

A COMPREHENSIVE MATHEMATICAL MODEL  
TO PREDICT HYDRODYNAMICS AND MASS TRANSPORT  
AT A COMPLEX MINE TAILINGS DISPOSAL FACILITY

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## 1.0 INTRODUCTION

The purpose of this paper is to present the development and adaptation of a comprehensive mathematical model to the Rossing Uranium Mine site located in Southwest Africa/Namibia. The activity of model adaptation was begun in late 1983 and is designed to predict the flow and mass transport consequences of seepage from the uranium mill tailings impoundment operated at the mine. The terrain is complex with severe inhomogeneities and anisotropies in the materials. Fractured rock of distorted shapes occur at the site and show strong directionally-dependent hydrological behaviour. These factors together with the time-dependent nature of operations together dictated the use of a mathematical model to manage the tailings disposal in a manner such as to cause the minimum of environmental impacts. The activity of model adaptation to site conditions, model calibrations to these conditions and its use to predict the consequences of tailings seepage is being continued to this day. The model is called TARGET, a mnemonic name which denotes: Transient Analyzer of Responses to Ground water flow with Effluent Transport.

## 2.0 BACKGROUND INFORMATION

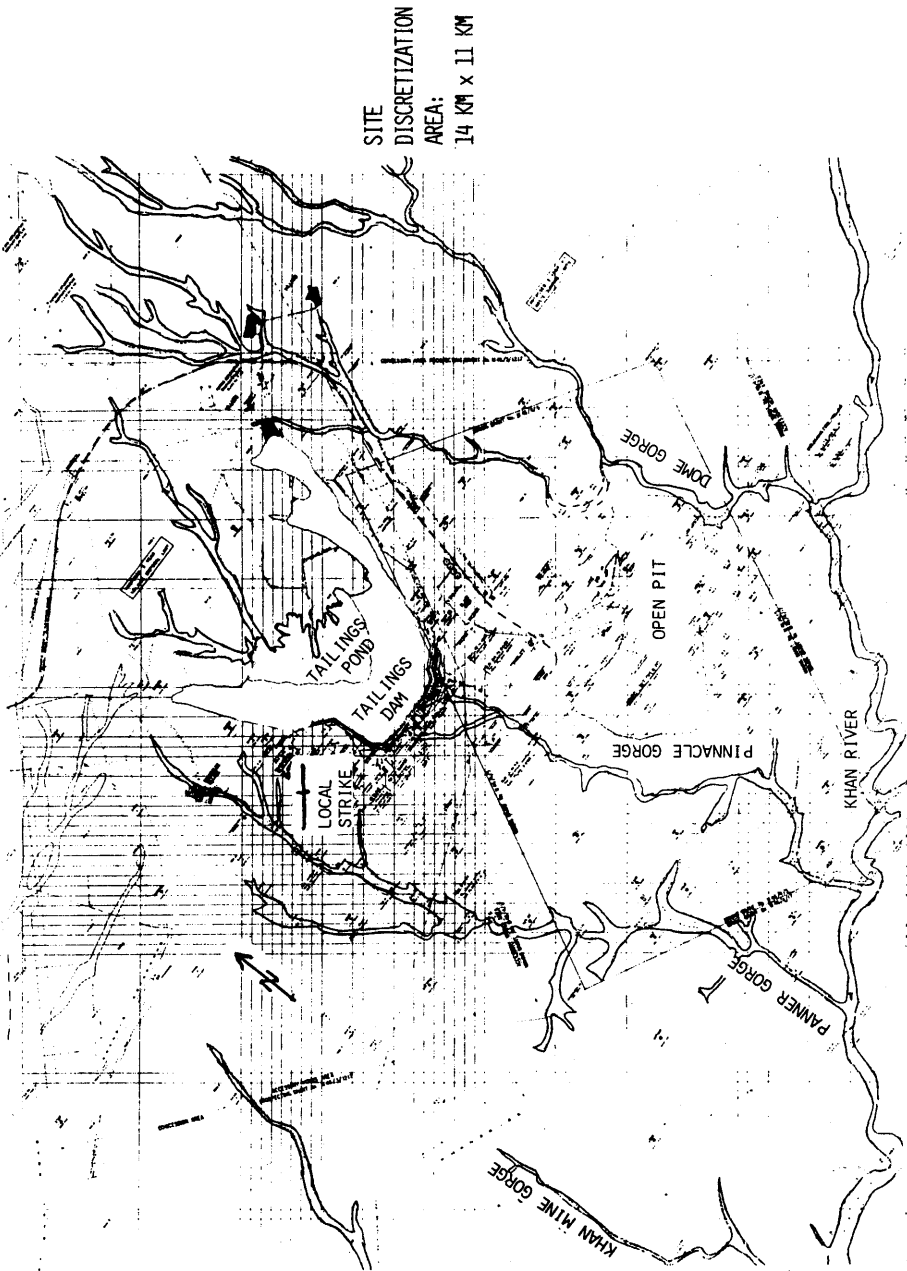
### 2.1 Historical Overview

In this paper the term "groundwater" is used to describe naturally occurring groundwater and the term "seepage" is used to describe effluent from the tailings dam seeping into the natural occurring groundwater.

