licence for an Environmental Review Committee (ERC) to be formed. The ERC is chaired by a representative of the Department of Primary Industry (DPI) and is made up of State and local regulators and two community members. SGM requested the DPI to open the meeting to a wider public audience. The quarterly meetings are now attended by a wide range of interested and concerned people. Invitations are sent out to all clubs and societies; service groups; schools; neighbours and known complainants. Any members of the public are welcome to attend as observers. This open forum allows more people to be aware of the mine's production and environmental performance. It is a forum where the mine can listen to the Community's concerns and interests.

SGM is committed to open communication with the Community. Communication is via; Annual Sustainable Development Report; quarterly newsletters to the Community; regular features in the newspaper; an audio and visual interactive observation area; regular tours, annual open day, Community dinners, regular presentations to Community groups and updates to specific areas of the Community on relevant projects such as exploration.

The Northern Grampians Shire and SGM have entered into a formal Council Protocol to promote the interests of both parties. Meetings are held on a regular basis with Council Officers and monthly with the Mayor and CEO. The meetings are designed to keep both parties abreast of ongoing activities and plans. Open and honest communications are the aims.

## 5. CONCLUSIONS

The lessons learned by SGM apply to all sectors of the mining industry on both a local and national level.

- ✓ Mining needs to justify it's presence in understandable terms
- ✓ Understand the dynamics of the community you work within
- ✓ Get to know people from Day 1. Maintain and grow the relationships
- ✓ Keep the links as regular as possible
- ✓ Give freely of your information
- ✓ Be open and honest
- ✓ Share your good times and bad times
- ✓ Listen and learn


## 6. ACKNOWLEDGMENTS

The authors acknowledge the support and assistance of MPI Mines and Stawell Gold Mines and the many employees that have made this paper possible. Thanks to Augustine Doronila and Dave Oldmeadow for providing sections on their PhD studies and Helena Gercovich for the figures and PowerPoint slides.

# GOLDFIELDS WEED STRATEGY

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## ABSTRACT

*The Goldfields region is an important part of the State from an agricultural, ecological, economic and cultural perspective. Weed invasion is an increasing problem in the region, compromising the integrity of pastoral enterprises, remnant bushland, and creating aesthetically unappealing landscapes. Of the weeds that have been identified in the Goldfields, twelve weeds are listed on the Department of Agriculture's Declared Weeds list, eighteen weeds are environmentally declared weeds for Western Australia and three weeds are listed in Weeds of National Significance.*

*One of the main groups strategically addressing the weed issue in the Goldfields region is the Kalgoorlie Land Conservation District Committee (LCDC). This group has been gathering comprehensive information on the type and extent of weed infestation on pastoral properties within the Kalgoorlie region over the last five years.*

*The Kalgoorlie LCDC received funds from the Natural Heritage Trust (NHT) to develop a Weed Strategy for the Goldfields region. At the end of 2003 the LCDC completed the draft Strategy which included the development of a Web site which provides an up-to-date and interactive platform for the management of weeds in the region. The website includes images of the most important weeds, control techniques, distribution maps, alert species and images of the weed species. A report and action plan has also been produced as part of the Goldfields Weed Strategy.*

*One of the main aims of the strategy is to involve all the relevant stakeholders in the Goldfields in the fight against weeds. The Weed Strategy advocates the establishment of the Goldfields Weed Task Group to oversee the co-ordination and implementation of the Weed Strategy.*

## BACKGROUND

The Goldfields region is located in the southeast corner of Western Australia. It is bordered by the Great Victorian Desert to the north, the South Australian border to the east, Esperance (southwest region) to the south and the Wheatbelt to the west. The City of Kalgoorlie-Boulder is the region's economic centre with the main industries being mining and agriculture. Mining activity is primarily centred on Kalgoorlie-Boulder and northwards into the area known as the Northern Goldfields Mineral Province with agricultural activity centred on pastoral leases across the region (Patterson Market Research *et al.*, 1999).

The Kalgoorlie Land Conservation District Committee (LCDC) is a statutory body formed (under section 23 of the *Soil and Land Conservation Act 1945*) for a range of functions relating to land degradation and soil conservation including preventing, remedying or mitigating land degradation and for promoting soil conservation and reclamation.

The Kalgoorlie LCDC was concerned that the weed situation in the Kalgoorlie district was growing out of control. This is a major concern to pastoralists as their operations are affected if their property becomes 'quarantined' due to infestations of declared plants. Aside from the environmental impact on pastoral country, the commercial implications of these weeds to the pastoral industry are twofold. Wool contaminated with declared plants can be sold for *export only*; therefore a stigma exists when marketing. Secondly, no livestock can be moved off leases on properties declared to have certain noxious weeds (sheep must be trucked out within six weeks of shearing), such as Bathurst Burr (*Xanthium spinosum*), Horehound (*Marrubium vulgare L.*) and Thornapple (*Datura ferox*) prior to inspection. Any livestock found to be contaminated with declared plants are not allowed to be freighted before either handpicking any plant matter out or re-shearing.

## WHY ARE PLANTS 'DECLARED'

Plants may be 'declared' by the Agriculture Protection Board under the *Agriculture and Related Resources Protection Act 1976*. If a plant is declared, all landholders are obliged to control that plant on their properties. Declarations specify a category, or categories, for each plant according to the control strategies or objectives which the Agriculture Protection Board deems are appropriate in a particular place. Among the factors considered in categorising declared plants are:

- the impact of the plant on individuals and agricultural production;
- the community in general;
- whether it is already established in the area; and
- the feasibility and cost of possible control measures.

Declared plants are gazetted under five categories, which define the action required. The category may apply to the whole of the State, or to districts, individual properties or even paddocks.

The five categories are:

**P1 Prevention**

Plants which can not be introduced or spread. Most declared plants fall under this category.

**P2 Eradication**

Includes potentially serious weeds which are not yet widely established.

**P3 Control**

Plant infestations should be reduced over time if eradication is not realistic.

**P4 Containment**

Plants should be prevented from further spread. Includes plants that are so well established that reducing the areas of infestation is not practical or economical. Also includes plants that can not be controlled with existing technology.

**P5 Special action on public land**

This provides for control on land under the control of local Government, saleyards and roadsides.

A current list of declared plants can be found at the departmental web site (http://www.agric.wa.gov.au). (Peirce, JR., Pratt RA., 2002)

## WEEDS IN THE KALGOORLIE DISTRICT

In order to understand the extent of the weed problem in the district, the Kalgoorlie LCDC created a sub-committee called the Weed Taskforce. The group organised a questionnaire for pastoral properties to gather information on weed species and occurrence. Statistics from the questionnaire revealed sixteen weeds of major occurrence on pastoral lands, eight of these being 'declared plants' (**DP**). Table 1 shows these weeds and the approximate area of infestation within the Kalgoorlie LCDC.

In order to rank the recorded weed species for the region in order of priority for control, the *Environmental Weed Strategy for Western Australia* (EWSWA) (CALM, 1999) was used.

**Table 1: Major weeds in Kalgoorlie LCDC pastoral leases and their area of spread**

| Infestations | Area (ha) |
|---|---|
| Kalgoorlie LCDC *(pastoral leases only)* | 3,798,229 |
| 1. Tansy (*Pentzia suffruticosa*) | 319,413 |
| 2. Maltese Cockspur (*Centaurea melitensis*) | 159,871 |
| 3. Saffron Thistle (*Carthamus lanatus*) **DP** | 127,047 |
| 4. Woody Weeds | 100,000 |
| 5. Bathurst Burr (*Xanthium spinosum*) **DP** | 29,752 |
| 6. Horehound (*Marrubium vulgare L.*) **DP** | 11,010 |
| 7. Ruby Dock (*Rumex vesicarius*) | 2,785 |
| 8. Thornapple (*Datura ferox*) **DP** | 2,353 |
| 9. Wards Weed (*Carrichtera annua*) | 2,040 |
| 10. Paterson's Curse (*Echium plantagineum*) **DP** | 1,101 |
| 11. Onion Weed (*Asphodelus fistulosus*) | 500 |
| 12. Doublegee (*Emex australis*) **DP** | 200 |
| 13. Mint Weed (*Salvia reflexa*) **DP** | 41 |
| 14. Tobacco Tree (*Nicotiana glauca*) | 26 |
| 15. Stinkwort (*Dittrichia graveolens*) | 10 |
| 16. Mexican Poppy (*Argemone ochroleuca*) **DP** | 5 |

The EWSWA (CALM, 1999) criteria, developed to assess over 1,300 weed species in Western Australia, were as follows:

- Invasiveness – ability to invade bushland in good to excellent condition or ability to invade waterways;
- Distribution – wide current or potential distribution including consideration of known history of widespread distribution elsewhere in the world; and
- Environmental Impacts – ability to change the structure, composition and function of an ecosystem, in particular, an ability to form a monoculture in a vegetation community.

Using this source, and community consultation, the 15 priority weeds were ranked as shown in Table 2.

The Goldfields Weed Taskforce, appointed by the LCDC and managed by Centaur Mining and Exploration, concentrated on the control and eradication of agricultural and environmental weeds in the region. This is done through gathering comprehensive information regarding the type and size of weed infestations on each pastoral property, with a view to calculating a cost for the required control actions for the entire LCD.

The Weed Taskforce has three goals:

- compile a framework for the ongoing management of weeds in the region;
- prevent the introduction of new weed species; and
- reduce the severity of the existing problem.

In their approach to land management, the Kalgoorlie LCDC has adopted the Ecosystem Management Understanding project (EMU). The EMU projects primary purpose is to introduce pastoralists and other land managers to the ecological management of landscapes and habitats in the outback. This involves reading and recognising landscapes (the terrain elements), internal and linking processes (function), condition and trend (Tinley and Pringle, no date).

The Goldfields Weed Strategy was commissioned to help achieve these goals. It has been designed to link with other weed strategies for Western Australia, namely the Weed Plan for Western Australia, the Environmental Weed Strategy for Western Australia and the National Weed Strategy. In this way, the Weed Strategy will complement these established strategies in order to achieve the same goals for weed control.

The development of the Goldfields Weeds Strategy is also very timely with the new Natural Resource Management (NRM) program being implemented across the Rangelands right at this moment. This is a joint Federal and State Government initiative and future funding opportunities for projects such as this one will benefit from NHT2 funds which will be administered by NRM.

**Table 2: The top 15 priority weed species for the Kalgoorlie LCDC**

| Scientific Name | Common Name | EWSWA Rating | Declared Weed |
|---|---|---|---|
| *Carrichtera annua* | Ward's Weed | High | - |
| *Rumex vesicarius* | Ruby Dock | High | - |
| *Centaurea melitensis* | Maltese Cockspur | Moderate | - |
| *Asphodelus fistulosis* | Onion Weed | Mild | - |
| *Dittrichia graveolens* | Stinkwort | Mild | - |
| *Nicotiana glauca* | Tree Tobacco | Mild | - |
| *Argemone ochroleuca* | Mexican Poppy | Mild | P4 |
| *Carthamus lanatus* | Saffron Thistle | Low | P4 |
| *Datura ferox* | Thornapple | Low | P4 |
| *Echium plantagineum* | Paterson's Curse | Low | P1 |
| *Emex australis* | Doublegee | Low | P1-P5 |
| *Marrubium vulgare* | Horehound | Low | P1,P4 |
| *Pentzia suffruticosa* | Tansy / Matricaria | Low | - |
| *Xanthium spinosum* | Bathurst Burr | Low | P3 |
| *Salvia reflexa* | Mint Weed | TBA | P1,P4 |

The Goldfields Weed Strategy is designed to improve knowledge of key weed species that threaten pastoral activities, and identify weed control methods to assist in controlling weeds in the long term.

The specific objective of the Goldfields Weed Strategy is to prevent the introduction of new weeds, reduce existing weeds and devise a framework for ongoing management, through a range of general objectives:

- identifying the weed species with the highest priority for control due to their detrimental effects on pastoral activities, invasive characteristics and threats to remnant vegetation and road verge environments through a process of consultation with the community, land managers and government agencies;
- developing mapping protocols to determine the extent of priority weed species so that the data can be imported into a Geographic Information System (GIS) environment;
- determining cost effective control strategies for priority weed species taking into account rangeland condition, land tenure and ownership and the need to achieve a co-ordinated weed control response;
- prepare an action plan for the implementation of weed strategy;
- identifying potential performance targets aimed at demonstrating the effectiveness of control strategies, reductions in weed populations and improvement in rangeland/bushland condition; and
- identify targeted education strategies aimed at landowners and the wider community.

Some of the key areas that need to be addressed include:

### *Rangeland Management*

The condition of rangeland vegetation is a determining factor in the establishment and spread of weeds. Areas that are heavily stocked or overgrazed begin to lose vegetation structure and cover and similarly lose their natural resilience to weed invasion. The loss of vegetation cover increases water flow across the landscape, resulting in increased soil erosion. The soil and weed seeds accumulate in drainage lines providing new sites and ideal conditions for weed growth. These areas are recurring infestation sites within the Kalgoorlie region.

There is therefore an economic incentive to manage rangelands to promote resilience, which is more cost effective and less resource draining than controlling weeds after a decline in vegetation condition. Strategic resting of pastures from grazing and management of kangaroo and feral animal populations is an important component of weed management.

### *Mining Impacts*

Mining is an important industry within the Goldfields region. Most mining is open cut, resulting in massive disturbance to the vegetation and soil structure of a localised area. Disturbed areas are often colonised by weed species and therefore mining operators need to be aware of the potential to create sites for weed invasion.

Rehabilitation of the waste dumps associated with mining can help arrest the invasion of weeds by establishing a robust native plant community. Control of weed populations within newly established mining sites is important so that they do not become established and make it difficult for the rehabilitation of the area in future.

### *Infrastructure Development*

The development of infrastructure projects such as rail, roads and telecommunication lines and other similar projects can foster conditions favourable to weed invasion. Roads can be important conduits for weeds as the margins of roads often contain bare ground producing vacant niches for the establishment of weed populations. Other infrastructure projects also contribute to the spread of weed populations through the development of bare sites.

While it may not be possible to control all weeds within the confines of infrastructure projects it is important to manage the type of weeds that do occur there. That is, it may be preferable to have some weed species that are potentially more benign than others that can cause bigger problems agriculturally or environmentally. Some weeds have the capacity to out-compete other weed species. Management of the appropriate species may have long term benefits rather than the continual application of costly and potentially environmentally harmful herbicides.

### *Urban Development*

Urban areas accumulate a number of weeds on unmanaged private and public land. Large land areas with absentee landowners can result in significant weed infestations. These can produce subsequent problems such as increased fire hazards. Landowners need to be made aware of their responsibilities to manage weeds on their land.

It was also important to identify specific weed control measures to reduce the extent of weeds, while also improving the condition of the rangelands. This approach enables the LCDC to implement a structured weed control regime to address the threats from weeds through targeted activities and by monitoring the progress of weed control measures.

The knowledge of weed control techniques gained through this process will lead to improved weed control outcomes and provide a model to address weed control problems across the region.

Over time, it is hoped that the costs of weed control will reduce as the extent of the infestations is reduced. The Goldfields Weed Strategy will enable the LCDC to work more effectively with their community, thereby achieving increased activity and success in weed control.

At the end of 2003 the LCDC completed the draft Strategy which included the development of a Web site which provides an up-to-date and interactive platform for the management of weeds in the region. The website includes images of the most important weeds, control techniques, distribution maps, alert species and images of the weed species. A report and action plan has also been produced as part of the Goldfields Weed Strategy.

One of the main aims of the strategy is to involve all the relevant stakeholders in the Goldfields in the fight against weeds. The Weed Strategy advocates the establishment of the Goldfields Weed Task Group to oversee the co-ordination and implementation of the Weed Strategy.

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**NB:** We have had contact from 2 major telecommunication companies in relation to upgrading and installation of infrastructure in the region. These contacts have been in relation to the development of best practice weed management plans while operating in our region. Please fell free to contact Sam on the above details or speak to LCDC members during the break after this session.

# REHABILITATION: BEING ENVIRONMENTALLY NEUTRAL

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## ABSTRACT

*This paper argues that mining should strive to be environmentally neutral, and this has significant implications for how we plan and evaluate our rehabilitated areas. We explore the concept of 'environmental neutrality' in the rehabilitation of disturbed sites, and argue that the primary objective of rehabilitation programs should be to create near-natural, self-sustaining, functional ecosystems. Where it is not possible for companies to repair the environmental damage done by mining then they should make a significant contribution to improving the environment that offsets the damage. We argue that the government regulators must provide greater leadership in this area, and mine site environmental staff and their umbrella groups can also hasten developments in this area.*

## INTRODUCTION

We start from the premise that as environmental officers, landcare officers or environmental scientists we are the custodians or stewards of the environment, and as a consequence we should be endeavouring to leave this planet an environmentally better place. For many mine site environmental officers the rehabilitation of disturbed areas is one aspect of mining where they can have a significant positive impact on the environment.

Mines must:

a) contribute economic benefits to the stakeholders, otherwise they will not exist;

b) socially responsible, contributing real social benefits to the stakeholders; and

c) be environmentally neutral. Being environmentally neutral means two things:
   - when a mining company has finished with a site, there are no negative environmental impacts on that site, or
   - doing something positive for the environment that balances out the negative impact or damage that mining has done to the environment.

We are reminded here of an advertisement by a private consulting company that regularly appeared in AMEEF's *Groundwork* that said 'Our aim is to leave a site without anyone knowing we've been there'. If this company was arguing that their rehabilitation programs resulted in the development of functional ecosystems similar to that which existed before the disturbance, then this is a commendable outcome, and in line with what we believe is being environmentally neutral.

Environmental neutrality is a realistic and reasonable objective for a mining company's rehabilitation programs in the goldfields of Western Australia. To be environmentally neutral in the rehabilitation of disturbed areas, there are a number of possible outcomes. The first is that rehabilitated areas should be to returned to near-natural, self-sustaining, functional ecosystems similar to that in the adjacent undisturbed area or to the habitat that existed before the disturbance.

### Self-sustaining, functional ecosystems as a rehabilitation objective

There are many components that contribute to a functional ecosystem in rehabilitated mine sites. They include appropriate geological and landform processes; the foundation of the ecosystem (Fig. 1). This includes the shape and form of the terrain, the soil structure and soil chemistry. For a functional ecosystem to be established, vegetation communities in the rehabilitated area should resemble those in adjacent undisturbed areas or be similar to that which existed before the disturbance. When appropriate soils and vegetation are in place it is likely that a suite of soil microbes and invertebrates from the adjacent habitat will eventually colonise the rehabilitated area presuming there is no barrier between these areas. When the necessary habitat and energy resources are available, vertebrates from the adjacent area will also colonise the rehabilitated area. The sequence of succession suggested above is overly simplistic, but it makes a couple of primary points. Firstly, appropriate landforms, soils and vegetation must be put in place to provide the habitat and energy sources necessary for the microbial organisms and invertebrates to colonise the area. Vegetation and invertebrates are an important food source for many of the vertebrates, and are therefore a prerequisite for many of these animals to colonise rehabilitated areas.

It is reasonable to assume that if the abundance and diversity of vertebrates in the rehabilitated area resembles that in the adjacent undisturbed area, then the landforms, soil and vegetation in the rehabilitated area are generally appropriate for the creation of a near-natural, self-sustaining, functional ecosystem. However, the converse is probably not true. That is, the presence of appropriate landforms, soil and vegetation does not necessarily imply that the assemblage of vertebrates in the adjacent undisturbed area will eventually colonise the rehabilitated area. Therefore, it is important we include the higher order vertebrates in any program to monitor the success of rehabilitated areas.