At Rossing, seepage from the tailings impoundment was first identified below the seepage dam in the Pinnacle Gorge (Figure 1). A cut-off trench was immediately constructed to prevent this seepage from reaching the Khan River which is the main drainage channel away from the mine site.

Dames and Moore were retained as consultants; they initiated a comprehensive drilling programme to establish the routes and extent of any seepage migration from the impoundment. Geological mapping both on surface and interpreted from specially flown air photography as well as geophysical

Figure 1



surveys were undertaken. All this work was subsequently extended by Rossing staff appointed to the Environmental Control department of the Mine. Based on this work a borehole water sampling routine was initiated. Subsequently, a data management computer program, written by Dames and Moore, was used to store and analyse these data.

A very sensitive and accurate chemical "fingerprint" was found that could establish the presence of seepage in groundwater. Two conservative chemical species, sulphates and chlorides occur in both tailings solution and groundwater. The tailings solution concentration of about 25 000 ppm SO<sub>4</sub> and 1 500 ppm Cl are normal and in groundwater these values range from 500 to 2 500 ppm SO<sub>4</sub> and 1 000 to 13 000 ppm Cl. From routine sampling the first increase in the SO<sub>4</sub>/Cl ratio indicates the presence of seepage in groundwater.

The leading author, formerly with Dames and Moore, was commissioned to supply the mine with a comprehensive mathematical computer model. This model was specifically designed to predict future seepage movement, evaluate the effectiveness of seepage control measures, pinpoint any gaps in the control measures, predict changes in seepage movement with changes in tailings depositional practices. In addition, it is intended to predict the extent of seepage movement after close down of the mine, thus enabling management to plan for continuing seepage control. This model and its application form the central theme of this paper.

## 2.2 General Information on the Site

The Rossing mine/mill complex is situated approximately 65 km north-east of the town of Swakopmund in Namibia/South West Africa. The complex consists of an open pit mine, an uranium mill, a tailings pile and associated support facilities. Approximately 150 000 tons of ore, sub-ore and waste rock is excavated daily from the pit.

The primary uranium ores are uraninite (55 % of the uranium) and betafite (5 %) together with secondary minerals (40 %) principally beta-uranophane. The ore body is a granitic rock known as Alaskite and is recovered by open pit methods. The 20 year plan involves the formation of a pit 3 km long by 1 km wide by a series of 15 m high benches to a final depth of some 400 m.

## 2.3 Relevant Details of Mine Operation

Approximately 40 000 metric tons per day of low grade ore is crushed, ground and acid leached. The dilute leachate is concentrated first in a counter-current ion exchange plant and then by solvent extraction. Final precipitation as ammonium diuranate (yellow cake) and calcining to uranium oxide follows to complete the process.

## 2.4 Tailings Disposal Practices

Waste from the extraction plant, some 80 000 m<sup>3</sup>/day of slurry containing about 50 % solids, is pumped to the tailings impoundment. In mid 1976 a starter dam was built with mine waste across a gorge over a length of about 900 m. This mine waste forms the downstream filter through which the seepage flows before collection in a seepage dam.

Tailings are generally deposited either through spigots or open-end directed towards the tailings pond. The dam is constructed in benches, each bench being 15 m wide and 6 m above the previous one. From the crest of the dam tailing forms a beach at a natural slope of between 4 % and 6 % to the pond.

Acidic tailings solution (pH of 2) is neutralised whilst seeping through the embankment and underlying rock types to a pH of about 6.5 - 7.0.

## 2.5 Water Management

Currently more than 50 % of the mine's total water consumption is from recycled neutralised seepage and acidic tailings pond solution.

Seepage is recycled from the seepage dam, the seepage collection trenches and seepage collection wells. The trenches were constructed in the streambeds draining the tailings dam area by excavating the alluvium to bedrock, blasting a 3 m deep slot across the stream valley and installing french drains and well points. Dewatering boreholes were sited on the known aquifers "downstream" of the tailings impoundment mainly by using local experience and geological knowledge. Geophysical surveys (resistivity, electro-magnetic and seismic refraction) were tried with limited success, electro magnetic being the most successful.

Use of acidic tailings pond solution (pH of 2), gave rise to major corrosion problems in the Plant, but these problems have all been resolved.

Typical unit consumptions of seepage, tailings solution and fresh water as a percentage of rodmill feed are summarised below.

	% Rodmill Feed
Fresh water	19
Seepage water	14
Tailings solution	67

## 3.0 SITE CHARACTERISTICS

### 3.1 Geological Setting

Rossing Uranium Mine is situated in the Precambrian Damara super group in SWA/Namibia. Regional and local geology of the area is adequately described in the literature. [Smith, 1965; Berning, 1976; Nash; 1971; Kroener, 1977].