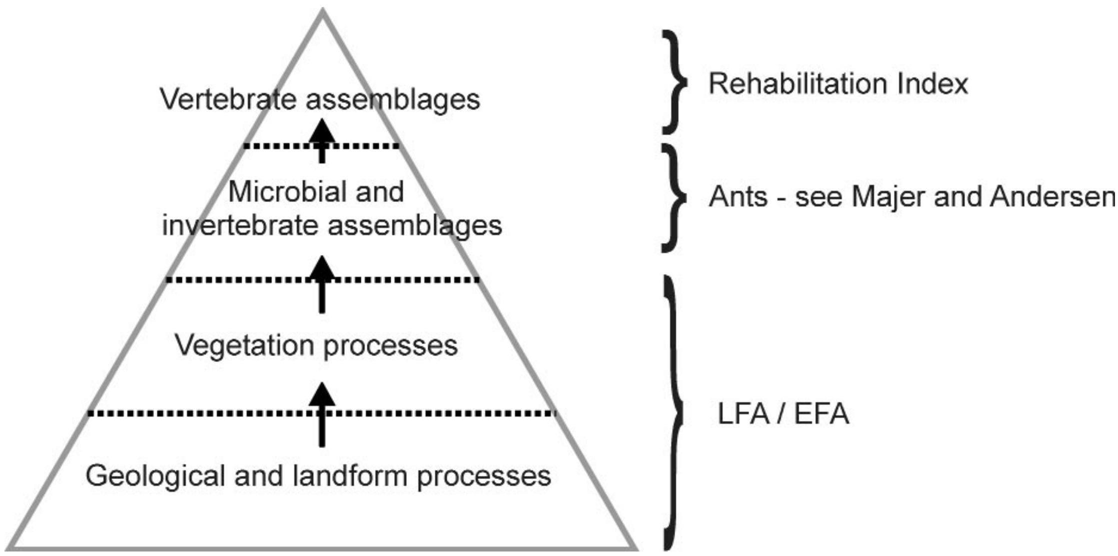


*Figure 1: Components of a functional ecosystem and their relationship to available monitoring strategies*

If a near-natural, self-sustaining, functional ecosystem is the objective for rehabilitated areas, then we should assess the performance of these rehabilitated areas in these terms. Where the objective of a rehabilitation program is the creation of a near-natural, self-sustaining, functional ecosystem there are a number of monitoring strategies available to assist in the assessment of the development of the area. Ecosystem Function Analysis (EFA) is one such metric.

Tongway and Hindley (nd) indicated that a combination of 11 indicators are used in the EFA (Fig. 2) to assess the functionality of the area. It is evident that within the 'pyramid of the components of a functional ecosystem' (Fig. 1) that the EFA primarily monitors the lower two levels, and is therefore a useful tool in assessing the early stages of the development of a rehabilitated area.

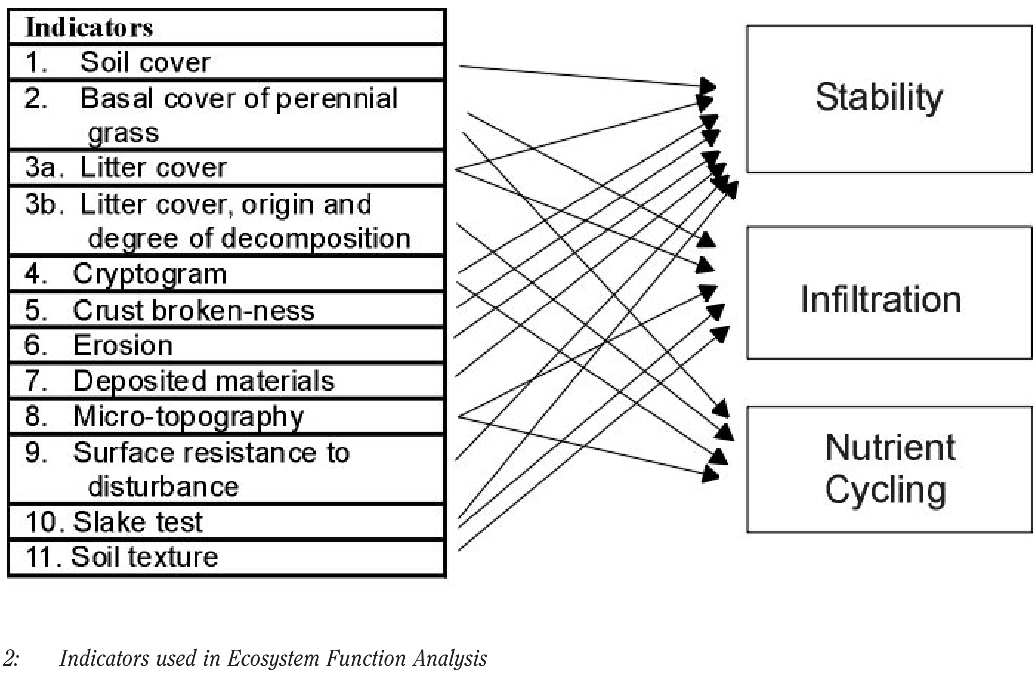


*Figure 2: Indicators used in Ecosystem Function Analysis (taken from Tongway and Hindley nd; http://www.cse.csio.au/research/Program3/efa/lfa_summary.htm)*

Invertebrates, in particular ants, have been used as bio-indicators of rehabilitation progress in mine sites for a number of years (Andersen, 1993; Majer & Beeston, 1996; Majer & Nichols, 1998; Andersen, *et al.*, 2003). Although both Majer (1983) and Andersen *et al.* (2004) argue that ants are good indicators because they are abundant and species rich at most sites, have many specialist species that occupy higher trophic levels, and are responsive to changing environments, Andersen *et al.* (2003) reported that the taxonomy of northern Australian ants is poorly known, and Majer in his many articles on using ants as indicators was often unable to identify many of the species caught (see Majer, 1983/84, 1985; Majer & Nichols, 1998). Andersen *et al.* (2003) in their recent research using ants as indicators reported that they were the first to demonstrate convergence between the ant assemblage on a rehabilitated area and the adjacent undisturbed area, and even then they were only able to do this for one of eight sites examined. There are other problems with using invertebrates as bio-indicators for rehabilitation success. These relate to the enormous seasonal and year-to-year variability in species abundance that are unrelated to rehabilitation progress (Majer & Nichols, 1998), and Hilty and Merenlender (2000) argued that invertebrate numbers generally do not correlate with changes in the ecosystem health and function, although there are conflicting views on this issue (see Andersen *et al.* 2004 and references therein). Monitoring invertebrates in rehabilitated areas can provide an early indication of whether a rehabilitated area is developing into a functional ecosystem (Fig. 1), but they do not provide an indication of whether the higher order vertebrates are colonising the area.

Recently, researchers have used the higher order trophic vertebrates to monitor rehabilitation success or as bio-indicators. For example, Fox and colleagues (Fox, 1997; Fox, 1979, 1990, 1996; Letnic & Fox, 1997; Monamy & Fox, 2000) have used small mammals to monitor progress in the restoration of disturbed areas. Reptiles have also been used to monitor rehabilitation progress in disturbed areas (e.g. Nichols, *et al.*, 1985; Halliger, 1993; Ireland, *et al.*, 1994; Read, 1999). Read (2002) argued that small reptiles may be useful bio-indicators of the impact of cattle grazing in chenopod shrublands in South Australia because they are easily sampled and identified, respond quickly to environmental change, are abundant, and are not subject to dramatic seasonal fluctuations in population size and composition to the same degree as arid zone mammal and bird communities. Between 2000 and 2004, with the support of OMG Cawse Nickel and Placer Dome Asia Pacific Kalgoorlie West Operations, we developed a Rehabilitation Index to measure the progress of rehabilitated waste dumps in establishing functional ecosystems by comparing the reptile assemblage on the waste dump with that in the adjacent undisturbed area (Thompson & Thompson, 2003). This rehabilitation index presumes that if the complete suite of reptiles in the adjacent undisturbed area has colonised the rehabilitated area, then the habitat, shelter and prey availability in the rehabilitated area must resemble that in the rehabilitated area, and a functional ecosystem is well down the path to being created. Therefore, to achieve a high score on the rehabilitation index the geological structures, vegetation and invertebrates necessary to sustain a functional ecosystem will be in place.

It is therefore evident that there are a number of 'tool's (e.g. EFA, Rehabilitation Index, etc) being developed that can be used by mine site managers to assess the success or otherwise of rehabilitation programs to create near-natural, functional ecosystems, and thereby quantify the extent to which their rehabilitation programs are achieving objectives of environmental neutrality.

We believe the previously accepted standard for rehabilitated areas of being *safe, stable, non-polluting and aesthetically acceptable* does not guarantee the development of functional ecosystems in rehabilitated areas, and is therefore not an indication of achieving environmental neutrality. We would argue that the mining industry should abandon this as a desirable end result for rehabilitated areas and adopted the primary objective of creating near-natural, self-sustaining, functional ecosystems.

Similarly, 'sustainable' rehabilitated areas are not necessarily near-natural, self-sustaining, functional ecosystems that are similar to that in the adjacent undisturbed area. The over used term of 'sustainability' in the context of rehabilitation on waste dumps or for mining voids can and does mean many things and should be avoided.

We acknowledge that there are other legitimate end outcomes for rehabilitated areas. If for example the mined area was used for pasture before mining commenced, then this must be considered to be an acceptable end use for the land after mine closure. Similarly, the community maybe prepared to accept the development of a recreation facility (e.g., water skiing area), industry (e.g. salt production) or agriculture (e.g. aquaculture) for rehabilitated mine sites after closure. These are acceptable closure options for mine sites presuming the appropriate approvals have been obtained.

The third option we wish to address is when it is recognised that the creation of a near-natural, self-sustaining, functional ecosystem in a rehabilitated site will never be achieved (e.g., saline water-filled quarry, acidified or saline waste dump). In these circumstances we would advocate that the mining company should make the site safe, stable, non-polluting and as aesthetically acceptable as possible, but it should not be released from its environmental obligations at this point, as the end result is clearly not environmentally neutral. To offset the environmental damage or impact that cannot be repaired, the mine should make some significant contribution to improving the environment. Options in the goldfields area could include: reducing feral goat numbers, destocking pastoral leases damaged by overgrazing, reducing feral cat numbers, sealing off and rehabilitating abandoned mine shafts, lowering lake salinity levels increased by mining activity, reducing salt affected habitats and environmental research into issues relevant the local environment. If such alternatives are considered appropriate then there are a number of issues that need to be addressed:

a) how do we define 'acceptable' alternative significant contributions?;

b) how can we integrate the notion of 'environmental neutrality' into the existing policies and procedures?;

c) how do we get closure on significant environmental contributions?; and

d) how do we obtain public acceptance of this concept when they see some poorly vegetated waste dumps and large quarries in the ground?

These four issues are addressed below.

## Acceptable alternative significant contributions

If we adopt the strategy of using *significant environmental contributions* to off-set our inability to create functional ecosystems in rehabilitated areas, then there are an number of issues that need to be addressed. These include:

### Guidelines

The government regulators must provide suitable guidelines for mining companies on what are suitable alternative environmental contributions. Input from science and industry will be required to develop these guidelines. In all probability some applied research will also be required to ensure the guidelines are appropriate, adequate and comprehensive.

### Negotiated outcomes

Very clearly 'one size will not fit all'. Alternative significant contributions should relate to the specific mine site, local environmental conditions and the scale and level of environmental impact that cannot be repaired. Regulators will need to encourage both innovative and problem solving approaches when establishing offsetting environmental contributions. This is only likely to be achieved if mining companies can negotiate significant environmental contributions with the appropriate government agencies.

### Independent arbitrator

It is difficult being both 'adviser' and 'decision maker' in obtaining closure for rehabilitated areas. We believe that at least one of the government agencies needs to accept the role of the 'developer' and 'adviser', and another the responsibility as the 'decision maker' to ensure the process has integrity, accountability and transparency. All negotiated offsetting alternatives need to be available for public scrutiny. A description of the alterative significant contributions that mining companies will make to offset the irreparable damage done to the environment should be placed on the web site of those mining companies.

### Quantifiable outcomes

We must endeavour to avoid the current system of vague, non-descript closure criteria. Clear progressions and performance indicators need to be devised at the outset for each significant environmental contribution. Progress must be monitored and the outcomes available for public scrutiny. Again, placing the performance data on the web site of those mining companies should be required.

## Closure for rehabilitated areas in the context of being environmental neutral

Where the rehabilitation objective is the creation of near-natural, self-sustaining, functional ecosystems, then the mine needs to demonstrate that rehabilitated areas have progressed to the point, that without further management, the site will eventually return to an appropriate self-sustaining, functional ecosystem. There needs to be quantifiable data to support these claims. Similarly, where the objective includes an alternative significant environmental contribution to offset the irreparable environmental damage, clearly identifiable and publicly documented outcomes need to be provided. It also seems advisable for mining companies to provide the public with an appropriate opportunity to comment on their intent to seek closure based on the achievement of some previously agreed outcomes.

## Public acceptance of this alternative approach

The public will initially be suspicious that mining companies will want to use this alternative to walk away from their environmental obligations. There will no doubt be those in the community that will advance strong arguments against the idea. To gain public acceptance the following five strategies should be put in place:

a) Departments of Industry and Resources, and Conservation and Land Management and the Environmental Protection Authority will have to show considerable leadership in promoting the alternative options to the creation of near-natural, functional ecosystems on rehabilitated areas.

b) Industry umbrella groups such as the Chamber of Minerals and Energy, Goldfields Environmental Management Group, etc, will have to advocate and raise the issue with the regulators, and discuss the alternatives in open forums.

c) The alternative offsetting environmental contributions will need to be supported by the appropriate applied research. There will need to be a demonstration that the alternative environmental contributions are in fact positive contributions to the environment.

d) The preparation and distribution of a formal discussion paper on the issue by the appropriate authorities (e.g. Department of Industry and Resources, Environmental Protection Authority) and the subsequent discussion in public forums will go a long way toward attracting public support for the idea.

e) There will need to be a significant dialogue with the various conservation groups. We would expect most of these groups would be supportive of this type of initiative; but they will want to understand the process and the benefits before lending support.

Both the regulators and mine site environmental staff are able to advance these ideas.

Firstly, we believe the regulators should:

- make a clear statement about their commitment to environmental neutrality in mine site rehabilitation;
- provide much clearer closure criteria for rehabilitated areas in terms of the creation of near-natural, self-sustaining, functional ecosystems;
- actively promote self-sustaining, functional ecosystems as the desirable end result for rehabilitated areas;
- actively promote the idea of using off-setting environmental initiatives, where near-natural, self-sustaining, functional ecosystems cannot be achieved;
- require quantifiable and publicly available closure criteria for mine sites; and
- publish or require mining companies to publish performance data against nominated criteria for rehabilitated areas.

Where a self-sustaining, functional ecosystem is a desirable end result for a rehabilitated area, then mine site environmental staff might:

- use the umbrella groups to promote environmental neutrality as a primary objective for mining companies;
- request that 'environmental neutrality' be included in their company's mission statement and objectives;
- state their rehabilitation objectives in terms of self-sustaining, functional ecosystems;
- monitor rehabilitation progress in terms of establishing functional ecosystems and use higher order vertebrates as bio-indicators; and
- publicly report rehabilitation success in terms of the extent to which near-natural, self-sustaining functional ecosystems have been achieved in rehabilitated areas.

Where a functional ecosystem cannot be a reasonable outcome, then mine site environmental staff might:

- use umbrella groups to promote significant environmental contributions as an offsetting alternative;
- put pressure on the regulators to accept clearly defined, quantifiable, alternative environmental outcomes to offset the irreparable damage done to the environment;
- engage in research that enables your company to defend its use of alternative significant environmental contributions;
- talk with your mine site colleagues (e.g. engineers, geologists, managers) about the alternatives; and
- publicly report what you have achieved in terms of the negotiated alternative outcomes.

Where we go from here is largely going to be determined by whether there is a consensus that:

a) it is no longer adequate for rehabilitated areas to be just *safe, stable, non-polluting and aesthetically pleasing* before they are given closure; and

b) environmental neutrality is an acceptable and achievable outcome for rehabilitated areas.

*Do you think mining companies should be environmentally neutral?*

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# SOIL BIODIVERSITY AND LANDSCAPE FUNCTION: SOME IMPLICATIONS FOR MONITORING RESTORATION OF LANDSCAPE PROCESSES.

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## 1. INTRODUCTION

A considerable proportion of the terrestrial biosphere's biodiversity resides in the soil. On a species richness per unit area basis, the soil and litter subsystem rivals tropical systems, a comparison which has led to the subsystem being described as the "poor man's rainforest" (Giller, 1996). The great bulk of this diversity is contained in the litter and top 10 cm of soil, making it one of the most vulnerable and, some believe, the least resilient, of the soil's resources (Brussard *et al.,* 1998).

The soil/litter biota are most easily described by relative size, ranging from the microscopic bacteria to the larger arthropods living in the leaf litter. The main groups are:

(i) the microorganisms or *microflora,* the bacteria and fungi;

(ii) the *microfauna* (animals smaller than 0.2 mm) represented by the single-celled Protista and the Nematoda (roundworms);

(iii) the *mesofauna* (animals between 0.2 mm and 1 cm), of which the Collembola (springtails) and the Acari (mites) are by far the most numerically dominant and small numbers of a variety of other groups such as Pseudoscorpionidae (pseudoscorpions), Araneae (spiders), Enchytraeidae (potworms), small species of Chilopoda (centipedes), Diplopoda (millipedes) and Psocoptera (booklice);

(iv) the *macrofauna* (animals larger than 1 cm) found in the litter layer and including better known groups such as diverse Insecta and Annelida (earthworms).

The free-living Acari or mites of the soil/litter subsystem are the focus of this paper.They are particularly significant to discussions of biodiversity in semi-arid systems, one of the contexts of this workshop, for a number of reasons:

- They are far more diverse and abundant than any other arthropod group below ground, even insects. In semi-arid systems, they make up 70 – 90% of the soil invertebrates. The studies we have completed of soil/litter mite assemblages in dryland systems in Western Australia suggest that our soils harbour a particularly species-rich fauna. For example, approximately 100 species have been found in the lateritic soils of Widgiemoooltha (Kinnear, 1991) and in the duplex soils of grazed chenopod rangeland in the Gascoyne Region (Kinnear & Tongway, 2004).
- They are particularly important to nutrient cycling in low rainfall systems. They can be responsible for 50%- 60% of nitrogen mobilisation in these areas.
- Unlike other invertebrates below ground, the soil mites remain active in hot and dry conditions and contribute to maintaining decomposition processes in conditions of high temperatures and low moisture (Whitford *et al.,* 1983).
- Mites of the Order Oribatida (the 'beetle mites') have potential as disturbance indicators (Behan-Pelletier, 1999).

Given the importance of the soil/litter mites on decomposition in the semi-arid zone and their high levels of diversity, it would seem appropriate, if not essential, that they be included in programs designed to improve, manage and/or monitor biodiversity.

This paper argues that if management for biodiversity is an important focus, then we cannot ignore the soil mite assemblages (a) because of their inherent diversity and (b) because they can control processes leading to decomposition of organic matter and nutrient dynamics in dryland systems.

## 2. THE ROLE OF THE SOIL/LITTER MITES IN DECOMPOSITION AND NUTRIENT CYCLING.

Our image of the soil/litter subsystem has changed considerably from the diagrams in early soil texts which focussed soley on the physico-chemical nature of soils. A biological view of a fully-formed and functioning soil is of a complex set of microhabitats, each supporting different interacting assemblages of biota. For example, the macropores formed within and between soil aggregates harbour the air-breathing mesofaunal assemblages and fungal communities. The aquatic micropores and associated water films on aggregate surfaces harbour the aquatic microfauna and active bacteria. Maintenance of these microhabitats and their biota is dependendant on the maintenance of the soil structure and profile. The soil biota in turn affect soil structure and development by their activities and secretions. For example, the faecal materals produced by soil invertebrates are centres of baterial and fungal activity and promote soil aggregation. So the interactions between soil structure and biota are two-way.

Land use which impacts on soil structure affects the distribution and diversity of the microhabitats. For example, a disturbance such as heavy grazing reduces soil porosity and directly affects the abundance and diversity of the air-breathing fauna which occupy the macropores. Loss of organic matter can have the same affect by reducing soil aggregate size and soil porosity. Soil organic matter is also the primary energy resource for the system, supporting the entire food web below ground. So land use strategies which degrade soil profile, structure and organic matter will degrade soil biodiversity. Conversely, strategies which are specifically designed to rebuild/restore soil structure and increase organic matter will accelerate the restoration of diverse soil communities, with positive feedback effects on soil profiles and decomposition rates.

Different soil organisms play very different roles in the decomposition of organic matter and nutrient cycling. The roles of the bacteria and fungi are unequivocal and direct. They are the only organisms which can chemically degrade the recalcitrant components of plant litter, namely cellulose and lignin. They are the primary agents of decomposition. The soil invertebrates, of which the mites are the major group, cannot degrade cellulose or lignin. Their influence on organic matter decomposition and nutrient cycling is indirect but very significant, particularly in semi-arid systems. Mites influence every level of the decomposition cascade (Wolters *et al.*, 2000). They mediate the C and N turnover by their indirect effects on the other fauna and on the baterial and fungal populations, and their activities can increase decomposition rates. In dryland systems, removing the mite fauna from the decomposition process results in the decomposition rate being retarded by as much as 45 % and the mites can directly account for up to 37% of N mineralisation (Hunt *et al.*, 1987). They do this in a number of different ways:

- They comminute leaf litter as they graze on the resident bacteria and fungi. The repackaging of the litter into clusters of tiny, spherical fecal pellets mixed with the gut secretions enhances colonisation of bacterial and fungi and acclelerates the decay of the organic matter. *This is the major way in which they influence deomposition rates.*
- The feeding effects of predatory mites can influence the composition and abundances of microbial communities. For example, high numbers of nematode-feeding mites can result in reduced populations of bacterial-feeding nematodes. In turn, this can result in increased populations of bacteria and increased mineralisation rates of nitrogen. Fungivorous mites mediate and control the slower release of nutrients immobilised in fungal biomass. *These are the major ways in which mites can influence nutrient cycling.*
- Mites are effective transporters of fungal spores and bacterial cells, moving them through the litter layers and soil profile.

So not only are the soil/litter mites the most diverse of the soil/litter invertebrates in semi-arid systems, but they mediate and can control rates of decomposition and nutrient release. In addition, their trophic diversity places them at almost all feeding levels in the below-ground food web. This combination of impressive species and functional diversity makes them appropriate indicators of soil faunal biodiversity in general.

## 3. MITE COMMUNITIES IN WESTERN AUSTRALIAN SOILS AND IMPACTS OF DISTURBANCE

Our studies at ECU have focussed on describing the mite assemblages and the impact of selected land use strategies on their structure and diversity. In this paper, these studies are reviewed from the perspective of management, with the focus on two questions:

(i) Are there outcomes which inform strategies for restoration and management of disturbed or degraded landscapes?

(ii) Do the study outcomes provide useful suggestions for monitoring and assessing mite diversity as general diversity indicators?

### 3.1 Patterns of mite succession with revegetation of mined sites

The development of soil and litter mite assemblages occur concurrently with vegetation succession in revegetated sites (Table 1; Figure 1). In these successional sequences, the production of a multi-species litter layer and increases in soil carbon are the most important correlates of mite species richness (Cuccovia & Kinnear, 1999).

As the vegetation structure matures, a canopy cover provides initial climate ameleoration and roots provide energy sources below ground. As litter production proceeds, resource availability and microhabitat diversity at the soil surface increases and decomposition processes begin to alter soil properties and carbon resources below ground. This in turn develops soil profiles and microhabitat diversity. Litter cover is an important and early determinant of diversity at both levels. The combination of increasing development of habitat diversity through litter complexity, availability and diversity of carbon resources, soil development and microclimatic stability is reflected in the increasing species richness and abundance both above and below ground.

The morphological characteristics of the litter layer can affect faunal activity by maintaining favourable microhabitat conditions. For example, in Banskia communities north of Perth, the thicker, more fertile litter of *Nuytsia* floribunda retains moisture longer into the dry period than the coarse, scattered *Banskia* litter (Figure 2). As a result, large active populations of grazing mites are maintained for longer (Kinnear, 1992).

The restoration of microhabitats during revegetated succession, as reflected by the species richness of the mite assemblages, may be much slower in soil than in litter. Even after 10 – 20 years, revegetated sites may carry reduced numbers and richness of soil mites compared with mature forest. Additional work is required to identify is this pattern is a general one.

**Table 1.** **Mite abundance and species richness and the most significant plant correlates in variously aged rehabilitations sites and mature forest in the northern jarrah forest. (Cuccovia and Kinnear, manuscript in preparation).**

| | Revegetated sites | | | | Mature forest |
|---|---|---|---|---|---|
| | 2 years | 5 years | 10 years | 20 years | |
| Canopy cover (%) | 27 | 43 | 57 | 72 | 55 |
| Litter cover (%) | 23 | 36 | 55 | 90 | 75 |
| Litter depth (mm) | 8 | 21 | 21 | 48 | 16 |
| Soil organic carbon (%) | 2.9 | 3.0 | 3.3 | 7.1 | 7.2 |
| Soil mite density (N $m^{-2}$) | 3 742 | 4 022 | 9 418 | 17 411 | 25 331 |
| Litter mite density (N $kg^{-1}$) | 181 | 206 | 474 | 498 | 476 |
| Soil species richness | 7 | 14 | 22 | 31 | 49 |
| Litter species richness | 13 | 20 | 34 | 29 | 37 |

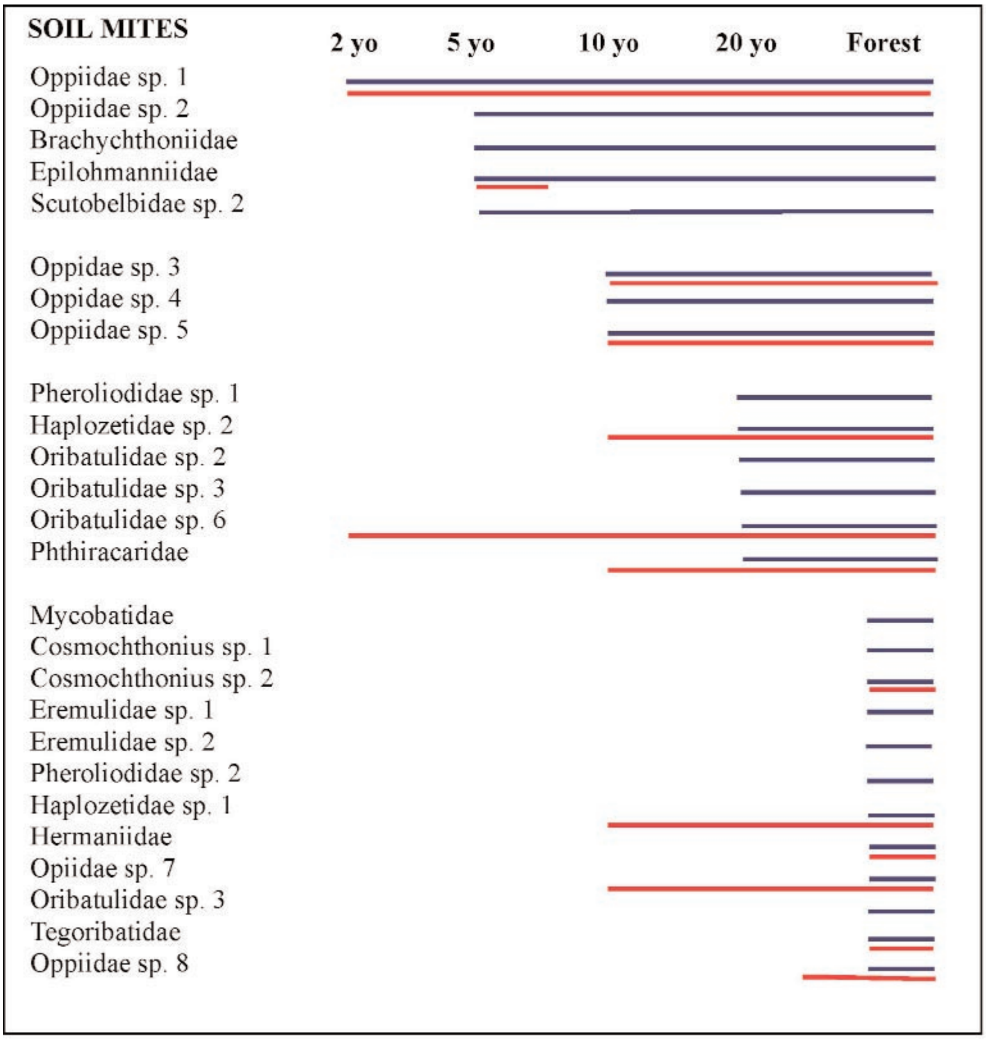


*Figure 1:* *Appearance of mite species in samples from variously aged revegetation sites. Top lines indicate presence in soil samples and, if the species was also found in litter, the lower line indicates presence in litter samples (Cuccovia, 1997; Cuccovia & Kinnear, 1999).*

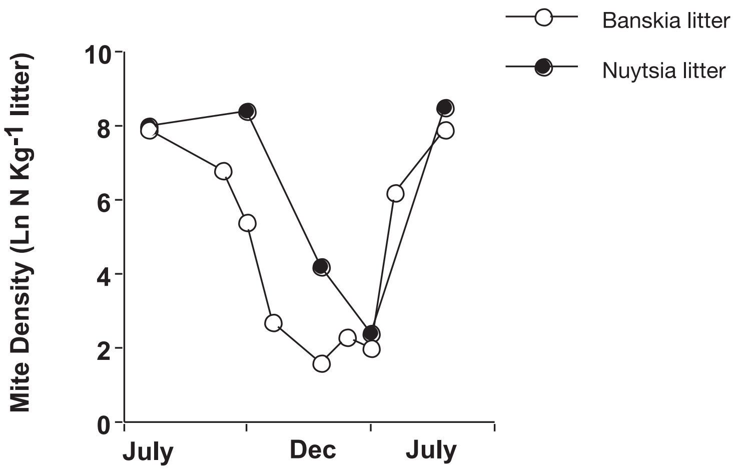


*Figure 2: Mite densities in* Banskia *and* Nuytsia *plant litter. The higher densities in the* Nuytsia *litter during the drier months are correlated with higher litter moisture levels.*

### 3.2 Mite assemblages in *E. globulus* plantations

The development of blue gum plantations on soil previously used for pasture or broad scale agriculture greatly increases species richness of the soil and litter mite assemblages which make up 90% of the mesofauna. This is not surprising given the depauperate communities found in the adjacent agricultural soils (Adolphson, 2000). What is perhaps surprising is that a blue gum plantation close to harvest and with a well-developed and continuous layer of litter, supports mite assemblages which are have only one third the richness of the multi-species litter of adjacent jarrah woodland. While the agricultural history of the site is an influencing factor, the single species plantation litter is also a factor. An important grazing functional group, the Oribatid mites, is most affected, with very low richness in the blue gum plantations compared with the species-rich adjacent jarrah woodland. Oribatid mites as a group are considered to have indicator potential, and species species have been used as indicators of disturbance. The single species nature of the blue gum litter is a likely factor here as research has shown that replacement of a diverse mult-species litter with a single species litter is known to reduce mite diversity, particularly oribatid mite diversity (Hansen & Coleman, 1998). Like the semi-arid sites we have sampled, jarrah woodland is very diverse in its mite fauna with 95 morphospecies/species distributed among 48 families.

In disturbed sites such as those in agricultural landscapes and plantations, it is common to find very large densities of a small, disturbance-coloniser (r-selected) of the Genus *Tyrophagus*. These tiny, fungivorous mites are very effective and fast colonisers of disturbed soil and litter habitats. (Mites of the same genus colonise grain stores and any human habitats where food resources are available). In all our studies large numbers of these mites have been found consistently associated with disturbance arising from various land uses such as irrigated and non-irrigated plantations (Swarts & Kinnear, *in press*) pasture (Adolphson 2000 ), early succession revegetated sites (Cuccovia, 1997) and heavily grazed rangeland sites (Kinnear & Tongway, 2004).

The degree to which revegated or plantation sites are recolonised by soil fauna depends greatly on the nature of the site 'preparation' or 'disturbance' prior to planting. We have shown that sites where the soil profile is considerably disturbed or destroyed (such as occurs with deep ripping and excavation prior to plantation establishment) have particularly depauperate soil communities – a characteristic which is evident at several trophic levels (Swarts & Kinnear, *in press*). These communities remain depauperate 7 – 8 years on, reflecting the relatively slow physico-chemical processes which are mediated by the biota and which govern soil profile formation. Swarts (*pers.com*) considers these highly disturbed soils to be bacterial dominated with bacterial based food chains of restricted diversity. This structure of the soil food web has implications for nutrient dynamics and the sequestration of soil carbon. For example, it has been shown that bacterial-dominated soil food webs which develop in heavily tilled agricultural systems accelerate nitrogen leaching and soil carbon degradation.

### 3.3 Soil mite diversity in grazed semi-arid rangelands

On the alluvial plains of chenopod shrublands of the Gascoyne region, the perennial vegetation determines the distribution, abundance and diversity of the soil mite assemblages. The soil accretion mounds that form at the base of the blue bush shrubs are 'hot spots' of abundant and diverse soil communities (Figure 3). These "islands" of fertility in nutrient-limited landscapes are important respositories of biodiversity and are likely to be hotspots of landscape function such as decomposition and C-sequestration. Fifty percent of the mite species in these soils are only found in these accretion mounds, an indication of how important retention of these shrubs is to the maintenance of below-ground biodiversity in the landscape.

When this system is overgrazed, and the bluebush degraded (even to the point of plant mortality), the soils below the degraded and dead bluebush take on the depauperate biotic and physico-chemical characteristics of interbush soil.

This reduction in soil mite diversity and abundance occurs with losses of soil porosity and aggregate stability, organic matter content and nutrient availability. However, the system shows considerable resilience in the face of this degradation. Within one year of cessation of ten years of heavy grazing, recolonisation of degraded bush mounds by soil mites can be observed even in the most severely affected areas, and there is evidence of development of faunal assemblages more typical of a lightly grazed landscape.

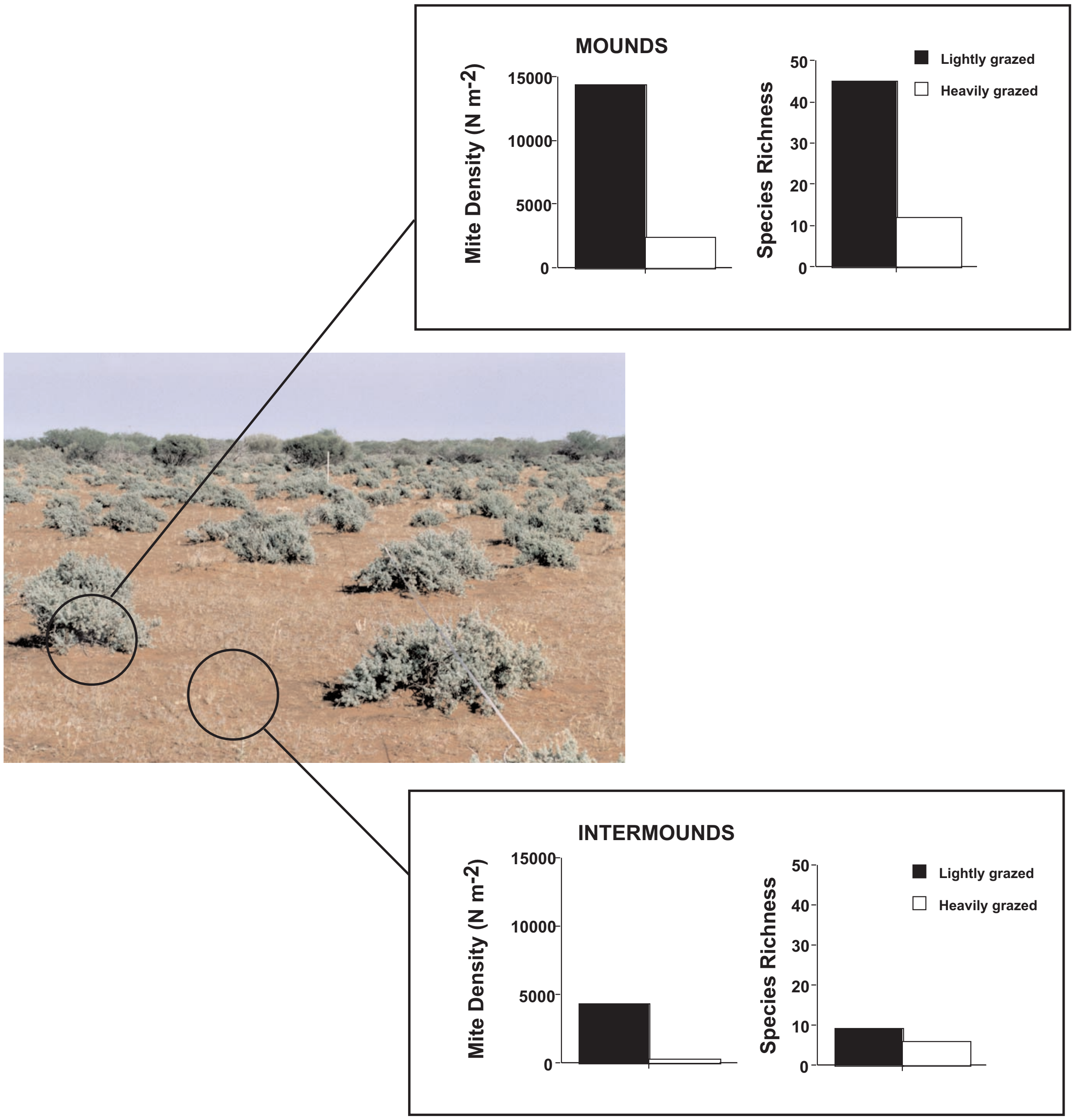


*Figure 3: Mite densities and species richness of soil accretion mounds and intermound areas in the blue bush chenopod rangelands of the Gascoyne Region (Kinnear & Tongway, 2004).*

## 3.4 Conclusions arising from the case studies

From these studies, a number of conclusions (many supported from studies elswhere) about biotic and abiotic influences on our local mite diversity can be made:

1. The development of an appropriate mixed-species litter cover and its associated diverse microhabitats in revegetated sites is one of the most important outcomes for restoring litter diversity and abundance of mesofauna, and subsequently soil diversity:
   - a well-structured litter will retain moisture and maintain active decomposition activity for longer after a rain event;
   - development of diverse litter assemblages precede and 'seed' the slower development of soil microhabitats and diversity;
   - stable litter and soil accretions are important hotspots of faunal diversity, soil development, decomposition function and nutrient return.
2. Where site-use or preparation prior to revegetation is intense and disruptive to profiles, microhabitat development is slow and soils may remain depauperate for many years with characteristics of early succession, baterial dominated communities. There is evidence from agricultural systems that such communities may make the system prone to nutrient leaching and soil carbon degradation. Strategies for accelerating litter and soil development processes may be a useful for preventing this.

   These conclusions suggest that 'litter management' is a useful focus for enhancing the development of suitable microhabitats and soil profiles. While revegetation alone will ensure litter development, additional attention could be given to the quality of the litter inputs and to strategies to ensure that the litter which is produced, remains in the system undergoing restoration in ways which encourage the development of decomposition and diversity hotspots. In natural systems a mix of litter species ensures a range of C:N ratios. Mixing highly sclerophyllous tree litter of a high C:N ratio with less recalitrant low C:N shrub litter has been shown to enhance decomposition rates of the former (though termite activity is likely to remove much of the standing annual grass litter from the soil/litter profile). Also, natural systems produce a range of 'litter barriers" such as shrub bases, and woody debris. Litter collects against these barriers, and in semi-arid landscapes becomes mixed with soil, further 'fixing' the litter mounds in place for a period of time (Plate).
3. Our knowledge of the biology and ecology of mites in Western Australian soils is far too rudimentary to identify groups or species as disturbance indicators. However, the studies raise two possibilities which warrant further investigation and monitoring:
   (i) a group of orbatid mites from the Family Oppiidae are relatively species-rich in semi-arid WA soils and species may have indicator potential, and
   (ii) the presence of the disturbance coloniser *Tyrophagus* in very high densities appears to be indicative of highly-disturbed soils.

There is no doubt that the mite assemblages of the soil/litter system have the potential to reflect the diversity of the soil/litter subsystem generally, though the concept of diversity surrogates (at the species or group level) needs to be approached with much care. However, of all the soil/litter taxa, the mites are the most diverse and abundant mesofauna in semi-arid systems and are far easier to work with than the remaining soil biota, the Protista and Nematoda. On the downside, their small size, high diversity and the level of taxonomic expertise required to separate 'species' are major disadvantages to working with this group.

Two approaches can reduce the difficulty somewhat – minimising the number of samples required to survey an area, and using family, rather than species taxa for assemblage description. Firstly, sampling can be limited to likely 'diversity hotspots' such as tree or shrub bases or litter/soil accretions because less favourable areas such as intershrub or exposed surfaces tend to support subsets of hotspot assemblages. Secondly, if the focus is assessing broad changes in diversity towards a 'benchmark', such as is likely to be the case if revegetation strategies are being evaluated, then taxonomic resolution to the family level is likely to be sufficient. The chenopod study mentioned earlier is one example where the mite assemblage patterns of the variously disturbed areas are reflected equally well by family-level taxa as by species. While identification to family taxon still required considerable expertise, it is a much faster procedure, hence less costly and with a considerably faster turn-around time.