Briefly, four major units occur in the tailings dam area. The Khan formation, consisting of basic metasediments mainly pyroxene gneisses and biotite hornblende schists, The Rossing formation, a heterogeneous lithological assemblage consisting of marble bands, quartzites, schists and gneisses, The Chuos formation, consisting of meta-tillite now schistose and highly granitized and The Karibib formation, consisting of marbles with interbedded schists and quartzites.

The regional geology is characterised by magmatization with the rock occurring in the upper amphibolite to granulite facies of metamorphism. Facies changes are the norm rather than the exception even over relatively short strike distances. The dominant structural trend is north-east, the regional strike of the meta sediments. F1 deformation caused the main regional anticlinorium and the prominent F2 structures are tight overturned folds. F3 structures form interference folds along an easterly oriented axis. Alaskite, a high potash granite rock ranging from aplite to pegmatite occurs as lenses of secretion origin, large intrusive and replacement bodies throughout the area. Locally these Alaskites are uraniferous and form the Rossing ore body.

At the tailings impoundment site the major direction of seepage is through the starter wall down Pinnacle Gorge in a sand-filled, normally dry river bed. Minor subsurface seepage is to the south-west along the structural grain of the marbles, schists and granitized sediments of the Rossing, Karibib and Khan formations.

### 3.2 Hydrological Features

Deeply incised gorges, all draining to the Khan River, are normally dry and sand-filled. In most areas the aluvium has in the past been lime cemented, forming an agglomerate which has subsequently eroded leaving remnants of agglomerate and various sand and gravel filled channels. Minor quantities of subsurface groundwater occur in the bedrock and experience has shown that this water drains along the structural grain of the rock into the gorges from all sides.

### 3.3 Geochemical Setting

In the vicinity of the tailings impoundment rock types encountered are marbles, granulites, pegmatites and various calcsilicate metasediments as well as streambed alluvium.

All rock types as well as tailings sands and slimes have a high buffering capacity. The CaCO<sub>3</sub> equivalent varies from 1.5 to 88 %. Analysis of typical pre-mining groundwater shows high TDS and high chloride contents (see below).

Date 31/07/68

WELL NO: BH 8400W/1

pH	6.6
Conductivity	11000
Total dissolved solids ppm	8550
Sodium (as Na) ppm	1465
Potassium (as K) ppm	120
Sulphate (as SO <sub>4</sub> ) ppm	2280
Nitrate (as N) ppm	29
Nitrite (as N) ppm	1.9
Silica (as SiO <sub>2</sub> ) ppm	25
Fluoride (as F) ppm	2.5
Chloride (as Cl) ppm	3150
Total Alkalinity (as CaCO <sub>3</sub> ) ppm	130
Total Hardness (as CaCO <sub>3</sub> ) ppm	3600
Calcium Hardness (as CaCO <sub>3</sub> ) ppm	2346
Magnesium Hardness (as CaCO <sub>3</sub> ) ppm	1254

#### 4.0 MATHEMATICAL MODEL FEATURES

A comprehensive mathematical model should consist of three essential components. These are:

- a sound mathematical formulation or representation of the physical and chemical mechanisms which are sought to be modelled;
- an efficient procedure to solve the mathematical set of equations in a manner which takes account of the initial and boundary conditions existing at the site as well as man-made operating conditions; and,
- a flexible computer program which, as a manifestation of the solution procedure, permits data on problem features to be supplied in a convenient fashion and generates output according to user choices.

The model TARGET is composed of these three parts. The governing equations which form the foundation of the model are derived from fundamental principles, in order to represent flow and contaminant transport within a single-layer, saturated geological formation. Such equations are referred to as 'depth-averaged' since they ignore motions in a vertical direction which may be inclined to the coordinates along which motions do occur. In the present mathematical formulation, general treatment has been provided for inhomogeneities and anisotropies of the site geological formations as well as for the interactions of the flowing fluid with porous formations. Several advantages, of physical comprehension and computational nature, accrue from such a formulation wherein all equations are expressed in mass-conservative, rather than volume-conservative, form. Such a formulation seeks to take advantage of the essential similarity of the governing equations in respects of both numerical solution and computer program efficiencies.

The reader is referred to several excellent available texts for rigorous mathematical derivation of all relevant governing and auxiliary equations employed in this section (Bear, 1979; Sharma, 1983). The coordinate system employed in the following derivations is cartesian and the nomenclature used is presented in the text but also described in the nomenclature list.

#### Hydrodynamics

The term hydrodynamics is employed here to denote all mechanisms of fluid motions within saturated porous media and, hence, includes principles of mass and momentum conservation. The following salient points may be made in respect of hydrodynamic formulation.

- (1) The piezometric head, otherwise referred to as the 'phreatic-surface' elevation, is defined with respect to the density of fluid at a reference state. However, since in the site problem no significant changes to fluid density are expected to be encountered, fluid density is considered to be constant at the reference state.
- (2) Since fluid density is essentially constant, the mass-conservative form of the governing equation for piezometric head is equivalent to the volume conservative form.