## 3.5 The Sturt Meadows project- a case study in progress

Sturt Meadows, 40 km north of Leonora is the site of a major tree planting project on severely-degraded land during 1996 – 2003 designed by a consortium of Japanese scientists (Yamada *et al.*, 2003). The Sturt Meadows Carbon Sequestration Project has left a valuable research legacy - a range of young plantantions with diverse histories of site preparation and maintenance strategies. Recently, we began the process of describing and monitoring the mite assemblages in the soil and leaf litter at one of the Sturt Meadows site, with the aim of documenting the development of the assemblages over time and identifying system function indicators (such as soil respiration, organic matter accumulation, decomposition potential) which might be correlated with the restoration of biotic diversity. The site chosen for initial study is one with a highly disturbed history which included soil blasting, and bunding earthworks prior to planting of local provinces of tree species and subsequent regular irrigation. This site provides us with an opportunity to document the early stages of litter accumulation, soil profile development, soil function and diversity return.

The identification of 'benchmark sites' –areas of relatively undisturbed woodland for comparison sampling has been an important requirement for the study. An *A. aneura* (mulga) woodland site near Mt Weld, south east of Laverton has been identified by one of us (P.C) as a 'mulga' benchmark site because of the long absence of grazing (about 40 years).

A unique component of semi-arid landscapes is the diverse cryptogamic assemblages which colonise the surfaces of undisturbed soils. In Western Australia, these organisms play significant roles in erosion prevention and are particularly vulnerable to disturbance, but have been little-studied. One of us (P.C.) is currently documenting the cryptogam assemblages at Mt Weld and at selected research sites on Sturt Meadows. These assemblages may play important roles in enhancing the diversity of the soil biota. Soil colonised by cryptogams can harbour significantly more biodiverse and dense communities of soil mites ( Shepard *et al.*, 2002) than bare soil. As part of the Sturt Meadows study, we are describing the mite communities in soil associated with cryptogamic crusts, to evaluate whether they play similar roles in enhancing soil diversity in Western Australian semi-arid landscapes.

To assess the impact of the tree plantings at Sturt Meadows on mite diversity, diversity hotspots under *A. aneura* (mulga) litter have been selected at both Mt Weld and Sturt Meadows. In this case, soil and covering litter samples are taken around the bases of randomly-selected mature (Mt Weld) or plantation (Sturt Meadows) mulga trees. This approach is being repeated for soil and litter under a second local species used in the revegetation strategies, *E. camaldulensis* (river gum). Comparisons are being made of the assemblage patterns at both species and family levels, to identify if family diversity patterns reflect those of species.

To date, soil mite communities of ungrazed mulga woodland show similar family and species diversity to the semi-arid soils of the Gascoyne Region. The heavily litter-covered soils of the semi-mature *E. camaldulensis* woodland community at the benchmark site at Doyle's Well (Sturt Meadows) have exceptionally high mite diversities for a semi-arid region, no doubt reflecting the impact of a well-developed and continuous litter layer which in turn, has resulted in the development of a well-structured organic soil.

The carbon sequestration trials at Sturt Meadows will provide a unique opportunity for correlating biodiversity characteristics with indicators of system function as they are restored to a very disturbed and degraded land system. This gives us the potential to evaluate the usefulness of biodiversity assessments as indicators of important ecosystem services such as decomposition, soil carbon sequestration and nutrient recycling – all measures of 'soil health'. It is hoped that such studies will help us to identify useful and practical soil quality indicators for land managers.

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# WASTE ROCK DUMP DECOMMISSIONING AT MINES IN NORTHERN WESTERN AUSTRALIA

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## ABSTRACT

*Mine waste rock dumps in northern Western Australia are frequently some 400 m high with bench faces of up to 60 m in height. The dumps are located in a region susceptible to tropical cyclones and regularly experience high intensity rainfall events over the wet season. The majority of the dumps are highly erodable and at the same time experience large consolidation settlements. Moreover, frequently, minerals such as pyrite, talc and chlorite present in the waste rock materials release hydroxides and inorganic salts such as Ca $SO_4$ and $MgSO_4$ which are mobilised by infiltrating water and are released as seepage at the toe of the dumps. The resulting contamination, together with large scale erosion issues, poses significant long term decommissioning challenges. A range of decommissioning alternatives that address infiltration, erosion, settlement, and storm control issues to varying degrees have been conceptualised and evaluated on the basis of practicality, effectiveness, cost and reliability. This paper describes the evaluations with an emphasis on the key issue of erosion management and control.*

## INTRODUCTION

Decommissioning of mine waste structures in northern Western Australia, a region susceptible to cyclone events, presents specific problems associated with erosion control as well as dispersion of leached salts through infiltration and seepage. Even where the waste comprises blasted waste rock the intensity of rainfall and associated runoff is sufficient to erode significant tonnages of rock from the slopes of the dump. This erosion is exacerbated if there are fines in the waste rock since the fines reduce infiltration and increase runoff. Slope erosion, and the subsequent deposition of eroded material on benched or terraced areas of waste rock dumps, results in re-profiling of the benches or terraces with time with the result that over time water ponds increasingly closer to the outer crest of the bench or terrace raising the probability of breaching crest walls. Once flow over the outer crest begins to occur slope erosion increases exponentially because the catchment area suddenly includes the bench or terrace area.

Mining economics frequently dictate that waste rock be dumped in a series of terraces so as to minimise the haul distances and gradients. More specifically, where, waste stripping is carried out at higher elevations, the tendency is for waste rock to be dumped along the natural slope in a series of benches. The benches are tied in to lower terraced areas and frequently result in effective waste rock dump heights of 400 m.

Figure 1 below indicates a typical waste rock dump in the Kimberley region of Western Australia. High elevation benches are evident together with lower elevation terraced areas.

Methods to reduce and control infiltration and leaching of acid drainage products or metals from minerals often work against measures to reduce erosion which would rather promote infiltration and reduce runoff. The issues are further complicated by the scale on which dumps from open cast mines are generated. Not only are these high and terraced, but they are also extensive in area due to the waste stripping ratios inherent to this form of mining.

*Figure 1: View of a waste rock dump in northern Western Australia*

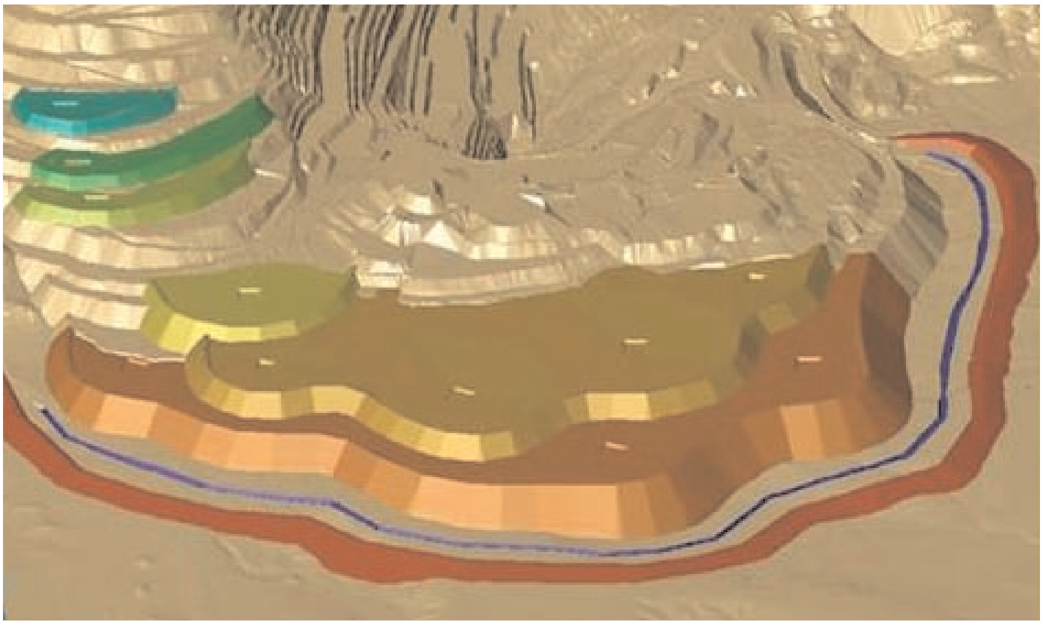

*Figure 2: View of the waste rock dump as at the end of mining*

Figure 2 shows the projected layout of the dumps indicated in Figure 1. The crest of the dump will advance some 700 m from that indicated in Figure 1.

This paper describes assessments carried out on a number of decommissioning concepts for a dump such as indicated in Figure 2. Each concept has been developed to reduce erosion and infiltration. The advantages and disadvantages are set out and a conclusions drawn as to the merits of a novel approach that would take advantage of specific waste rock types to simultaneously address both the infiltration as well the erosion issues.

## CONCEPTS EVALUATED

### Stepped profile concept

It has been well established by Willgoose and other researchers [1] and [2] that over the long term slopes erode to a concave profile where the eroded slope gradient is steeper at the upper reaches of the slope and flatter at the lower. It is therefore logical that if the slope profile is constructed as close as practical to the anticipated long term concave profile the total erosion would be minimised.

Figure 3 illustrates a stepped profile for a waste rock dump constructed on steeply sloping ground. The bench heights of the terrace are maintained constant and the terrace widths are widened in the lower parts of the slope to achieve the concave profile.

A number of drawbacks to the stepped profile concept become evident the moment the concept is considered in detail. These are:

- The profile can be costly to construct in as the bulk of the waste rock is placed in the wider terraces which are at low elevation and are also furthest from the source.
- While dozing of the slope faces between the benches would further improve the approximation to the long term eroded profile it would be costly and, seeing as nature would achieve the same end naturally, probably unnecessary. However, regulators are reluctant to allow residual slopes at natural angle of repose even on terraces and it will be necessary to doze these down to a slope of 20 to 25 degrees. Given the number and lengths of the slopes, dozing costs are likely to be high.

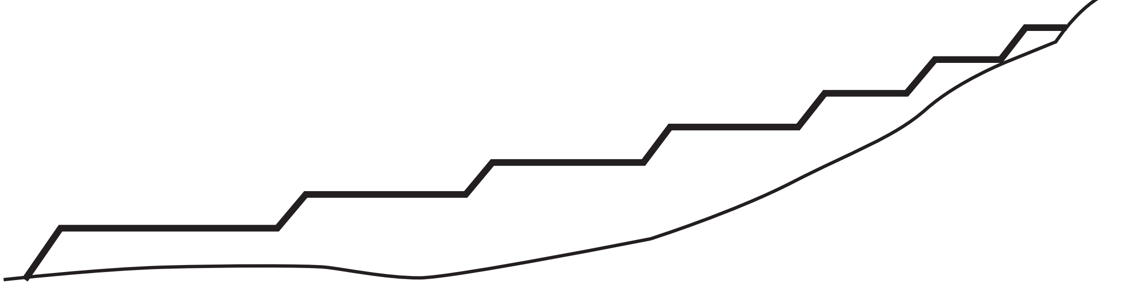

*Figure 3: Schematic of a stepped profile for a waste rock dump*

- The concept does little to reduce infiltration and therefore does not address leaching problems that may be associated with acid rock drainage products and the like.

## Surface drainage concept

Controlled discharge from the waste rock dump is a concept frequently considered. Figure 4 below illustrates a surface drainage concept in an application of a terraced waste rock dump of large area.

Notable features of the concept as illustrated are:

- Provision of discharge channels to transfer the water from one terrace level to the next as well as the provision of stilling basins with each discharge channel.
- Formation of drainage trenches on the surface to direct runoff to the discharge channels. These would be lined to reduce infiltration
- Paddocking off of the surface into controllable areas and shaping to encourage flow to controlled areas with minimal infiltration
- Provision of a toe bund to capture material eroded from the slopes.

Issues that emerge from detailed evaluation of this concept in the context of long term rainfall patterns are as follows:

- Flow rates down the drainage channels range from 10 to 15m$^3$/s and velocities are above 4m/s making it necessary to line the channels
- The channel linings need to be flexible as the rock will settle differentially after construction. This implies the use of gabion and reno mattress structures as liners and even then these are close to their limit at velocities of 4m/s.
- Differential settlements in the channels will cause localised concentration of flow and therefore localised velocities in excess of 6m/s which will considerably increase the risk of failure of the gabions and reno mattresses.
- The channels are costly to construct and costlier still to line. In the example illustrated costs were of the order of $15 million.
- Differential settlement of the terraces which may cause changes in surface drainage and thereby increase infiltration.

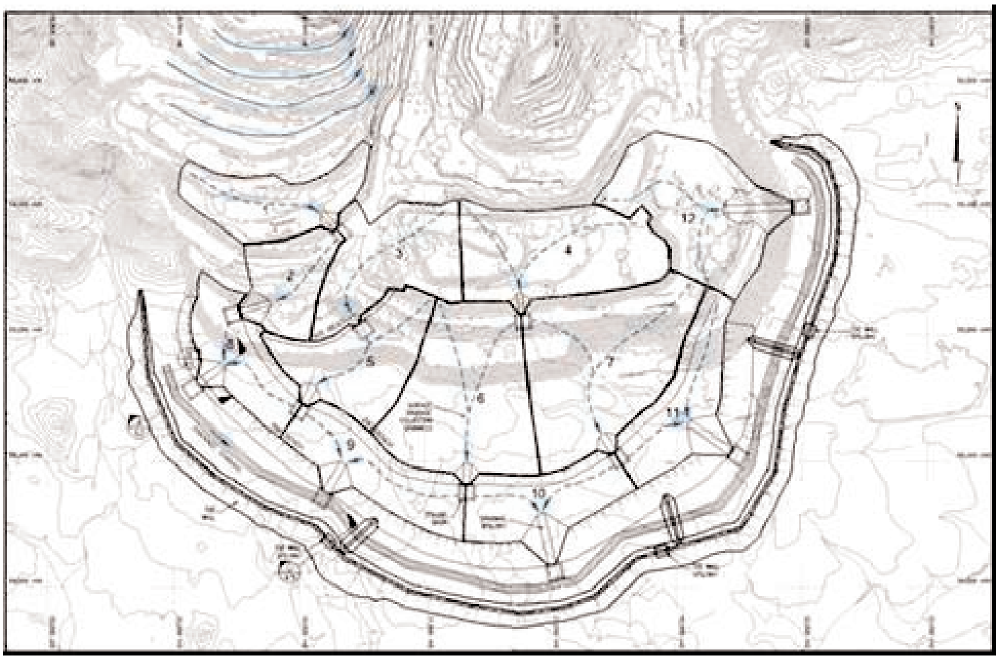


*Figure 4: Surface drainage concept applied to a waste rock dump of large area*

## Sub-surface drainage concept

A sub-surface drainage concept would make use of the fact that certain of the waste rock types on a mine may have lower fines and be inert. Typically zones of a benign hard rock such as quartzite could be interbedded with other materials and could be used to provide preferential drainage routes through the rock dump. The concept is illustrated in Figure 5.

Notable features of the concept are:

- Placement, as part of routine mining operations, of zones of quartzitic material 200 m wide and 30 m high aligned with natural drainage channels in the original topography
- The formation of sumps which connect the quartzitic zones. The sumps would capture surface runoff directed to the sumps via drainage trenches as per the surface drainage concept described above and then allow infiltration to the toe area via the quartzitic zone. This is illustrated in Figure 5 below. Drainage in the sumps would be predominantly from the side slopes as the base of the pit would be sealed by sediments drawn into the sumps. This is illustrated in Figure 6 below.

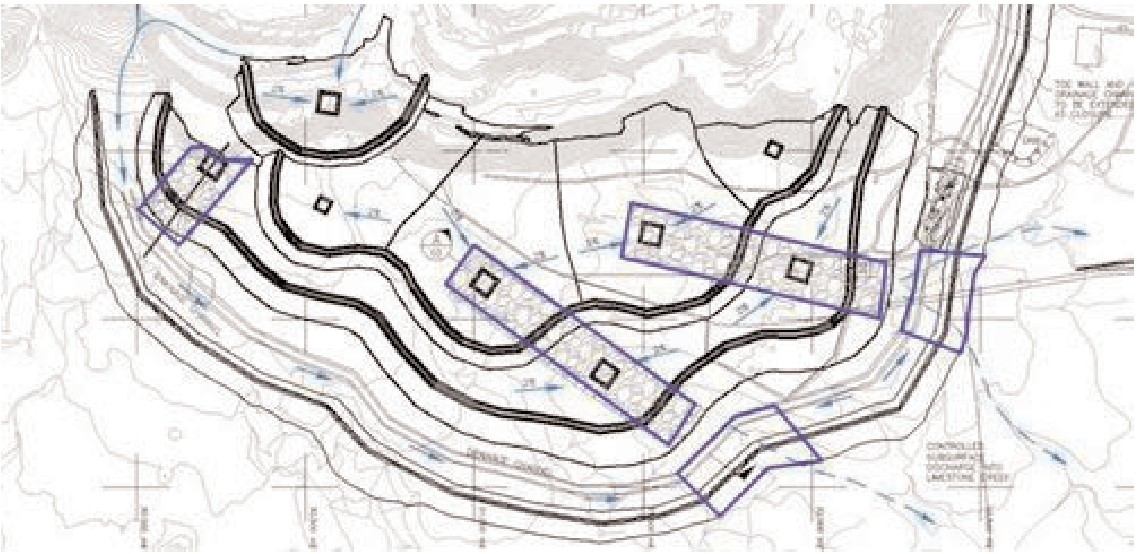

*Figure 5: Sub-surface drainage concept*

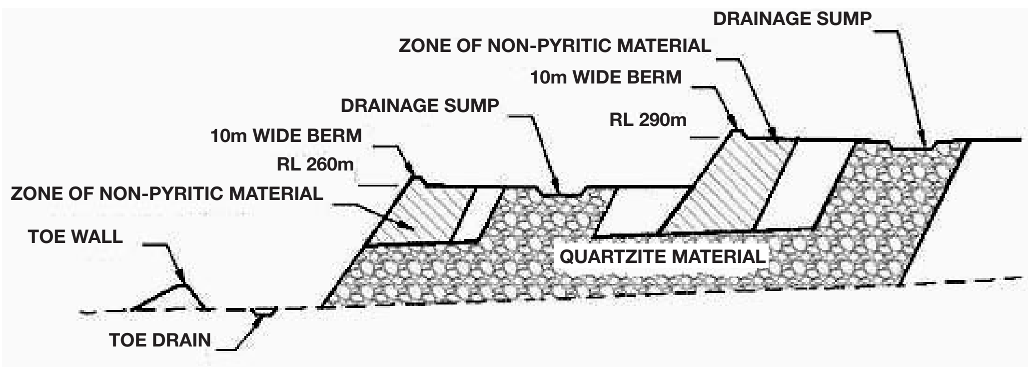


*Figure 6: Typical section through quartzitic rock preferential drainage zones*

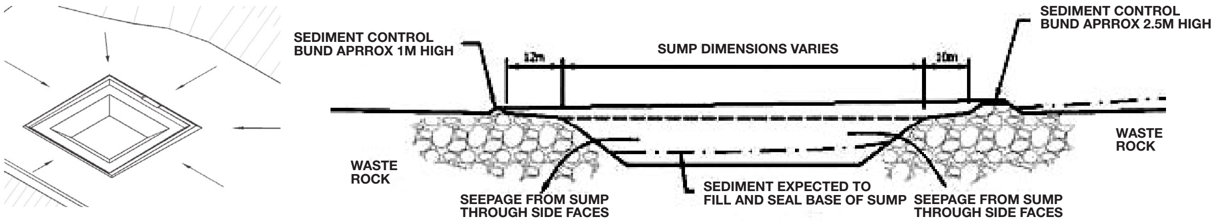


*Figure 7: Typical section through an excavated pit.*

Issues of concern relating to the above sub-surface drainage concept are :

- The reliability of the sumps in terms of long term drainage rate and rate of filling with sediments
- Blinding of the quartzitic zone by sediments drawn from the sumps
- Differential settlement of the terraces which may cause changes in surface drainage and thereby increase infiltration
- Reliability of construction given the vagaries of mining conditions and difficulty of controlling construction.

## Store and release concept

A typical store and release concept as applied to waste rock dumps would entail the following :

- Paddocking off of the dumps as in the surface and sub-surface concepts
- Placement of a 0.5m compacted clay layer or layer containing sufficient clay materials to form a plastic seal to the rock surface as well as sufficient clay to prevent migration of the clay during seepage
- Placement of a 2m zone of waste rock with fines. This zone is paddock dumped and flattened without introducing compaction. Vegetation is established in this zone (hence the reason for fines).

The store and release concept operates by trapping and storing rainfall runoff in a perched zone above the clay liner and within the loose waste rock zone during the wet season. Over the year this water is evapo-transpirated by the vegetation established in the uncompacted waste rock zone. The clay layer reduces infiltration to a minimum during the store and release cycle.

Issues of concern in regard to this concept are:

- Availability of suitable clay materials. These would need to come from disturbed areas and would have to be stockpiled until the dump is completed. Substitution of the clay materials with low permeability silty materials or even benign tailings would increase the risk of erosion of the layer into the waste rock and subsequent rat-holing.
- Differential settlements will cause cracking in the clay liner and possibly vertical displacements. These will reduce the effectiveness of the liner and concentrate flows into the rock fill.
- Double handling of the clay materials combined with strict control of clay placement and compaction will be costly. Over a 300 ha dump area the clay liner would cost of the order of $10 million.

## WHICH CONCEPT IS APPROPRIATE ?

Selection between the concepts will be dependent on specific site conditions and waste dump geometries. With the exception of the sub-surface drainage concept all of the other concepts have been applied in northern Western Australia with varying degrees of success. None of these concepts have been in place longer than 10 years.

The sub-surface drainage concept is untried but has considerable merit. Unlike the stepped profile it is able to address the issue of infiltration and has the potential to limit erosion rates to a greater extent. Unlike the surface drainage and the store and release concepts it is low cost provided the mining schedules allow placement of the preferential drainage zone as part of routine mining. There are increased costs for the mining of the drainage zone material but volumes are limited and costs relate only to the extra over haulage rate.

Since the sub-surface drainage concept has not been explored to the same extent as the other three, and it has specific merit in a number of operations, this paper goes on to describe evaluations relating to sedimentation of the sumps as well as to overall erosion performance. The hydraulic and hydrological assessments follow routine and established techniques well documented in the literature and therefore do not require in-depth exploration in this paper.

## EROSION ASSESSMENTS FOR THE SUB-SURFACE DRAINAGE CONCEPT

Since the primary issue of concern relates to sedimentation of the sumps and this sedimentation will occur as a result of erosion from terrace slopes above the sumps it was decided to carry out erosion simulations using SIBERIA as set out below.

### SIBERIA Model

SIBERIA is a long term erosion model developed by Willgoose [3] in 1989 to explore the linkages between the time evolving geomorphic form of natural landscapes and the hydrology and erosion processes occurring on them, and how these processes, in turn, determine the future evolution of the natural landform. SIBERIA works with a gridded digital terrain model which evolves in time in response to runoff and erosion derived from physically based erosion models. SIBERIA is the only commercially available erosion simulation software that is able to model gulley development as well as overall erosion rates.

SIBERIA is based on commonly accepted erosion physics specifically relationships between catchment area and runoff rate such as that typically used in regional flood frequency analysis :

$$Q = \beta_3 A^{m_3} \qquad (1)$$

where $Q$ is the characteristic discharge out of the catchment, $\beta_3$, is the runoff rate and A is the catchment area. The characteristic discharge is the mean peak discharge.

The erosion model is similar to that used in traditional agricultural sediment transport models where the rate of sediment transport is related to discharge, slope and a transport threshold :

$$Q_s = \beta_1 Q^{m_1} S^{n_1} \text{ - threshold} \qquad (2)$$

where $Q_s$ is the mean annual sedimentation rate, $\beta_1$ is the erodability (including the material erodability, vegetation cover factor and any cropping practice factors (USLE terminology)), $S$ the slope and $m_1$ and $n_1$ are parameters to be calibrated for the erosion process. The erosion is relatively insensitive to the exponent $n_1$ which is commonly taken as 2. The exponent $m_1$ is modified during calibration to ensure that the concavity of the modelled slope is similar to the prototype. Commonly $m_1$ is in the range 1 to 1.5. The threshold is a simple allowance for shear stress mobilisation of the material.

The threshold term applies to armoured slopes of clean (no fines) or bound materials which is not the case for the surface materials at Osborne and may therefore be discarded.

Equations (1) and (2) may be combined to yield equation 3 below :

$$Q_s = \beta_1 \beta_3^{m_1} A^{m_1 m_3} S^{n_1} \text{ - threshold} \qquad (3)$$

Solution of the above two equations by finite elements at each grid point is effected by Siberia to derive the eroded position of the grid point at the end of each time step. The eroded topography is therefore being continuously updated thus enabling the simulation of gulley formation.

### Model calibration

A number of methods for obtaining the erosion parameters for SIBERIA exist :

- Rainfall and runoff testing using rainfall simulators on test areas of 10 m by 2m. This testing is routinely carried out within Australia and involves the calibration of erosion rates using WEPP and translation of these erosion rates to SIBERIA by calibrating erosion over the test area. Dr Rob Loch [3] has been a leader in this form of testing.
- Controlled flow through a series of flumes constructed on the sides of dumps and tailings dams. This method does not simulate rainfall runoff but allows the impact of high flow rates on a range of armouring methods to be assessed.
- Calibration of erosion rates from digital mapping of eroded slopes.

In the assessments described below the approach of calibrating erosion rates from digital mapping has been carried out.

Figure 8 shows a slope comprising waste rock materials in northern Western Australia where, other than for reinstatement of the crest of the slope, no significant dumping has taken place over 7 years. This slope has been mapped, initially from aerial photography and later using laser mapping techniques. The slope as at 1996 has been set up as an initial surface within SIBERIA and a series of simulations over a 7 year period carried out with a range of parameters and the predicted and actual eroded surfaces compared on the basis of hypsometry and overall eroded surface. Figure 9 shows a section along the slope and indicates the initial surface (blue) the final surface (red) and the calibrated surface (green). It should be noted that a specific flood event occurred in 2001/2 that caused overtopping of the crest wall and the erosion of a number of deep gulleys. It is has not been possible to simulate these deep gulleys. SIBERIA is not suited to modelling of specific flood events. However, the calibration on the long term surface in matching overall erosion depth and gulley spacing is good.

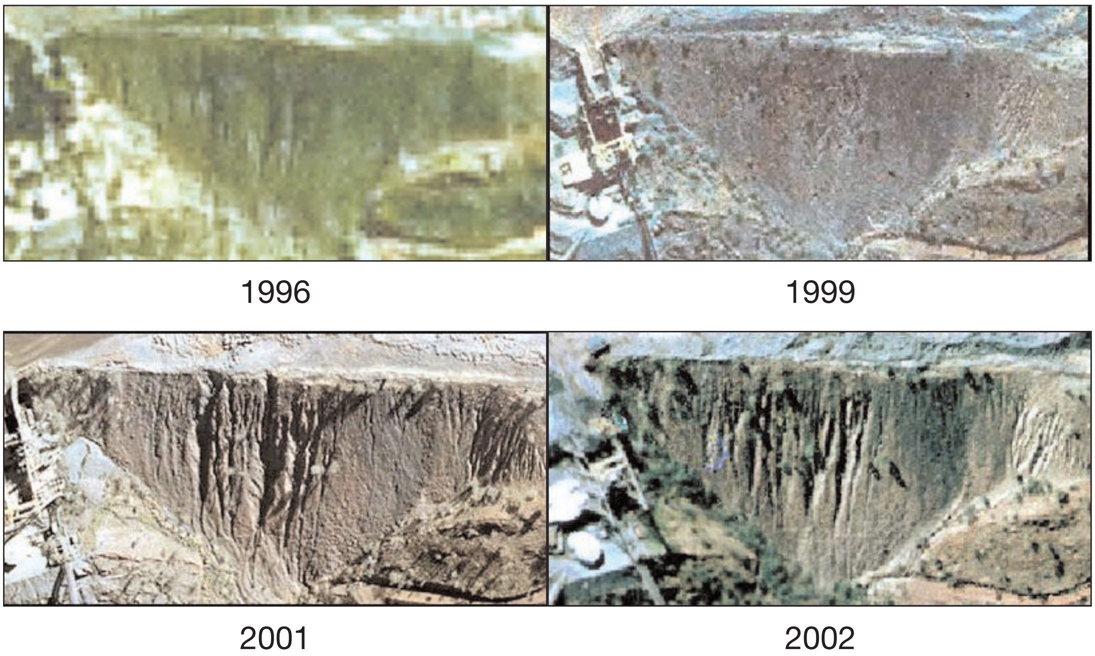


*Figure 8: Aerial photos of a slope subject to erosion over 7 years*

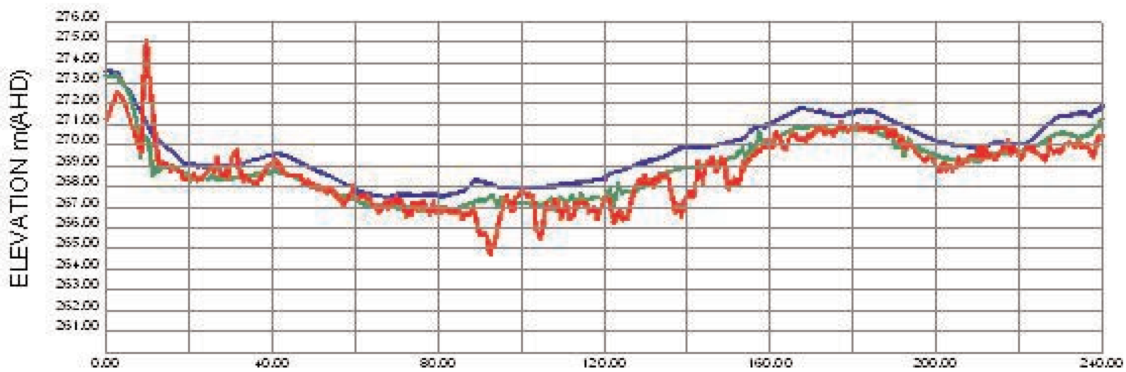


*Figure 9: Section through eroded slope showing the initial and final surveyed surfaces as well as the calibrated surface*

The parameters derived from the calibration are considered reasonable for long term simulation because it is evident from assessment of the slope area characteristics of the long term gulleys that they have eroded to depths characteristic of the natural armouring of the rock. Over the long term, therefore, while there will be continued erosion of the slope, gulley depths will remain relatively consistent for cases for cases where slopes erode due to runoff only from the slope i.e. not from an areas above the slope.

Erosion rates are significantly reduced where vegetation is established on a slope. In this respect the slope in Figure 8 provided useful calibration information as, other than for the large gulleys, the remainder of the slope has some vegetation cover.

## Overall dump erosion

Based on the above parameters, SIBERIA has been used to simulate erosion of the waste rock dump indicated in Figure 2. It was found in initial simulations based on the pit layout indicated in Figure 5 that the sumps filled with sediment within 50 years. This was clearly unacceptable so the layout in Figure 5 was modified to that indicated in the initial dump in Figure 10. Figure 11 shows the geometry of the main terrace.

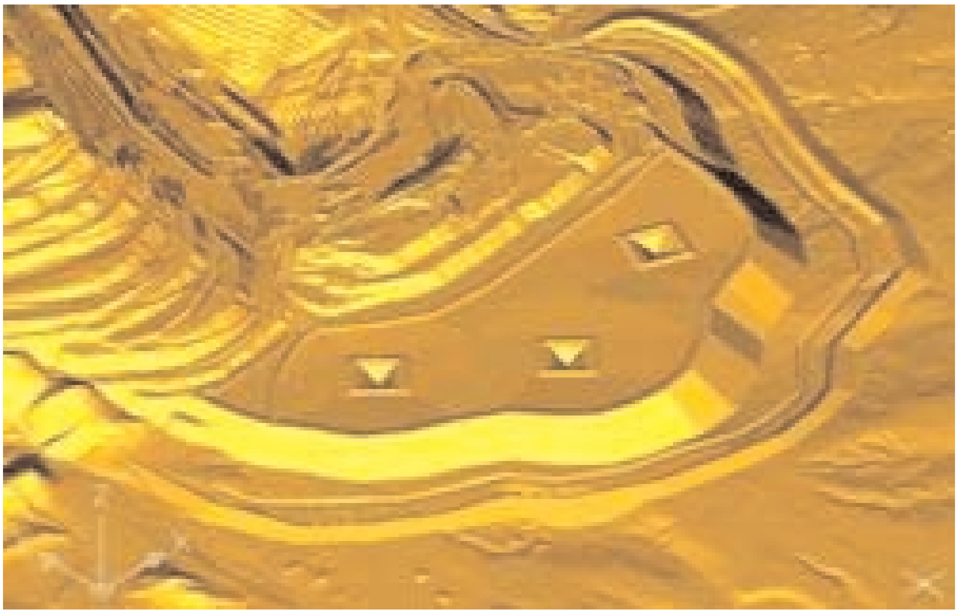

*Figure 10:* *Modified layout of sumps in sub-surface drainage concept*

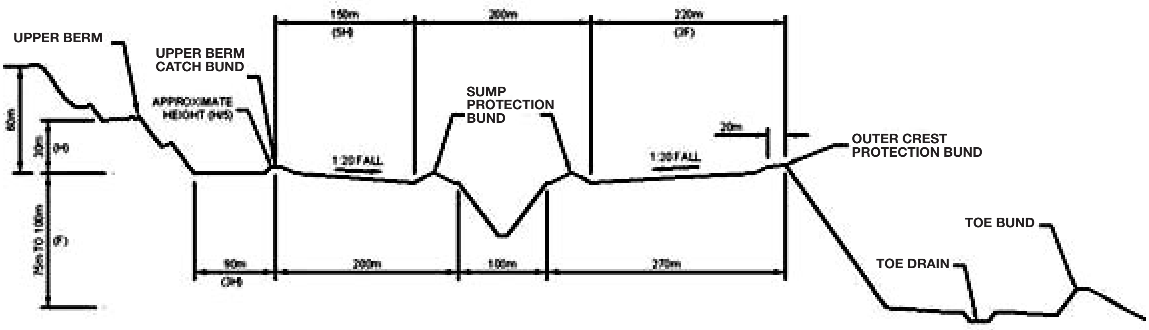


*Figure 11:* *Preferred terrace geometry from SIBERIA simulations*

Features of Figures 10 and 11 that are note worthy are :

- The application of a waste rock bund along the back of the main terrace. The purpose of this bund is to retain the majority of the sediments eroded from the slope and terrace above. Because the bund is constructed of waste rock, runoff would permeate through to the main terrace.
- The use of deeper sumps protected by waste rock bunds around the crest of each pit. Pit numbers have been reduced and the pit areas increased accordingly. The increased pit depth arises from controlled dumping of the waste rock and makes it unnecessary to do any excavation.
- The elimination of the front terrace which, it was found, overtopped within 100 years due to erosion from the slope above.

Figure 12 shows the eroded dump at 100, 300 and 500 years.

From a design perspective, two aspects are immediately apparent from the results indicated in Figure 12. These are:

- The toe confining bund can be lowered over most of its length i.e. the initial assumptions are conservative.
- The bund along the back of the main terrace should be raised. This will provide additional sediment holding capacity and protect the sumps to a greater extent.

Figure 13 shows the eroded profiles along a section through the main terrace at intervals up to 1000 years. It is interesting to note that by 1,000 years the main terrace has overtopped and the terrace as a whole begins to erode.

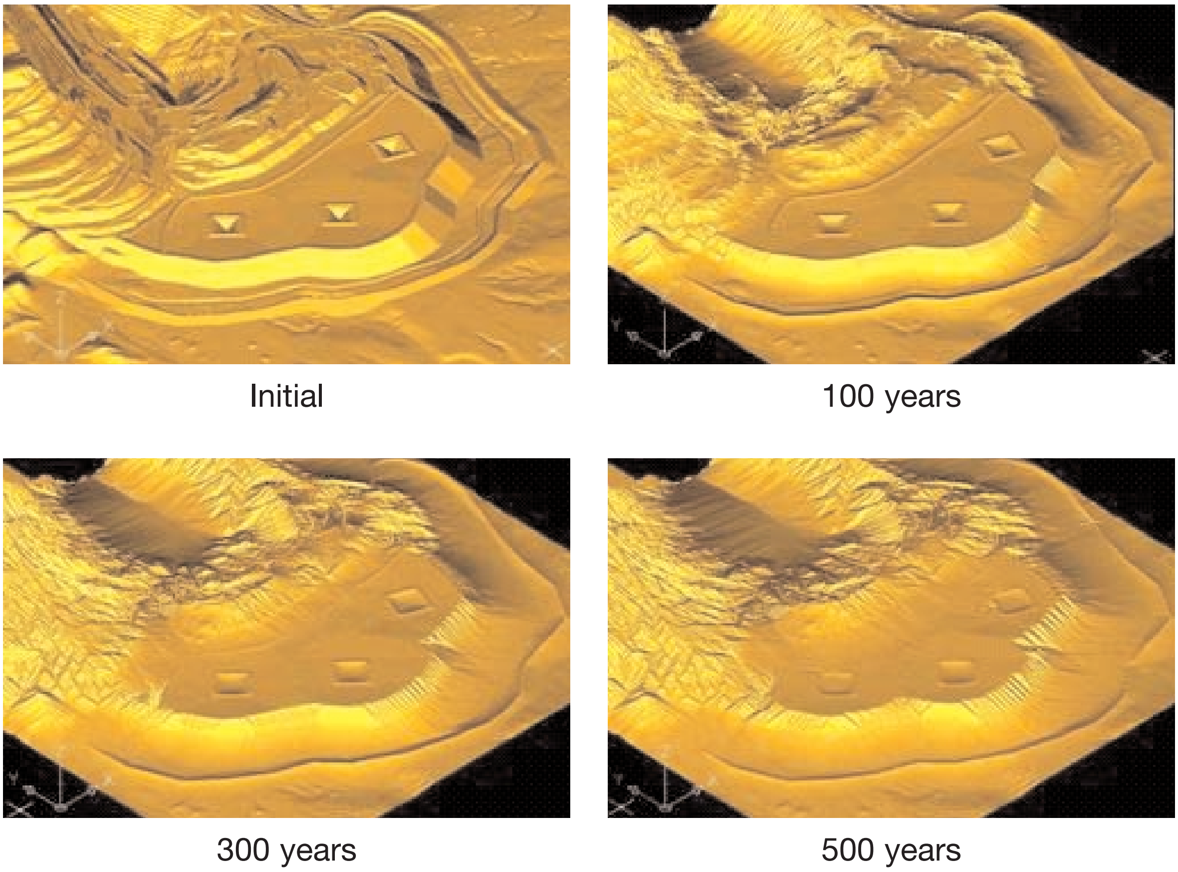


*Figure 12 : Results of SIBERIA erosion simulations*

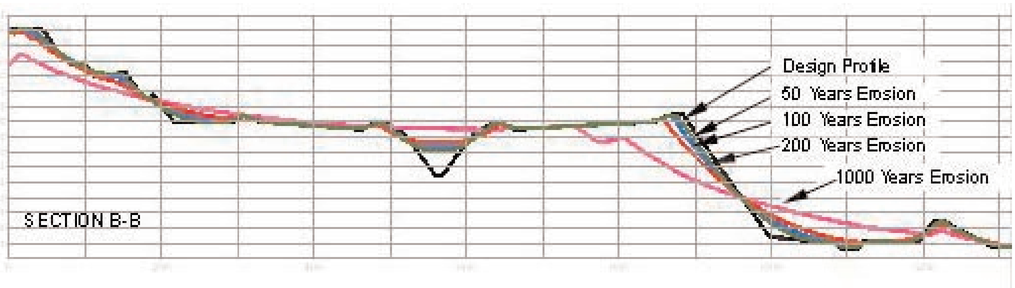


*Figure 13: Section through the main terrace showing eroded profiles*

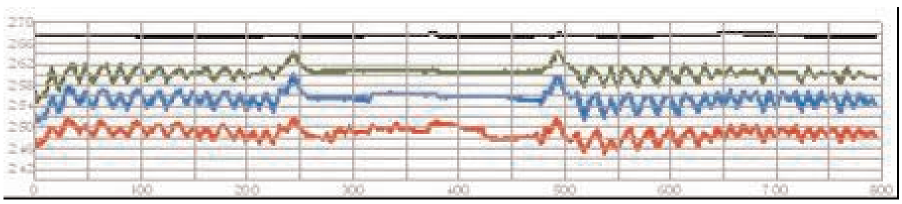

*Figure 14: Section along the slope of the main terrace showing eroded depths and gulleys*

Figure 14 shows a section along the slope of the main terrace and indicates erosion depths and gulley formation.

A key question that could be raised at this stage is that of reliability of erosion predictions. Clearly these are influenced by parameter selection and the extrapolation of the parameters derived from a 7 year calibration over 1,000 years. This is entirely valid but the fact is that there is no way of being able to improve reliability without a more extensive record. However, the value of the simulations lies primarily use in comparing design concepts. In the final analysis whether the predicted erosion profile occurs in 200 years instead of 300 years is largely immaterial provided the design is robust enough.