- (3) The saturated thickness is defined as the distance from the base elevation to the position of the phreatic surface, or to the position of the top surface of the formation along a true vertical direction.
- (4) Vertical components of fluid motions through the saturated formation are negligible. The components of flow along the formation are parallel to its base.
- (5) The terms  $StK_x$ , and  $StK_y$ , are synonymous with "transmissivities" along the x- and y- directions respectively.

The partial differential equation which governs hydrodynamics is the so-called piezometric head equation, which, in TARGET, is expressed as follows:

$$S_c \frac{\partial h}{\partial t} = \frac{\partial}{\partial x} \left\{ S_t K_x \frac{\partial h}{\partial x} \right\} + \frac{\partial}{\partial y} \left\{ S_t K_y \frac{\partial h}{\partial y} \right\} + \frac{\dot{m}'''}{\rho_0} \quad (1)$$

where the symbols are defined in the nomenclature list.

#### Flow Velocities and Flow Rates

It is important to note that it is the Darcy velocity, ie the product of formation porosity and fluid particle velocity, which appears in the equations derived above. This point becomes especially important when dealing with interfaces between formations of differing porosities, since at such interfaces an inherent mathematical discontinuity occurs. More will be made of this point in the following section on the numerical algorithm. Furthermore, it is the product of Darcy velocity and saturated thickness  $S_t$ , which appears in the formulation adopted for present purposes. Thus the term 'velocity', in each of the cartesian coordinate directions x and y, is actually the product:

$$\hat{U}_i = n U_i S_t \quad (2)$$

and is employed in all further discussions of the model. It is a simple matter to see the computational advantages of dealing with a single variable which is composed of three distinct factors of which two, at least, can demonstrate mathematical discontinuities.

The generalised definitions of these 'velocities' using the derivations presented above are:

$$\hat{U} = - [K_x S_t] \frac{\partial h}{\partial x}$$

and:

$$\hat{V} = - [K_y S_t] \frac{\partial h}{\partial y} \tag{4}$$

From the above definitions, it is a matter of simple extension to calculate the corresponding flow rates in each of the two coordinate directions. These are, in volumetric units, expressed as follows:

$$F_x = \int_y \hat{U} dy \tag{5}$$

and:

$$F_y = \int_x \hat{V} dx \tag{6}$$

Thus, whereas the units of equations (3) and (4) are (LxL/T), those of equations (5) and (6) are (LxLxL/T). Provisions have been made in the model not only to compute values of the 'velocity' which are needed in other calculations, but also flow rates for the user's information and guidance.

Mass Transport

The fundamental partial differential equation governing the transport of chemical species, may be expressed in a general form (see Bear, 1979; Sharma, 1983) as follows.

$$\begin{aligned} S_t \left\{ \frac{\partial}{\partial t} (n m_j) \right\} &+ \frac{\partial}{\partial t} \left( \left[ \frac{\rho_s}{\rho_o} \right] [1 - n] m_{j,s} \right) \\ + \frac{\partial}{\partial x_i} \left\{ \hat{U}_i m_j \right\} &= \frac{\partial}{\partial x_i} \left\{ n S_t D_{ii} \frac{\partial m_j}{\partial x_i} \right\} \\ &+ \left[ \frac{\dot{m}'''}{\rho_o} \right] S_t \hat{m}_j \end{aligned} \tag{7}$$

Note, in this equation, the occurrence of 'velocities' as defined above and the normalisation with respect to the reference fluid density  $\rho_o$ . Note also that the term representing the storage and/or release of chemical-specie concentration in the solid, or immobile, phase is retained as a separate term which will be discussed below. Further, note that in the general formulation of equation (7), chemical-specie concentrations may be expressed in volumetric units (ie mg/l), mass fraction units (ie mg/g or as dimensionless 'normalised' form thus:



$$m_j \equiv \frac{C_j - C_{j,b}}{C_{j,0} - C_{j,b}} \quad (8)$$

Finally, note that man-made features of mass extraction, or injection, are indeed taken into account.

#### Interactions of Fluid with Porous Formations

Flows of a constant-density fluid through porous formations interact with the latter in two essential ways. It is assumed here that changes to fluid viscosity do not occur throughout its motion. The two mechanisms of interaction are: through dispersion; and, through geochemical reactions with the porous matrix. Each of these mechanisms is considered separately below.

#### Dispersion

Hydrodynamic dispersion is the mechanism whereby miscible fluids, and air-water combinations, displace one another within the pores of a porous medium. In representing motions of groundwater, the term signifies the transport of contaminants which are soluble in, and miscible with, the flowing water through the simultaneous actions of mechanical and physico-chemical phenomena. General discussions of the subject are provided by Scheidegger (1963) and Bear (1964). Methods to measure them have been reported by several authors, notably Lenda and Zuber (1970), and Klotz and Moser (1974). In recent years several research workers have paid attention to the field measurement of dispersion coefficients which are quantitative measures of the mechanism.