**Table 1: Comparison of total eroded volumes for a range of slope profiles**

| Case | Description | Eroded volume as a percentage of the volume for a natural angle of repose slope |
|---|---|---|
| Base | Erosion of natural angle of repose slope | 100% |
| 1 | Slope dozed to constant 20 degrees | 85% |
| 2 | Optimal stepped profile (based on construction constraints) | 72% |
| 3 | Theoretical profile dozed initially to 500 year natural angle of repose eroded profile | 50% |

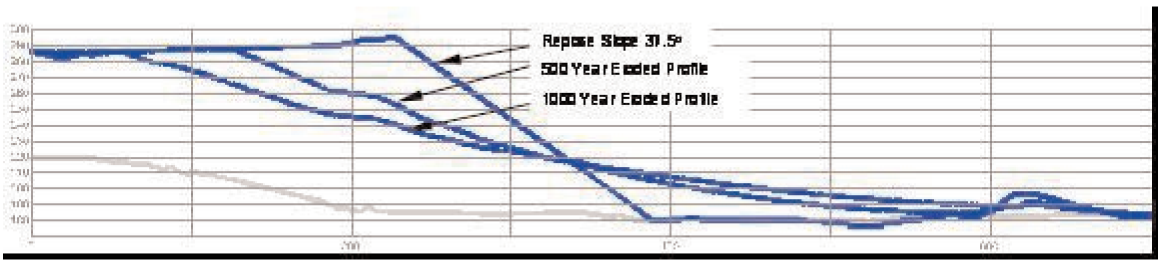


*Figure 15: Eroded profiles for slope at natural angle of repose*

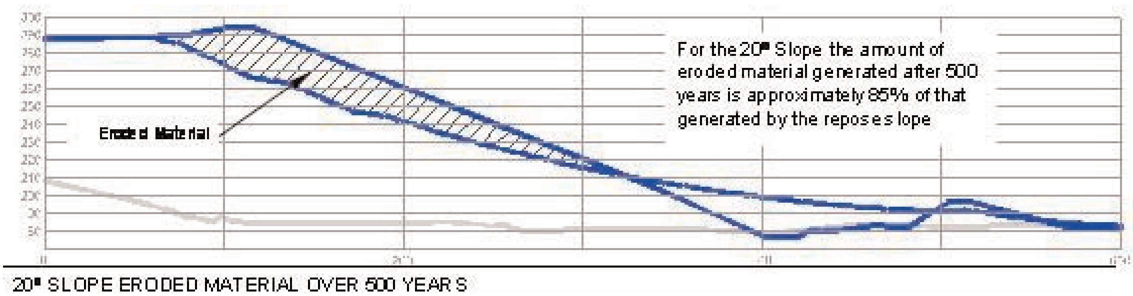


*Figure 16: Eroded profile at 500 years for slope at an initial slope of 20 degrees*

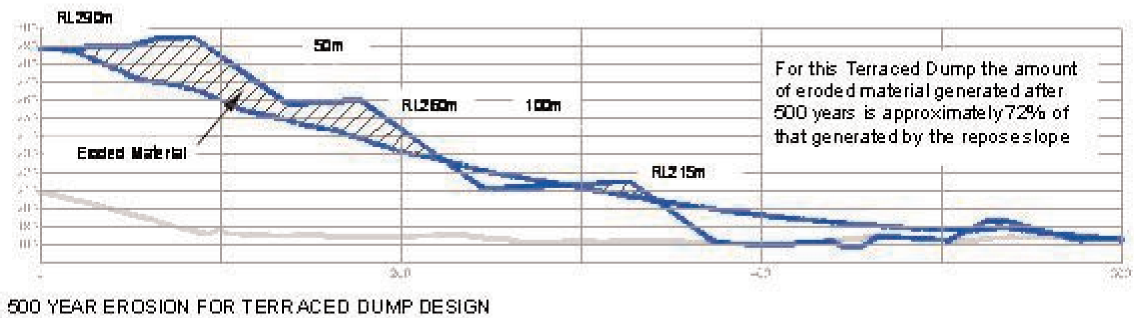


*Figure 17: Eroded profile at 500 years for a stepped profile*

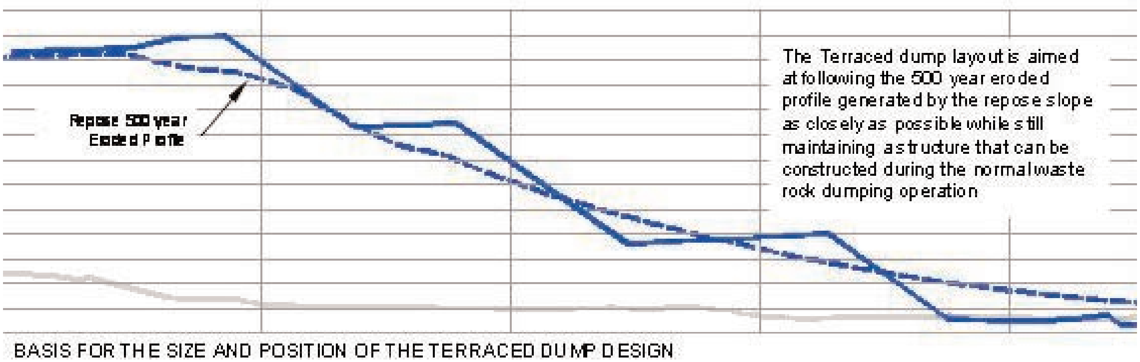


*Figure 18: Optimised stepped profile.*

## Side slopes

The erosion simulations described in the previous section were based on a single slope at natural angle of repose. The simulations indicated the extent of erosion of this slope which could be taken as the worst case or maximum erosion scenario. Figure 15 below shows the eroded profiles in the slope face at 500 and 1,000 years. Figure 16 shows the 500 year eroded profile for a 20 degree slope after simulation in SIBERIA and Figure 17 the 500 year eroded profile of a stepped slope.

Table 1 shows a comparison of the eroded volumes for a range of potential profiles

Table 1 shows that even if the slope is dozed to the projected 500 year profile for the natural angle of repose, it is unlikely that the total erosion after 500 years will be less than 50% of that for the natural angle of repose. Further optimisation of the stepped profile has shown that it could be reduced to 68% but this will require an impractical number of benches.

It should be noted that in Western Australia, the regulators take the viewpoint that no slope should be left at natural angle of repose for reasons of safety of the public who may chose to go climbing up the slopes. This is not a stability criterion but one based on issue of public liability.

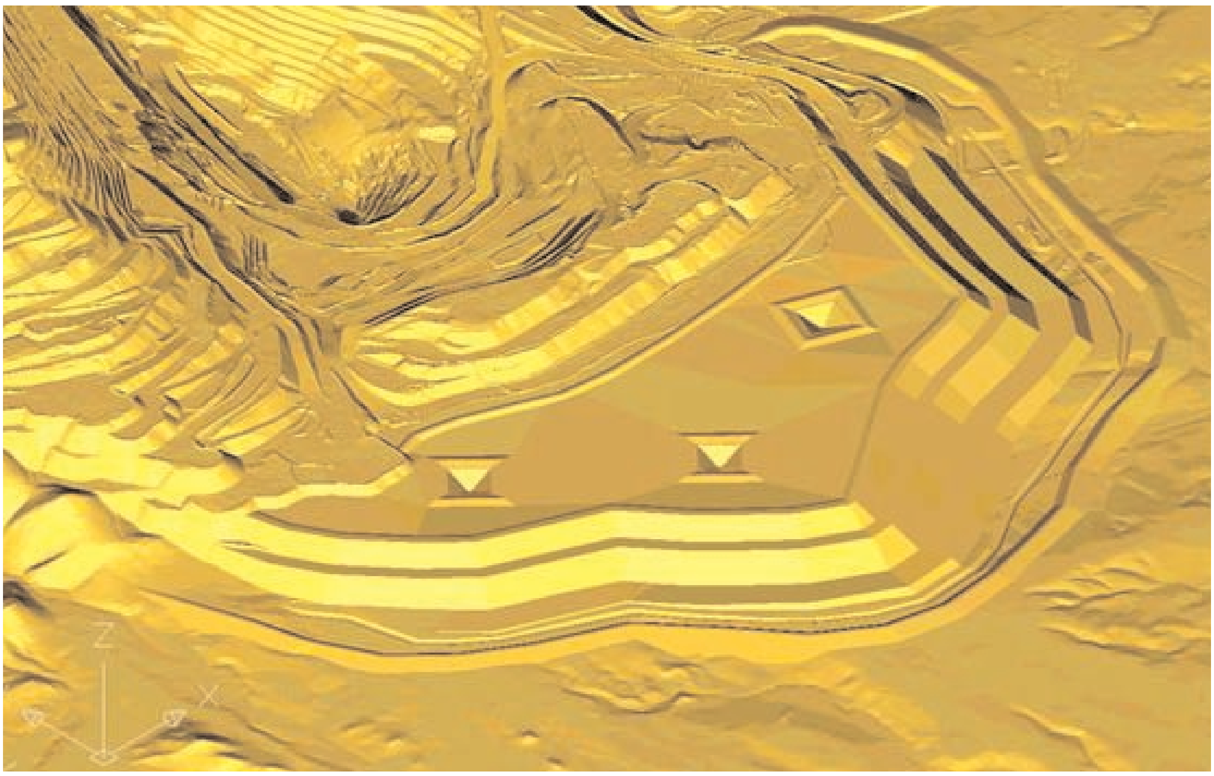

*Figure 19: Isometric showing dump with optimised stepped profile.*

To meet this stipulation it would be best to create the stepped profile and doze individual benches down such that the final dozed profile is as close to the 500 year profile as practicable.

Figure 19 shows the waste rock dump with the optimised stepped profile.

## CONCLUSIONS

The following conclusions are drawn :

- There three erosion and infiltration control concepts that are generally being applied to the decommissioning of waste rock dumps, namely the construction of a concave, stepped profile that approximates the final predicted erosion profile, surface drainage control and shedding, and store and release. None of these has an extended track record in Western Australia and each has a number of issues that require detailed consideration. Selection between these will be a function of specific site conditions.
- A fourth concept of creating drainage sumps on the top surface of the dump and providing preferential drainage zones that enable water collected in the sumps to discharge at the toe via sub-surface flow has been described. Like the other three the efficacy of this approach is dependent on specific site conditions.
- Of the concepts evaluated all but that involving the creation of a stepped profile over the full dump height consider the issue of minimisation of infiltration, an important issue where infiltrated water will become contanminated with salts generated within the dump and then released as seepage at the toe.
- A key issue to be addressed in assessing the sub-surface drainage concept relates to reliability of the sump operation and most specifically to sedimentation of the sumps. This paper has shown that there are methods to assess this using SIBERIA to simulate long term erosion.
- Like all modelling the results are only as good as the input data and for this reason a method of calibration that takes account of natural armouring as well as the effects of vegetation by using historical survey data of an established eroding slope has been demonstrated.
- Erosion modelling provides a method for optimising between and within design options.

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# "OBJECTIVE MEASURES TO ASSESS LANDFORM REHABILITATION AND RESTORATION"

*S. Rusbridge[1], D. Swain[2], H. Lacy[3], M. Ward[4] and D. Jasper[5]*

## ABSTRACT

*Placer Dome Asia Pacific (PDAP) Kalgoorlie West Operations manage over 5000 ha of area disturbed by mining. This area represents the result of numerous mergers, acquisitions and restructures in the region since the mid 1980's. Reflecting this, there is a large diversity of rehabilitation issues to be managed on the landforms making up this area. This creates a substantial challenge in the process of advancing these landforms towards bond relinquishment.*

*The paper discusses a response to these challenges that has been developed by Placer Dome Asia-Pacific and Outback Ecology. The overall aim of this approach is to develop an objective classification program for all the PDAP landforms based on monitoring data, including regional natural analogues. The programme is designed to deliver to PDAP an objective process, that clearly identifies the potential rehabilitation management pathways.*

*The programme quantifies the key aspects of the rehabilitation process, allowing PDAP to identify rehabilitation that is achieving objectives and that can be considered for a reduction in monitoring frequency, and ultimately bond return. At the same time, investigations can be developed for landforms that are performing below expectations, and strategies for remedial works developed. Examples of the systems used will be provided.*

## HISTORICAL CHALLENGES

Placer Dome Asia Pacific – Kalgoorlie West Operations (PDAP) manage a large mining and exploration land package in the Kalgoorlie region of Western Australia (approx 1.5M ha). This area has been built up as a result of numerous acquisitions and mergers by many companies since the mid-1980's. This large land package contains a significant number of historical, inactive and active mining operations. In all, there are approximately 5000ha of mining-related disturbances, comprising open pits, waste dumps, tailings facilities and associated infrastructure (roads, power/pipeline corridors, plant sites) spread over a large geographical area (up to 100km from the Paddington Mill).

Management of this area of disturbed lands is aided by a custom-designed Land Management Database and associated Mapinfo GIS layer, which enables PDAP to track and report on the status of the disturbances. The system also allows for the calculation of bonds and anticipated bond reductions based on primary rehabilitation works conducted (ie. up to early stages of rehabilitation). These reports are submitted as part of the Annual Environmental Report (AER). However, the final step of obtaining full regulatory "sign off" for rehabilitated areas, requires additional support from environmental monitoring.

Ecosystem Function Analysis (EFA) was implemented at a small number of Paddington sites in 1999, this has since been expanded, with approximately 70 individual landforms monitored in 2003 across PDAP sites. Monitoring of such a large number of sites represents a significant investment of time and money.

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PDAP was keen to develop a system that helped to objectively guide when rehabilitation had reached an appropriate stage and monitoring could be stopped or reduced, alternatively it may indicate that rehabilitation is performing below expectations and monitoring should be stopped until remedial work can be conducted.

## A FRAMEWORK FOR CLASSIFYING AND MANAGING REHABILITATION

To assist in management of its large land holding, PDAP identified the need for a clear, science-based framework for classifying rehabilitation. There are several benefits in developing such a framework. Most importantly, it could provide an objective system that the mining industry and regulators could use to negotiate bond reconciliation, and to clearly identify areas that require remedial work.

Outback Ecology was commissioned to design a user-friendly framework for classifying rehabilitation on the basis of objective data, and incorporating a strategy that would be recognised and understood by regulators. PDAP's 3-year monitoring program based on Ecosystem Function Analysis (EFA) program provided the ideal data set for developing such a system, while the bond reconciliation stages used by DoIR (Table 1) provided a framework for considering the classification outcomes.

The Rehabilitation Classification system that was developed incorporates recent and historical EFA data as a means of identifying the current 'status' of each rehabilitation area. It documents how the status of each area has changed during the life of the EFA monitoring program, and allocates each rehabilitation area into a DoIR bond reconciliation category (Table 1). The Rehabilitation Classification strategy is integral to optimising the overall investment in monitoring and management of rehabilitation, for example, consideration can be given to reducing the monitoring frequency for high-performing areas (Figure 1).

Importantly, Rehabilitation Classification assists in providing a clear end point for EFA monitoring. This avoids the frequently-reported problem of monitoring programmes having no clear purpose or outcome (eg. Watson and Novelly, 2004). Rehabilitation Classification was also tailored for PDAP to incorporate its staged approach to landform development (Figure 2).

## Principles of the Outback Ecology Rehabilitation Classification system

The system of Rehabilitation Classification uses EFA data, ecological principles and published information from rangeland monitoring, to rate ecosystem development and resilience on a waste landform. As with EFA, the important principle of relating rehabilitation indices to those of local natural analogues is maintained.

**Table 1: DoIR Bond Reconciliation Categories (adapted from DoIR, 2003)**

| Stage | Stages of Rehabilitation |
|---|---|
| 0 | No earthworks have been completed |
| 1 | Completion of primary earthworks, reshaping and primary drainage |
| 2 | Completion of finishing earthworks, topsoil spreading and deep ripping |
| 3 | Seeding and planting has occurred |
| 4 | All actions are complete and all criteria are met |

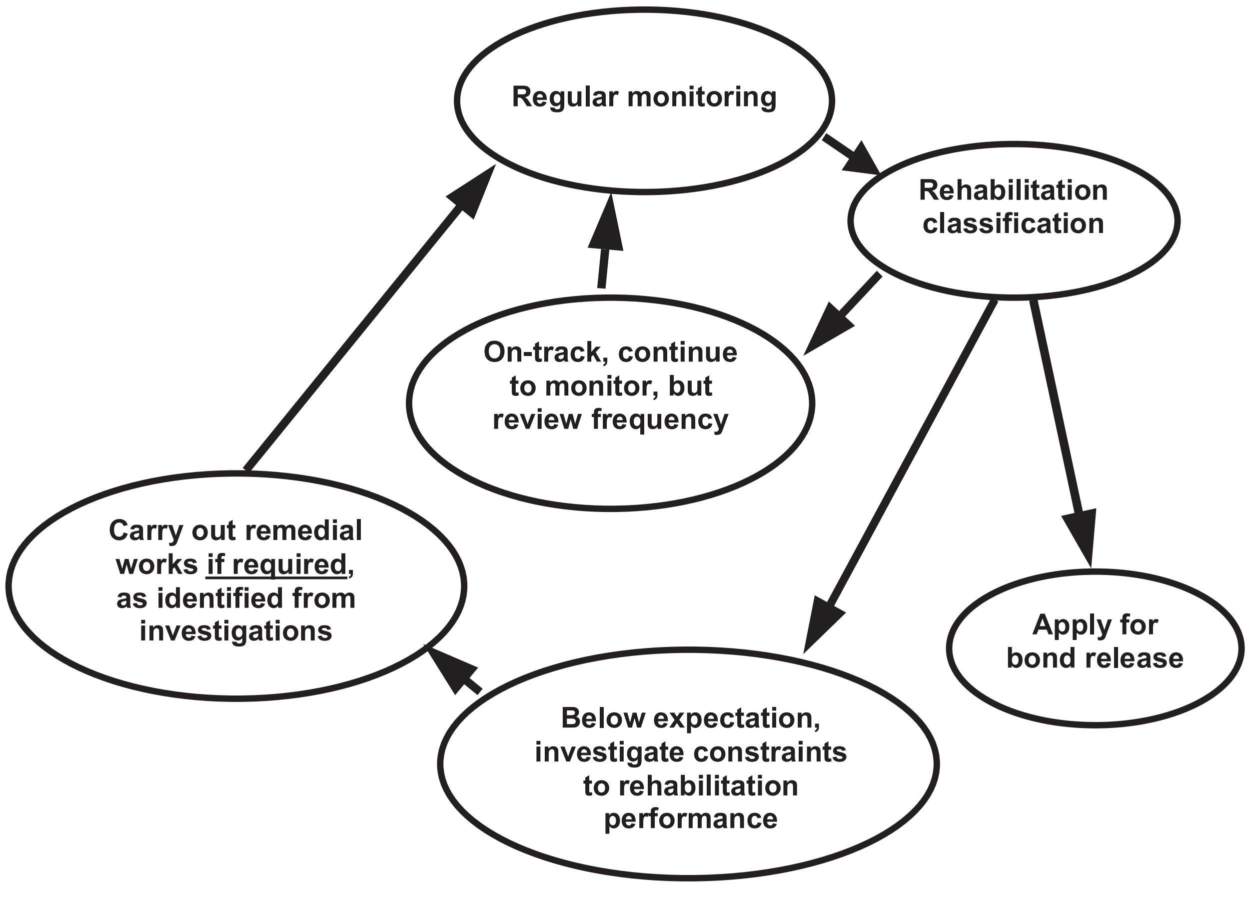


*Figure 1: A flow path for rehabilitation monitoring and classification, leading to eventual bond reduction or to site investigations and possible remediation of poor-performing areas.*

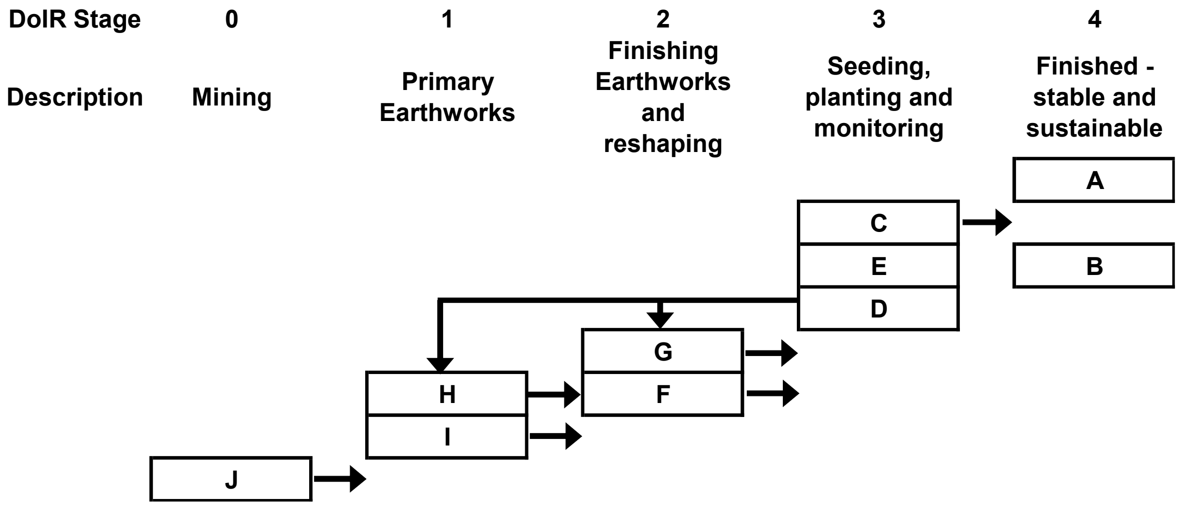


*Figure 2: A schematic illustration of the PDAP system developed to assist in managing rehabilitated landforms.*

The objective is not to attempt to 'match' the surrounding ecosystem in specific terms, rather, it was to determine whether rehabilitation areas were, or were not, attaining similar levels of functionality and productivity as the range of values for the local analogues. Importantly, the analogues also help to demonstrate seasonal effects that impact on the entire landscape (eg. drought, or above-average rainfall).