In summary, dispersion is a mechanism whereby a flowing fluid interacts with the porous formations through which it flows may be summarized as follows.

- Dispersion acts to reduce concentration gradients in all regions and hence to reduce the maxima in concentration values other than at the locations where constant concentrations, as for example at the pores are encountered.
- Dispersion causes concentration 'plumes' to spread both along and perpendicular to the directions of fluid motions. Hence, it may cause contaminants to be transported to previously uncontaminated areas even if the motion in that direction is negligible.
- The dispersion coefficient has been found to be proportional to fluid velocity (Klotz and Moser, 1974). The constant of proportionality is referred to as the 'dispersivity', which naturally has a directional dependence and units of length.

With the above discussion in mind it is possible to derive the following relation.

$$D_{ii} = D_0 + \alpha_{ii} U_i \quad (9)$$

### Geochemical Interaction

Interactions of chemical species, in the mobile (ie fluid) phase, with the formation matrix are sometimes referred to as 'sorption' meaning surface reactions. In fact such interactions are caused by a number of geochemical mechanisms such as precipitation and co-precipitation, buffering of acidity, radioactive decay, cation exchange and the like. Thus in some of these reactions the chemical species attach themselves to or detach themselves from, the grains of the porous medium through 'surface' reactions which may or may not be reversible. In others, the solid matrix merely serves as a catalyst for chemical reactions or as a means of neutralising the acidity of the flowing fluid and this, in turn, causes precipitation of certain chemical species onto the solid grains. Such precipitation may, under favourable circumstances, be irreversible, cause co-precipitation of other normally mobile chemical species and/or be accompanied by re-dissolution.

The mass concentration in the immobilised phase, which appears in the equation (8) is thus influenced by one or more of the mechanisms referred to above. A measure of the magnitude of this interaction is obtained from the empirical observation that the immobile-phase concentration  $m_{j,s}$  is directly proportional to the corresponding mobile-phase value  $m_j$ . The constant of proportionality is referred to as the 'distribution coefficient' which is akin to the partition coefficient of chemical physics but in empirical fashion, covers all possible geochemical mechanisms. The relationship is expressed as follows:

$$m_{j,s} = K_d m_j \quad (10)$$

where  $K_d$  is the distribution coefficient and has dimensions which are inverse to those employed for fluid density in the model. In short,  $K_d$  is the coefficient of proportionality in the linear relationship between the mobile-phase concentration and its immobile counterpart. It represents the potential for the solid matrix to adsorb, or otherwise reduce, the mobile phase concentration as the fluid flows through the matrix. The higher the value of  $K_d$ , the greater is this potential.

### Initial and Boundary Conditions

Initial conditions refer to the distribution of all primary and secondary variables within the modelled domain at the start of time-dependent calculations within the model. The specific reference here is to distributions of the piezometric head  $h$ , and the chemical-specie concentration  $m_j$ , as functions of  $x$  - and  $y$  - the selected coordinates. When a transient calculation is initiated these distributions should be mass-conservative, ie should themselves satisfy the conservation principles. In such cases the distributions are best evaluated as the steady-state solutions, obtained with the model, to the problem under the prescribed boundary conditions. In certain cases the initial conditions are merely the solutions obtained at some earlier time instant. The prescription of initial conditions thus presents few difficulties and is straightforward.

Boundary conditions signify values of the dependent variables  $h$  and  $m_j$  on the boundaries of the modelled domain. Such values may, on occasion, be functions of time. Hydrodynamic boundary conditions are of two types: supplied  $h$  - values; and supplied gradients of  $h$ . In either event, the model is equipped with means of accommodating the boundary conditions with the minimum of fuss. On the other hand, boundary conditions for mass transport are also of the same two types. In the event of inflows into the modelled domain through a boundary, boundary values of concentrations

are not to be prescribed but are calculable from the concentration distribution 'upstream' of the said boundary. When concentration gradients, ie fluxes of specie mass concentration  $m_j$  are to be prescribed, the method employed in the model is identical to that adopted for piezometric head  $h$ . This method will be described in the following section wherein the numerical solution procedures are described.

## 5.0 DISCRETIZATION OF SITE

### 5.1 Selection of Model Domain

The domain selected is shown on the map. No seepage is expected to move beyond this domain, but should any indications prove otherwise, extension of the domain can be made simply by the addition of more data points.

The model domain represents the major features found at the site. These features include the tailings impoundment itself, seepage control systems installed at the site, surface streams and the dominant geological formations.