Initially, all EFA indices were scrutinised to determine the most suitable and most important for inclusion in the classification system. This led to the selection of the EFA indices of soil stability, infiltration, and nutrient cycling, together with measured values for erosion, plant cover, plant density and plant diversity, as the basis for classification. In particular,erosion, soil stability and plant cover were considered to be vital attributes for rehabilitation success and eventual sign-off.

For all of the identified parameters, ranges of above-average, average and below-average values were allocated. These ranges were defined by considering rehabilitation data from several mine sites in the Kalgoorlie region. Published data (eg. McDonald *et al.*, 1990; Pringle *et al.*; 1994; Scanlan *et al.*, 1996) was used to validate the allocated data ranges.

A challenge in interpreting any set of monitoring data is to weigh up the implication of each of the parameters measured and its relative importance for rehabilitation development and resilience. To assist with this process of integrating data, a scoring system was developed so that no weighting or bias was given to any of the seven indices.

An Excel workbook was created to house annual data inputs on separate worksheets. Each worksheet accepts the EFA indices and details of the rehabilitation area for each year of monitoring.

From this, each rehabilitation area is scored for each year, and changes in scores are documented over successive years of monitoring.

The Outback Ecology EFA data set includes analogue sites across a wide area of Western Australian mining regions. These sites have been grouped for Rehabilitation Classification, to allow for local comparisons with rehabilitated areas. While there may be relatively little overall difference in the underlying biogeographic characteristics between some of these analogue groups (Environment Australia, 2004), localised variations in rainfall were considered to be an important factor that prevented comparison across a complete biogeographic zone.

## REHABILITATION CLASSIFICATION OUTCOMES

We consider that, at least three years of EFA data should be a pre-requisite for Rehabilitation Classification. It is not feasible to assess rehabilitation status or stability, with bond reconciliation in mind, with less monitoring data. For areas with less than three years of EFA monitoring data, Rehabilitation Classification can still be used, but will only provide a snapshot of rehabilitation performance.

Once an area of rehabilitation has been classified, a recommendation report is prepared. The report summarises the classification outcomes, and recommends the allocation of rehabilitation areas to one of the four DoIR stages and related PDAP categories (in parentheses below):

1. Stage 3 (D): Below expectation, investigation recommended
2. Stage 3 (E): Below expectation, continue monitoring
3. Stage 3 (C): On track, continue monitoring
4. Stage 4 (B): On track, reduce or discontinue monitoring

The classification of rehabilitation areas into these categories provides the operator with a clear summary of areas that are performing well, those that are 'on track' but require further monitoring, and those that are performing below expectation. Rehabilitation areas are allocated to the latter category, if any of the three key indicators (stability, erosion, plant cover) returns unacceptable values. The level and the nature of investigation that may be recommended for rehabilitation areas that fall into Stage 3 (D) will depend on the particular aspect that was highlighted as critically low. Typically it may involve an initial walk-over survey to assess the problem. This may need to be followed with targeted actions such as improved water control, or investigations of soil constraints. Walk-over surveys with the operator are an important extension of the Rehabilitation Classification process, assisting in decisions on areas where investigation is required, where monitoring may be reduced, or where bond reduction may be sought.

Once the classifications have been justified and agreed, the overall site monitoring program for that year can be reviewed, and identified transects may be excluded for that year of monitoring as appropriate. When areas recommended for bond reduction are identified, the Rehabilitation Classification sheet and recommendation may be presented to regulators as part of the information suite, to assist with negotiations for bond reconciliation.

The Rehabilitation Classification system has been used on the Menzies landforms with success. The system is currently being implemented at the remaining PDAP Kalgoorlie operations as a tool for re-defining the EFA monitoring program for 2004.

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# LANDFORMS CONTAINING DISPERSIVE SOILS: ACTIONS TO UNDERSTAND, ACTIONS TO MANAGE AND MITIGATE AT PLACER'S KUNDANA PROJECT

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## ABSTRACT

*Mining of auriferous paleo-channel material includes mine waste that is sodic, saline, potentially dispersive and consequently problematic. The Kundana operation has faced considerable challenges with a series of historic landforms becoming unstable over time and thus failing to meet Regulatory and PDAP corporate requirements. In addition, the site's current operations were faced with similar rehabilitation challenges.*

*Due to new gold discoveries and the development of a number of open cut operations, the "here and now" challenges of finding control measures for the dispersive soils being mined was presented. The transfer and acceptance of those ideas by the mining group was critical, and was embraced by the Kundana team.*

*The paper describes the approaches to tackling the challenges over the past five years at the operation and discusses and presents the various strategies implemented to facilitate landform construction and rehabilitation processes that meet both Regulatory and PDAP corporate objectives and requirements.*

## KUNDANA MINESITE -BACKGROUND

The Kundana operation is located 24 km west north west of the city of Kalgoorlie. The minesite is situated in an historic gold mining area discovered at the end of the 19th century. The Kundana mine commenced operations in 1988, with two open pits and a gold treatment plant with a process capacity of 750,000 tonne per annum. Underground mining commenced in 1994 and is ongoing, while the mill is no longer operational and ore is being transported to the Paddington operations for processing.

Prior to 1988, mining in the district was generally of a small scale with some prospector activity extending throughout the area. Mining activity since 1988 to the present day has included the completion of eight pits, and two underground operations. Due to the optimisation of mineral processing in the Kal west region and depleted underground resources, the Kundana treatment plant was closed in March 2004. The Barkers underground operation is scheduled to close in the 3rd quarter 2004. The Kundana complex today comprises administration offices, workshops and a mines rescue centre.

The Kundana region remains highly prospective, and further open pit and underground operations are proposed to commence in the Kundana region over the next 2-3 years.

The climate is classically semi -arid desert with mean daily maximum temperature for summer months (December to February) of 33 ˚C, with the mean daily minimum for winter (June to August) being 6.5˚C. The mean annual daily maximum temperature is 25.1˚C. Rainfall is generally well distributed throughout the year.

The region receives an annual rainfall of approximately 267mm, having an annual evaporation rate of approximately 2,664mm. The highest monthly rainfall is generally in June and the lowest recorded in December. The regions highest monthly rainfall recorded is 308 mm, with the highest daily rainfall recorded being 178 mm.

The mine is situated within the "Yilgarn Block", consisting of Archaean rocks of age ranging from 2,400 to 3,000 million years underlies the area, and consists of recurring often mineralised greenstone belts with sedimentary rocks between them. The region generally consists of gently undulating terrain interspersed with some small hills, and a major system of salt and playa lakes, the largest being White Flag Lake. Ridges formed by banded ironstone are found throughout. Clays and sands dominate the soils in the broad valley systems, and these oxidized saline layers commonly overlay the ore bodies.

## ACTION TO UNDERSTAND AND MANAGE KUNDANA MINE WASTE.

The Kundana Gold group was faced with the challenge of repairing three historic landforms that failed to meet both internal & regulatory closure requirements. Constructed some 10 years previous, all three landforms were based on regulatory guidelines. At the same time it was necessary to develop waste dump design and rehabilitation strategies for an additional three pits, with these Projects identified as having both dispersive and saline waste material. Notice of Intent documents continued to describe landform construction commitments that were guideline driven, even though the older landforms were clearly problematic.

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The Kundana team decided to implement a number of progressive rehabilitation strategies based on a need to take action to address the key closure criteria of stability with reference to landforms constructed from paleochannel wastes.

1. Understand the state of the older landforms by using Ecosystem Function Analysis.
2. Commence trials on the Moonbeam landform to identify the most appropriate method for stabilising existing and proposed paleochannel waste material using rock mulch / rock armouring techniques.
3. Trial the use of a large amount of wood mulch cleared and directly placed on the outer surface of the Moonbeam landform, as a final layer.
4. Instigate a reduction in berm size and a narrow forward sloping berm (rather than back sloping) with a 0.5 - 0.7 meter layer of waste rock sheeting the entire structure followed by shallow topsoil placement and then ripped into the rock, followed by seeding.

These strategies were based on investigation and review of current research in erosion control techniques, the cause of erosion processes in existing waste dumps at the operation, and the inability of engineered drainage structures to adequately control runoff on highly erodible material over an extended period (>5 years). Industry benchmarking was also conducted. As these strategies varied in some aspects from the original Notice of Intent design criteria, approval was obtained to implement these rehabilitation strategies.

It should be noted that a key to these new strategies was the recognition that there will always be some degree of erosion occurring, no matter what strategy is implemented. The aim is to minimise this degree.

## EFA studies - Strzelecki Pit Waste Landform

In 2001, an attempt to determine the status of these landforms in regard to stability and ecosystem development was undertaken using Ecosystem Function Analysis (EFA).

The Strzelecki pit waste landform has a overall footprint of 14.20 ha and an overall height of 23m. The batters of this landform were contoured to 20° with berms at 7 and 17 metres above the original land surface. By late 1992, the base of the landform had been topsoiled and ripped along the contour. The remainder of the site was topsoiled in early 1993 prior to winter rains. Topsoil placement was generally deeper than the original soil profile, in some areas in excess of 300mm. It appears that, as was standard for the time, the site was not seeded or fertilized. As was the standard practice for the time, the majority of hard rock material was placed in the centre of the landform with oxide material being placed on the outer surfaces as a means of assisting with vegetation establishment.

Assessment of transects within this rehabilitation indicated rilling to be prevalent with an average erosion level of 25% (proportion of bank eroded). In some areas the proportion of bank eroded was considerably greater than average, as evidenced by deep gullies as a result of tunnel formation. Short-lived perennial species and grasses, with an average plant cover of approximately 35% dominated the vegetation, with this figure considered low for rehabilitation of this age (8 – 9 years at the time of assessment). A comparison of the Ecosystem Function Analysis indices for this rehabilitation with those of analogue sites indicated the stability index for the rehabilitation to be lower as a result of the dispersive nature of the soil. Cryptogams were absent from the soil surface and rock coverage was minimal. However, due to the level of plant litter (predominantly from annual species) across the landform, the infiltration and nutrient cycling indices were high.

## EFA studies- South Pit Waste Landform

The South pit Waste landform is 45.86 ha in footprint area with a height of 30m. Batters were angled to 20° and inverted berms placed at height intervals of 10m. Main waste rock mineralogy types included pyrite/pyrorrhite/carbon (graphite and carbonate). Surface material consisted of competent rock on top and sandy clay on sides. Topsoil was replaced and the waste landform was contour ripped. The western face of the South waste landform was rehabilitated in 1989 – 1990 and the northern face in 1990 – 1991. A review of historic site records indicates that it is unlikely these areas were seeded, only topsoiled and ripped.

At the 2001 assessment, the average level of erosion across the landform (both ages of rehabilitation) was high at 32% (as evident in Plate 2) with the bank/trough system having eroded to either a series of slopes and flats or a single slope. Within the 1990 - 1991 rehabilitation a gully 2.3m in width and almost a metre in depth was encountered. The dispersive nature of the soil, a low level of rock cover and the subsequent high level of erosion resulted in a stability index that was low for rehabilitation of this age. Vegetation cover varied across the landform with the 1990 – 91 rehabilitation reporting the higher level (approximately 65%).

The unstable surface soils were indicating a high erosion rate and a low EFA Stability index (in comparison to Analogue sites) and despite good vegetation density and cover on the rehabilitation. The development of substantial vegetation registered adequate to high Nutrient and Infiltration indexes, however the system was failing from within - with the more viable topsoils clearly being stripped away from beneath the cover, revealing an even less viable and erosive subsurface soil. The indications were that despite favourable indices these waste dumps were failing due to the inadequacies in recognising and addressing basic stability requirements.

## RESPONSES TO THE CHALLENGES POSED BY THE DISPERSIVE WASTES

### Moonbeam Landform

Due to the dispersive nature of waste overburden encountered at the Kundana operation, two independent rehabilitation research projects were implemented at the Moonbeam pit landform. This involved the use of both rock and vegetation as a means of improving long term stability.

**Original** design criteria for the Moonbeam waste dump required:

| | |
|---|---|
| Maximum Face height | 10 metres |
| Berm Width | 5 metres |
| Maximum Face Slope Angle | 18 degrees |
| Drainage Rock lined drains & sediment traps | |

**Changes** to the original design criteria have primarily involved changing the width, with an undulating saddle now replacing the standard 4-5m back sloping berm. Literature provided by Rob Loch (Landloch Pty Ltd) argues that where dispersive or highly erodible materials are located, berm widths should be kept to a minimum so to minimise the potential for ponding and tunnel erosion developing, with a berm width of 1m considered effective in slowing up gradient flows.

Through the use of rock or vegetative material, the need for drainage lines and/or rock drains on the dumps berms and batters has been negated. The top of the dump has been designed to avoid over topping, with excess water the original dump ramp, which was rock lined and acts as the main drainage channel. To minimise the potential for down slope erosion on the dump berms and batters, contour ripping has been undertaken.

### Rock Mulch and Ripping Trial

The purpose of this research was to determine a cost effective rock/soil capping regime for waste materials that are dispersive and erodible in nature. The trial was constructed on the Moonbeam waste landform in June 2001 and seeded in February 2002. The variables considered in the trial were depth of rock armour, diameter of waste, and depth of ripping. 27 treatments were established as a result. The remainder of the Moonbeam waste landform was capped with soil and vegetation mulch obtained primarily from the footprint of the Raleigh stage 2 waste landform in June 2002 and ripped to a depth of approximately 0.3m. A transect was placed on this slope for comparison with the 27 trial treatments, and, as such, is considered to be the 28th treatment of the trial.

In 2003, additional vegetation material was placed on the dumps eastern batters and cap, with seeding of the cap then occurring using a highly salt tolerant seeding mix.

In order to ascertain the most effective depth of rock armouring in regard to erosion prevention and cost effectiveness, four depths were trialed (0.3m, 0.5m, 0.7m and 1m in addition to the control sites). It was decided that rock armouring would not exceed a depth of one metre due to the cost involved and supply restrictions. Underground waste rock (which is generally less than 200 mm and more consistent in diameter) and pit waste (which has a greater proportion of larger fraction >200mm, however is more variable in size distribution) were used as capping treatments to determine the capacity of different rock mulch types to reduce slope erosion. A deep (0.7m) and shallow (0.3m) ripping depth were trialed in comparison to unripped control sites. The northern half of the landform (Treatment 28) containing woodmulch on topsoil was ripped with a single tine. All treatments were spread with topsoil to a depth of 150 mm and seeded with a local native seed mix in February 2002. Topsoil is sampled and analysed for pH and EC to determine any evidence of capillary rise. Transects on each of the treatments are assessed on an annual basis using Ecosystem Function Analysis which included both soil and vegetation assessments.

Initial results indicate that treatments containing rock mulch that have been ripped display the least amount of erosion. The wood mulch treatment currently exhibits the highest EFA indices (stability, infiltration and nutrient cycling). Further monitoring will allow initial differences between rock mulch sources to be further defined, and as result, it is hoped clear recommendations for broad scale rehabilitation strategies will be able to be made.

### Vegetation Mulch Trial

Grubbed vegetative material (basically of large (4-5m) eucalypts and other understorey shrubs) was spread over the upper-surfaces and embankments of the landform, with the berm being left as a subsurface feature but not as a back sloping/ water management structure. The action of the spreading and then contour ripping of the material crushed and integrated the mulch into the topsoil. The area was not seeded, and is monitored using EFA.

Initially a dozer was used to push the material but this required a highly skilled operator. A more safer, quicker and efficient method was utilised later using a small (ex1100) excavator. Picking up the vegetative material as undertaken using 2 loaders.

### South and Strzelecki Waste Landforms competent rock capping

Rehabilitation earthworks to rework both the South and Strzelecki pit waste landforms commenced in January 2003, and the landforms were seeded later that year. As mentioned previously, dispersive and highly erodible materials were located within and on the outer surface of these structures.

The earthworks programme involved:

- Reduction of the number of lifts on the dump
- Recontouring of batters (max dump angle of 16 degrees), after removal of growth material and vegetation;
- Ripping of all faces prior to rock armouring to provide for something for the rock to “bite” into and reduce the potential for water to flow between the clay and rock layers.
- Placement of rock material to a min 0.5 m depth (considered an appropriate depth that was cost effective but could still provide dump stability) on all faces, including berms;
- Recontouring of dump tops for initial containment of water. In the event of excessive flooding, water to be directed to drains (old ramps) and shed off dump;
- Placement of topsoil (max 150mm), ripping to integrate the materials and seeding, but leaving approximately 300mm of undisturbed rock.

The program was extensive and involved using rock material from the Srzelecki pit cutback and stockpiles from the South pit underground operation. The dumps footprint was approximately 60 ha, with the total cost of this operation being in the order of $ 900,000.

### Raleigh - rock armoured and designed for containment of dispersive materials

The Raleigh deposit was a particularly challenging operation as it involved the mining of transported material from 15m thick in the north, comprising surface alluvium over playa-like clays, to 35m deep in the south of the pit, with surface alluvium over playa-like clays over a paleochannel with clay, running sand and a gravel base. Saprolite is also present and varies in thickness from 5m to 25m over the gabbro in the east, to 50m over the sediment.

Rehabilitation earthworks on the Raleigh waste dump commenced with the lifts rock armoured to a min. depth of 0.5m, with the lower lift slope angle being maintained at a max of 18˚. By moving the “tip to” peg to provide for a final saddle width of between 1 and 2 metres, the upper lifts subsequently had slope angles significantly <18˚. Again, berms were only utilised to assist with the earthwork operations, with the final saddle formed to assist in of minimising the potential for erosion due to down slope water flows.

Decisions on the final land form design for the Moonbeam, Strzelecki, South and Raleigh waste dumps were been undertaken utilising the following information sources:

- On site experience;
- Available industry literature and research findings
- An assessment of similar design features, such as the rock armouring and concave slopes being implemented at Gold Fields St Ives Gold operation
- Available independent knowledge bases (Landloch Pty Ltd and Outback Ecology);
- The mine continues to actively monitoring all the site projects

## CONCLUSION

The managers of the Placer Kundana Gold project were of the opinion that through the implementation of innovative design measures such as rock armouring, vegetation mulching, the minimisation of berm widths, the flattening of slope angles and as promoted with the St Ives concave profile, these measures provide an exciting alternative to the more traditional designs. The operation hope to assist in moving the industry forward so that effective pre-planning and solutions are available for the management of dispersive and problematic waste materials.