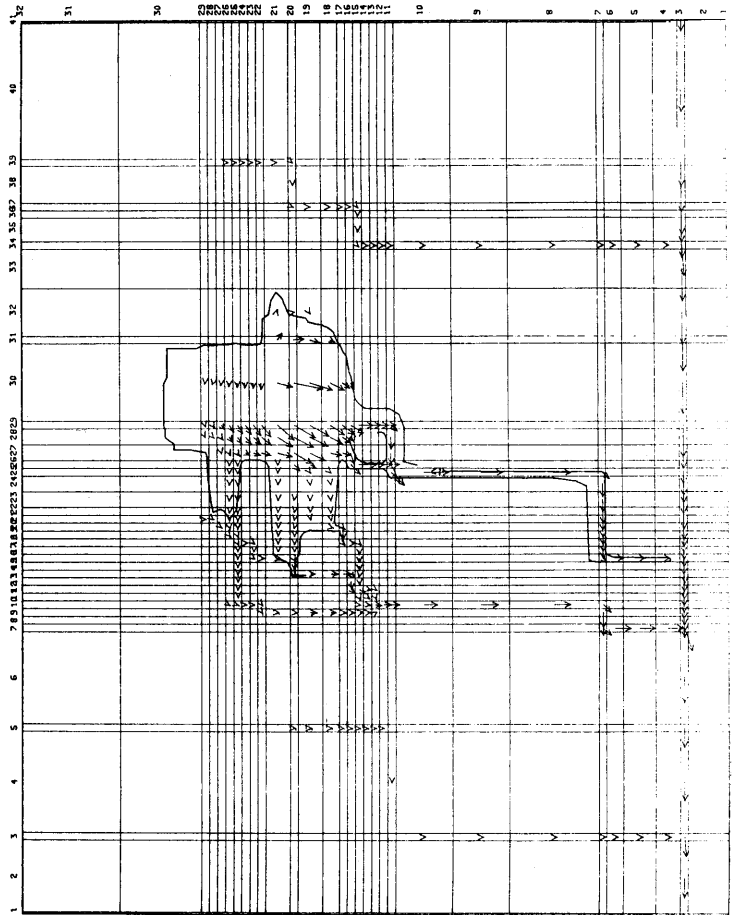
A numerical grid system consisting of regular cells of arbitrary aspect ratio, but mutually-orthogonal cell faces, served as the central framework of the numerical procedure. This cell system, with a unique grid node located at the centre of each cell, is selected so as to cover just exactly the region of interest, hereafter referred to as the computational domain or 'domain'. In the procedure, arbitrary curvatures of the domain boundaries are accommodated by 'flagging' all cells which are not part of the domain as being 'external' cells and treating the near-boundary cells in a special way. A set of discrete equations, ie the finite-difference equation set, for each dependent variable is obtained by integrating the appropriate differential equation over each of the numerical cells. Assumptions are of course necessary to permit such integrations to be made; a basic one being that dependent, and auxiliary, variables vary linearly from one grid node to the next. Finally, an efficient procedure is employed to solve this equation set, iteratively, at each time instant of interest.

### 5.2 Selection of Numerical Grid

The numerical grid selected to cover the domain consists of a 41 by 32 node system, ie a 39 by 30 grid cell system, which is illustrated in Figure (2). A minimum cell size of 120 m was selected since no individual geological or structural feature smaller than this was identified. This grid was selected after careful tests of the procedure, and with the purpose of accounting for the site features referred to above. In this grid system all variables, with

Figure 2

ROSSING URANIUM LIMITED  
TARGET PLOT  
3000 ppm SO<sub>4</sub> Contour  
2000 Days After Start Up  
Before Seepage Control Implemented



two exceptions, are presumed to be located at the grid nodes, ie at the geometric centres of the cells. The exceptions are: the velocity components in each of the coordinate directions; and, the corresponding effective diffusion coefficients. The velocity component in any given direction is presumed to be located at the intersection of the grid line in that direction with a cell face which is perpendicular to it. This grid line is, of course, a straight line which connects grid nodes along a given coordinate direction. Cell faces and the corresponding velocity-component locations will not, in general, lie exactly midway between adjacent grid nodes. It is only ON the boundaries of the domain, composed of true cell faces, that gridnode locations and velocity-component locations coincide. These features are illustrated in Figures (3) and (4).

Site specific data on material properties and site features were supplied to the grid-node locations identified by a set of flags. These flags, defined within the computer program, are also supplied with values in the data 'file' which contains all relevant data for the model. Special provisions were made to take account of:

- the current position, shape and elevation of the tailings pond;
- the location and operation of presently employed seepage control systems
- hydraulic connections between the highly-permeable marble formations and less well defined connections between other formations; and,
- the interactions of surface streams with sub-surface flows.

### 5.3 Supply of Site Specific Data

Classical methods for determining hydrological parameters were employed on a large number of boreholes with their necessary observation holes. Considering the very complex geological terrain with rapidly varying lithological units and structures. These methods met with limited success. Empirical methods were hence employed to determine hydrological parameters.

The main concern of Rossing management is naturally the rate and route of movement of the seepage front and the volume of seepage involved. The wealth of knowledge gained from the drilling, monitoring and dewatering programs preceding the computer model calibration permitted the calculation of the necessary hydrological parameters for each of eight different hydrological regimes occurring on the site. Historically the position and elevation of the tailings pond and impoundment are known, and the "first arrival" of seepage as measured by the first upward trend in the  $SO_4/CI$  ratio at various monitoring points gives a good measure of the velocity and route of the seepage front.

In Pinnacle Gorge highly efficient dewatering cut-off trenches give an accurate measure of volume. Volumes of flow in other directions were obtained indirectly by volume measurement for dewatering holes, water balance calculations and site knowledge. The two input parameters affecting flow rate and flow volume to be calculated are permeability and effective saturated thickness.

Figure 3

ROSSING URANIUM LIMITED

TARGET PLOT

3000 ppm SO<sub>4</sub> Contour

3500 Days After Start Up

Seepage Control Installed 2000-2300 Days After Start Up

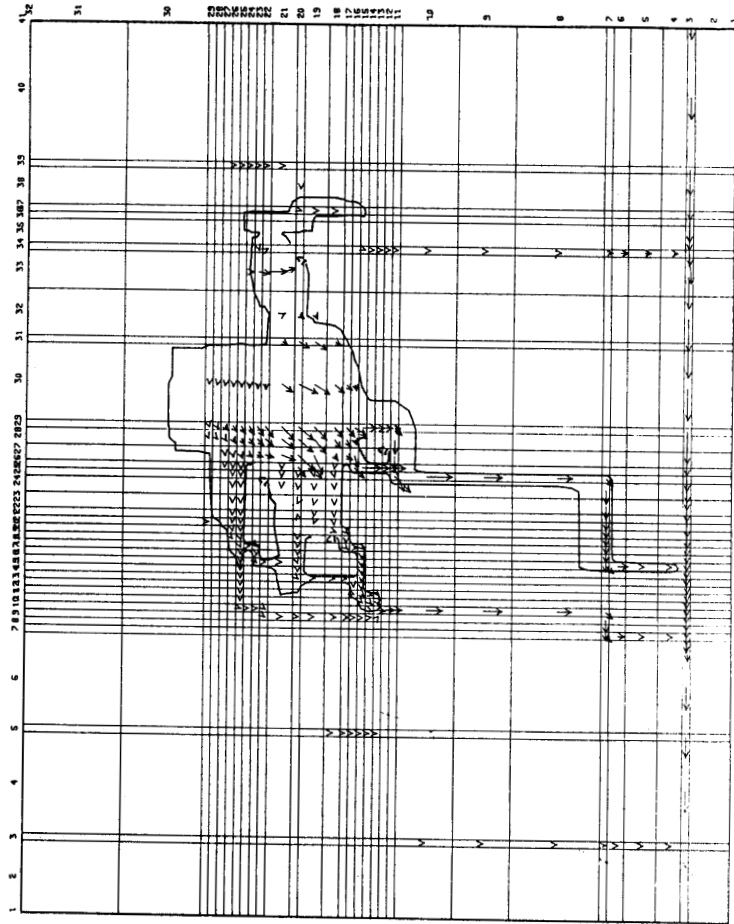


Figure 4

ROSSING URANIUM LIMITED

TARGET PLOT

3000 ppm  $SO_4$  Contours

3500 Days After Start Up

If no seepage control measures installed

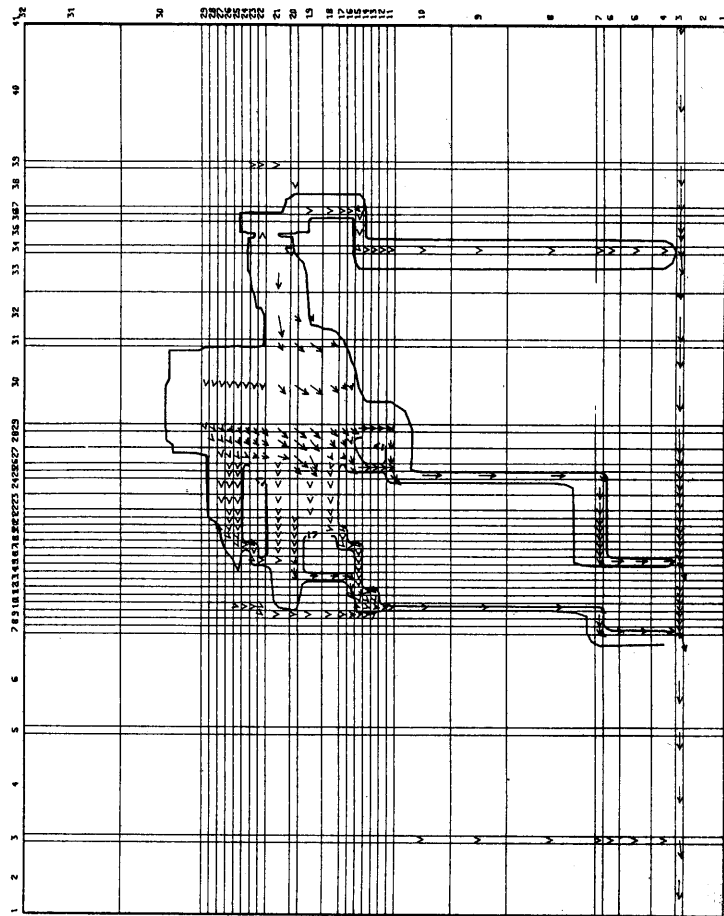
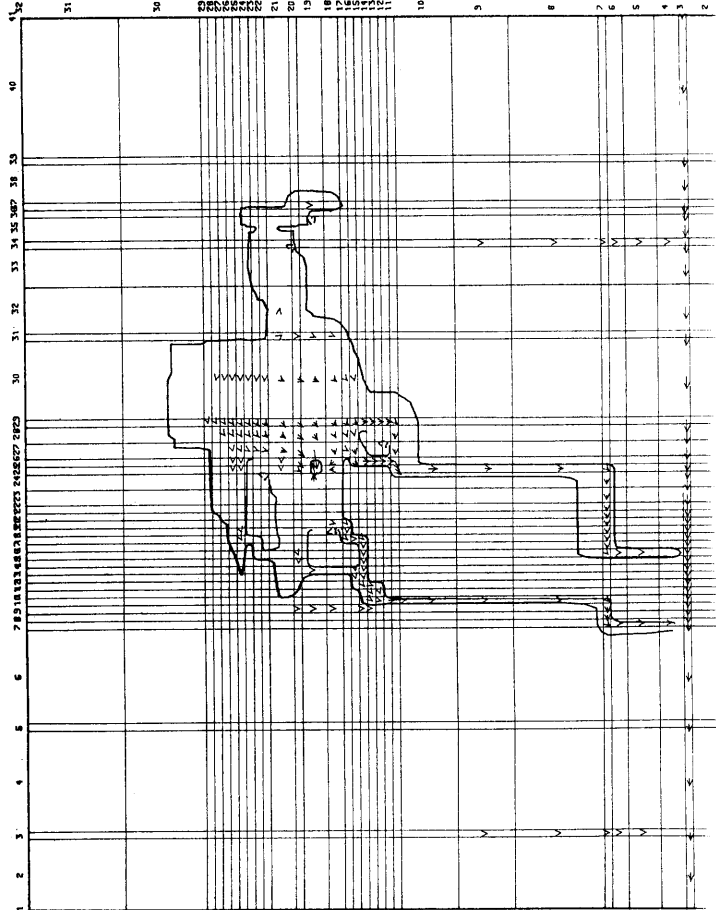


Figure 5

ROSSING URANIUM LIMITED  
TARGET PLOT  
3000 ppm  $SO_4$  Contour  
4000 Days After Start-Up, ie 500 days from now





Calibration was done by varying these parameters and using transient runs, with the necessary time related changes in geometry, from start-up to 1980 until the hydrodynamic conditions, i.e. velocity and volume matched as best possible with known conditions. Predictive runs from 1980 to the present time were then made and matched with known conditions.