# TUNNEL EROSION IN WASTE ROCK DUMPS

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## ABSTRACT

*Open-cut mining activities typically excavate large quantities of overburden, or spoil. This spoil is generally disposed of in above-ground waste rock dumps, commonly 10-40 m high with outer batter slopes at gradients of 25-40%.*

*A general requirement of mine site closure is that such waste rock dumps should be rehabilitated to create stable, sustainable landforms. There are, however, many factors that affect the success or failure of waste rock dump rehabilitation. Dump "failure" (where major erosion has occurred at points on the landform) is often associated with the occurrence of unstable, dispersive materials. The presence of these materials in waste rock dumps commonly results in the development of tunnel erosion. This can subsequently lead to: failure of berms at points where tunnels develop; creation of unsafe landforms with widespread tunnels present below the soil surface; development of large gullies once tunnels collapse; and instability of rock drains overlying dispersive materials.*

*This paper reports on current research directed at characterising the risk of tunnelling failure on the basis of soil physical properties and the potential increase of this risk associated with changes in those physical properties over time. A methodology designed to establish if a given spoil should be considered potentially tunnel forming has been developed and is outlined. The factors leading to initiation of tunnelling and subsequent failure on waste rock dumps are also discussed. In addition, waste rock dump design and management practices are reviewed and recommendations made on the usefulness of alternative strategies for prevention and control of tunnel erosion of dispersive spoils.*

## INTRODUCTION

Open-cut mining activities typically excavate large quantities of overburden or spoil to gain access to the mineral that is sought. Overburden is usually placed in above-ground waste rock dumps, which are commonly 10-40 m high, and may have outer batter slopes at gradients of 25-40%. This paper reports on current research directed at characterising the risk of tunnelling failure on the basis of soil physical properties and dump design.

In general, the development of tunnel erosion is associated with the presence of dispersive materials. These materials are typically sodic (containing relatively high quantities of exchangeable sodium) causing them to break down when wet and release clay particles into solution – the process of dispersion. Another form of tunnelling is through soil particle liquefaction and is normally associated with materials dominated by the silt and fine sand components (typically >70%). In such materials inter-particle bonds are so weak that they are readily destroyed by flowing water when the material is wet. Moving water increases the area of weakness within the soil structure, causing tunnels and surface collapse above the tunnels.

Stabilisation of mine site waste rock dumps is a major component of mine site rehabilitation works. The presence of materials susceptible to tunnelling or piping has large impacts on landform stability and rehabilitation, as tunnel erosion tends to specifically impact on important structural elements of dumps such as berms and drains (Figure 1). Damage can then result either directly from the failure of those structural elements and the discharge of concentrated flows onto slopes below, or from the expansion of tunnels and their eventual collapse to form large gullies (Figures 2) (Schafer and Tragmar 1981).

*Figure 1: Tunnel developed from a berm on a waste rock dump constructed of sodic spoil.*

*Figure 2: Large tunnel collapsed to form a gully.*

**Table 1: Summary of material properties used in testing**

| Mine site | EC (mS/cm) | ESP (%) | Sand (%) | Silt (%) | Clay (%) | Mineralogy |
|---|---|---|---|---|---|---|
| Coppabella | 0.1-1.9 | 20 - 36 | 51 - 90 | 6 - 21 | 5 - 34 | Quartz, Kaolinite |
| Jundee | 0.06 – 0.76 | 10 - 35 | 44 - 78 | 4 - 42 | 17 – 33 | Quartz, Kaolinite |
| Higginsville | 7.5 – 12.8 | 38 - 56 | 15 - 31 | 7 - 10 | 59 – 76 | Quartz, Kaolinite, Smectite, Ilite |
| St Ives | 4.9 - 46 | 25 – 89 | 19 - 83 | 8 – 60 | 8 – 22 | Quartz, Kaolinite, Smectite, Ilite |
| Telfer | 0.1 – 1.9 | 3 – 7.2 | 40 - 68 | 26 - 54 | 5 - 12 | Quartz, Kaolinite, Ilite |

The presence of tunnel erosion also typically means that site remediation and stabilisation are extremely difficult, and that erosion problems are likely to be particularly persistent, showing little tendency for armouring and natural stabilisation.

## MATERIALS AND METHODS

### Material Properties

Broadly, materials susceptible to tunnel erosion (and selected for study) fall into three main groups:

(a) non-saline sodic

(b) saline sodic

(c) non-saline, non-sodic, silty

These groups have distinctly different patterns of tunnel erosion under field conditions and thus will have quite different management requirements. For classification purposes, measurements were taken on all materials collected from 5 sites for electrolyte content (EC), exchangeable cations, particle size distribution (clay, silt, fine and coarse sand categories) and clay mineralogy (using X-ray diffraction). A total of 5 materials from each site were tested covering a wide range of material properties (Table 1).

The Coppabella (central Queensland coalmine) and Jundee (central Western Australia gold mine) materials are largely non-saline, sodic, dispersive and mostly sandy.

The Higginsville and St Ives (both from Western Australia Goldfields near Kalgoorlie) materials are largely saline and sodic. This is to be expected for paleochannel materials in an environment where high salt levels are common in subsoils. The predominantly clay materials from Higginsville contain various levels of quartz, kaolinite and smectite minerals. The smectite component in some of these materials caused high levels of swelling during testing followed by shrinkage upon drying. This swelling and shrinking cycle forms cracks, which appear to be a major pathway for water to move through these materials and initiate tunnels. (Dispersive clays, when wet, can be highly impermeable, and without water movement, tunnel formation is impossible.) The St Ives materials are highly sodic and saline, with salinity levels varying considerably. The St Ives materials varied greater than the Higginsville materials with 1 markedly different from the other materials, being primarily a sandy material and non-dispersive.

The Telfer (northern Western Australia gold mine) materials are non-saline and have relatively low sodicity. Initial particle instability was only observed in samples with the highest ESP (only 7%). The mineralogy of these materials consisted primarily of quartz, kaolinite and illite, with no trace of swelling smectites. The tunnelling characteristics associated with this material are driven by liquefaction within the soil structure.

### Testing Methods

The Emerson test (AS 1289.3.8.1 – 1997) initially measures both slaking and spontaneous dispersion of an air-dry soil aggregate immersed in excess water (Emerson 1967). If spontaneous dispersion is “slight to nil”, the soil is remoulded at near maximum field water content, and dispersion is again observed. Finally, if soil does not disperse after remoulding, the soil is shaken in water. Initially if the sample demonstrated no slaking, then any presence of swelling within the soil aggregate indicates the variation for these stable materials. High levels of gypsum or calcite also influence this test and need to be indicated if present.

The Pinhole Test (AS 1289.3.8.3) applies mechanical energy to sample via water flow through a pinhole of 1.07mm diameter (Schafer 1978) placed in a compacted soil specimen at its plastic limit moisture content. Distilled water is passed through the pinhole, with an initial mean velocity 0.4 to 0.8 m/s, and measurements are taken of the water turbidity and flow rates exiting the pinhole. Visual inspection of the pinhole is carried out after testing is complete (Schafer 1978). Dispersive clay soils produce turbid water with a rapidly eroding hole, whereas non-dispersive clay soils result in clear water at the outlet and little change in pinhole size (Sherard *et al.* 1976).

Short leaching columns were used to assess sample hydraulic conductivity and the extent to which leaching of soluble salts reduces the stability of the surface layer of each material. The short leaching columns used a soil layer 10mm deep with 40mm depth of water ponded above it. Leachate depth, leachate sediment loads and soil and leachate EC were measured at 50 to 100 mL leachate output intervals (intervals based on infiltration rates) to assess changes in infiltration rate through time and in response to amounts of leaching of soluble salts from the sample. Longer leaching columns (soil layer of 100 mm depth, with 300 mm depth of water ponded above it) were used to assess both sample hydraulic conductivity and potential for tunnel generation. Infiltration rates, leachate EC and total sediment in leachate were measured at 50 to 100 mL leachate output intervals. Soil layers for these columns typically formed a seal that reduced water movement through the soil layer. The impact of shrinkage cracks on the tunnel erosion potential of samples that formed strong surface seals were then assessed by drying samples and then ponding water on them again. Potential remediation techniques for various materials were assessed using leaching columns, particularly the use of gypsum and compaction levels.

## TUNNELLING INFLUENCES

### Tunnel Mechanisms

There are a variety of mechanisms that influence the formation of tunnels within a material. These include; rainfall seasonality, heterogenous surface layer infiltration, exits/entrances, hydraulic conductivity of subsurface horizons and dispersion of soil layers subject to water flow (Crouch *et al* 1986).

In climates with distinct seasonality of rainfall, the action of drying and wetting cycles has an important effect on soil structure. Main processes affected are the slaking of soil exposed to evaporative drying and the formation and closure of shrinkage cracks (particularly associated with swelling clay materials). Shrinkage cracks generated by soil drying provide inlet areas for water, and expose dispersive sub-surface clays to free water.

Crouch (1976) lists a set of processes that can lead to tunnelling. They are:

- Surface cracking due to desiccation
- Rapid infiltration down the cracks, and super-saturation of a subsurface layer
- Dispersion of the super-saturated layer
- Movement of the dispersed particles in soil water due to a hydrostatic gradient that produces lateral flow. Generation of a "subsurface rill" or tunnel results from this movement. Over time and with increased flow volumes the tunnel will increase in size and may merge with other tunnels. The size of tunnels is limited by the strength of the upper layer, which will collapse once the tunnel achieves a certain size to form a tunnel-gully.
- Expansion of the tunnel inlet and outlet. Tunnel inlets typically start as small holes generated below subsurface cracks. Progressive collapse may cause this inlet point to become a large depression although the tunnel inlet size may remain small depending on the volume of water concentrated at this point.

Tunnel outlets are formed through the continued progress of tunnelling below the surface layer finding an outlet (an existing gully or point of weakness such as surface cracking). In some cases, exits form as "blowholes" resulting from the hydraulic pressure forcing its way through the surface layer at a lower point in the landscape.

Crouch (1976) reports the work of Downes (1946) who found that infiltration rates into the surface of tunnelling areas can vary by up to 50 times (Floyd 1974). A significant impact on the formation of tunnels in an earthwork construction or in the field is any factor allowing concentration of water and causing uneven infiltration rates into the soil. Features identified as causing a concentration of water to influence tunnel formation include:

- soil cracks formed by construction works or wetting drying cycles;
- animal burrows (rabbit burrows are mentioned significantly in many articles from NSW agricultural regions, although it is uncertain as to which came first-the tunnels or the rabbits (Floyd 1974)),
- holes from root system and rock outcropping and their removal; and
- small depressions.

Many of these features exist on mine waste rock dumps, with added influences caused by waste dump construction design and requirements, for example the construction of level berms. Constructions formed through the use of differing materials (particularly with differing hydraulic conductivities) on the surface may also serve to increase subsurface flow levels at certain points of the construction. Increasing infiltration rate at one point will drain the ponding water on a nearby less permeable material increasing the flow through the area of higher permeability. Floyd (1974) found tunnelling to be less severe for bank construction when graded banks were constructed, and where ponding did not occur.

### Waste Rock Dump Design

During initial site visits, a strong difference was observed between the patterns of tunnel erosion at Coppabella (non-saline / sodic) and Higginsville (saline / sodic) Mines.

At Coppabella, tunnels were extremely frequent on waste dump batter slopes, tended to be relatively small (up 50 cm diameter), and developed at depths of 50-70 cm in the soil. In contrast, at Higginsville, tunnels developed almost entirely on dump tops and berms, were relatively large (up to a metre or more in diameter), and relatively infrequent (spacings of 50 m being common in some areas).

When spoils are first excavated at Higginsville, they are actually non-dispersive, due to their high salt content. However, if leached, their salt content reduces, and they then become highly dispersive. Therefore, leaching of salt from the spoil is a major factor in making the soil dispersive. Most of the leaching occurs at points where water is ponded - on dump tops and berms. This ponded water then also provides the driving force for the tunnel erosion process. So, where spoils are initially saline / sodic, ponding water on them is a guaranteed way to create tunnels. This indicates that the traditional water-retaining waste dump profiles (flat tops, berms), are a major cause of the tunnelling of these sorts of spoils.

For non-saline / sodic spoils like Coppabella, clearly the tunnelling process can start immediately, and at any point on the landscape, and this seems to be consistent with the observations. For saline / sodic spoils it is plain that waste rock dump design is a major issue for tunnelling on this group of spoils and there are a range of issues to consider for spoil instability. Quirk and Schofield (1955) and many others since that time (Quirk 2001) have used plots of ESP (sodicity) against Electrolyte Concentration (EC) (salinity) to define regions of stable *versus* reducing hydraulic conductivity or soil flocculation *versus* deflocculation/dispersion.

## RESULTS AND DISCUSSION

In general, the management options available to mine sites that excavate materials susceptible to tunnelling are to either:

(a) avoid the problem by ensuring that tunnelling materials are not exposed to runoff and shallow drainage: or

(b) remediate the problem by applying some form of amendment.

Avoidance of the problem is undoubtedly the easier and most cost-effective option, but relies on mine site management being able to accurately identify materials that will be susceptible to tunnelling. Laboratory tests for the identification of dispersive materials have been developed and tested, but there has been little research on relationships between test results and the development of tunnel erosion.

In dealing with mine spoils, it must be emphasised that literature on characterisation procedures, and associated prediction/modelling of erosion processes, suffers from the central assumption that 'as mined' materials have properties that do not change after placement in dumps. This is a severe weakness for many Australian mine spoils that are saprolitic (rather than pedological) in nature and are commonly saline, sodic, at extremes of pH and devoid of biological materials/activity. In order to predict the mid to longer-term performance of dumps, it is essential that the inevitable microstructural, chemical and mineralogical evolution of wastes can be predicted and the impact of these changes on erosion hazard determined.

Remediation of materials susceptible to tunnelling is typically seen as relying on application of gypsum to remove exchangeable sodium and to increase the stability of the material of concern (Sumner 1993). Gypsum applications were tested on 2 materials from Coppabella (CPS1 and CPS5). These samples were selected for testing as CPS1 varied greatly in behaviour to the other four Coppabella samples during testing and CPS5 provided the highest sediment loads in leachate during earlier testing.

Application rates equivalent to 5, 10 and 20 t/ha of gypsum were thoroughly mixed into 100 mm deep samples of spoil. Treated samples and a control sample were then assessed using the long leaching column tests measuring infiltration rates, leachate Electrical Conductivity (EC) and sediment concentrations in the leachate. Bulk densities were kept constant during this test.

To test long-term persistence of gypsum effects, a total of approximately 1900 mm depth of deionised water was leached through samples with 5 t/ha gypsum before the reduction in soil EC caused by the leaching resulted in some dispersion, indicated by the leachate becoming cloudy due to the presence of dispersed material. (In agriculture, gypsum applications commonly need to be repeated a number of times before soil Exchangeable Sodium Percentage (ESP) is reduced to a level such that the soil remains stable).

Compaction trials were conducted using long leaching columns for all materials supplied by Telfer. Two levels of compaction were applied to each material, consisting of:

1. loosely placing the material to a depth of 100 mm, and
2. heavily compacting material to a depth of 100 mm.

Bulk density of the variously compacted materials was measured, and then an initial leaching trial was run over 24 hours to assess infiltration rates and leachate sediment levels.

The development of laboratory tests of soil chemical parameters has relied on correlation between some test result and measured soil responses or behaviour in the field. Fundamental to that approach is an expectation that a quantitative test result will have some mathematical relationship (neither necessarily linear nor precise) with a quantifiable field soil behaviour or response. Experience in this project indicates that that approach is not appropriate in this case.

Primarily, tests of dispersion or of tunnelling potential do not provide a quantitative result. In general, the tests provide a rating, with the test developer providing an assessment of which ratings indicate a high risk of tunnelling or dispersion, and which ratings carry a low risk. The following analysis has relied heavily on understanding of processes, and on logical application of knowledge with respect to fundamental processes of soil behaviour.

Emerson testing provides a quick, good indication of the presence of instantaneously dispersive material. The application of the test does not allow for high salinity materials, encountered in measurements on some mine spoils, particularly those of marine origin. If the salt content of a material is very high, then spontaneous dispersion may not occur, even when immersed in excess water. Reassessing Emerson test ratings may be necessary following leaching of saline materials to determine the impact of the salinity and potential tunnel formation over time. Is not effective in identifying materials susceptible to liquefaction failures.

The pinhole test was originally designed to assess the dispersion failure of clay-rich materials. The main mode of failure was expected to be clay dispersion, allowing soil around the pinhole to be removed by flow through it. However, during pinhole testing, materials with low cohesive strength (sandy and silty materials) suggested the importance of liquefaction as a mechanism for tunnel formation in these materials. All materials with low clay contents and/or low cohesive strength (Coppabella, Jundee and Telfer samples and 1 from St Ives) resulted in rapid failures, producing predominantly highly dispersive (D1) ratings. The highly saline clay-rich materials from Higginsville and St Ives mines provided the greatest variations in pinhole test results. The localised leaching around the pinhole during testing reduces the influence of salinity on the dispersion/failure of the samples during testing. This lessens the salinity impacts noted for the Emerson Test. The reduced influence of salinity was observed in many of the materials tested.

## CONCLUSIONS

This research has highlighted a number of issues related to the assessment of the risk associated with tunnelling problems on a mine site. Irrespective of the method by which tunnels form, the project has indicated strong interactions between the design of constructed landforms and the development of tunnel erosion.

Firstly, it has shown the importance of soluble salt content in some spoils, and the need to manage salt content to maintain stability. Where water is ponded over saline sodic spoil, with leaching of salt by the ponded water, resulting in reduced soluble salt, increased dispersion, and development of tunnel erosion. For non-cohesive materials, long durations of ponding are also a major factor in developing tunnel erosion.

Secondly, the project has shown the existence of effectively two mechanisms for tunnel erosion (movement of dispersed clay and also movement of non-cohesive fine particles), where previously tunnel erosion was attributed solely to clay dispersion. This finding has been supported by considerable field observation, and means that the range of materials at risk from tunnel erosion is greater than initially considered.

Across the entire range of materials considered and the range of mechanisms by which tunnel erosion develops it was identified that no single test will provide optimal information to assess tunnelling risk. Rather, it appears that initial assessment of soil chemical and physical data is required, followed by specific tests to assess the specific tunnel erosion mechanism indicated by material properties. Initial soil/spoil parameters that provide information on tunnel erosion potential are:

i) EC (to assess potential salinity impacts on dispersion);

ii) Cations, with particular emphasis on exchangeable sodium percentage (ESP) to assess dispersion potential (calcium content is also of interest if it is in the form of gypsum or calcite as per Emerson testing procedures);

iii) Particle size distribution (to provide an indication of soil cohesion and liquefaction contributions to tunnel formation/failure), and

iv) Clay mineralogy (for swelling influence).

Based on the data obtained, a judgment can be made on further appropriate testing (ie. Emerson, pinhole or leaching test applications).

The testing can identify which of the three groups of materials susceptible to tunnel erosion any individual material belongs to:

- saline sodic
- non-saline sodic
- fine, non-sodic materials of low cohesive strength

Following the characterisation of a material, potential placement options can be considered.

Saline sodic materials may initially be stable. Therefore, it may be acceptable to place these materials relatively close to the surface of a waste rock dump, provided leaching (over the long term) is limited. Leaching of salts and conversion of these materials to a non-saline sodic and dispersive condition is highly undesirable. This means that:

(a) prolonged ponding of water at any point on the landscape should be completely avoided as it will accelerate salt leaching and tunnel formation; and

(b) deep drainage below the topsoil layer should be minimised so that salt leaching is not significant.

Non-saline sodic materials will be susceptible to tunnel erosion as soon as they are placed on or near a waste dump surface. Options for constructing stable landforms of this type of material are limited. Where stable topsoil can be placed over the spoil, there is still potential for water draining below the topsoil to cause tunnel development. Options to avoid or minimise the potential for tunnel development in this type of material include:

(a) avoiding placing the material closer than 1 m to the surface (if possible);

(b) placing at least 0.5 m of stable (non-cracking) topsoil over the spoil;

(c) keeping waste dump outer batter gradients very low (as low as 5% if possible), so that gravitational forces aiding tunnel formation are drastically reduced;

(d) avoiding ponding of water; and

(e) ensuring that cracks and other pathways for water to enter the spoil are minimised.

There is also potential to use gypsum to stabilise these materials.

For non-saline, non-sodic materials of low cohesion, the major priority is to avoid prolonged ponding. Deep drainage into the spoil from an overlying topsoil layer is not of concern, provided the water moves as unsaturated flow.

The problem with existing unstable waste rock dumps is not only that erosion rates can, in some instances, be high. As well, unlike rocky materials, finer spoils susceptible to tunnel erosion are most unlikely to armour, or to have any mechanism by which erosion would be reduced over time. Therefore, those relatively high rates of erosion can be expected to continue indefinitely. For existing dumps subject to tunnel erosion, remediation and repair appears to be difficult in some cases and often impossible. Access to perform remedial works for suitable equipment on waste rock dumps is difficult and potentially dangerous due to existing tunnel-gullies and/or un-collapsed tunnels.

Therefore, the importance of early diagnosis of potential tunnelling problems (identifying potentially tunnel generating materials) and adoption of strategies to prevent such long-term instability is essential for successful mine closure.

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