Species transport calibration was undertaken once the hydrodynamic calibration was completed. Each chemical species was treated as a separate problem and  $K_d$  values assigned to each hydrological regime for each species individually.

For example, the present day species concentration immediately outside the impoundment is known from monitoring. A transient run, with the hydrodynamics already calibrated, from mine start-up to present day was used to calibrate the  $K_d$  value of the impoundment solids and underlying sediments, i.e. actual value which reasonably predict the present conditions. The next step was to establish  $K_d$  values for each of the hydrological regimes abutting on the impoundment until the necessary fit was obtained. Figures 2, 3, 4 and 5 are typical output plots.

#### 6.0 ACKNOWLEDGEMENTS

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#### 8.0 NOMENCLATURE LIST

In the units presented below, L denotes length in any consistent unit, T denotes time and M the mass each in consistent units.

<u>Symbol</u> (Units)	<u>Meaning</u>
$C_j, C_{j,b}, C_{j,0}$	: Concentrations of local, background and source locations in volumetric units (mg/L).
$D_0$	: Molecular diffusion coefficient (LxL/T).
$D_x, D_y$	: Dispersion coefficient in the x - and y - directions respectively (LxL/T).
$F_z$	: Formation thickness (L).
$F_x, F_y$	: Volumetric flow rates in the x - and y - directions (LxLxL/T).
$g$	: Constant of gravitational acceleration (L/TxT).
$h$	: Piezometric head of the fluid (L).
$h_b$	: Elevation of the formation impermeable base (L).

$K_{ij}$	: Hydraulic conductivity tensor (L/T).
$K_d$	: Distribution coefficient (LxLxLxT).
$\dot{m}'''$	: Mass sources and/or sinks [M/(LxLxLxT)].
$m_J$	: Mass concentration of chemical species 'J' (either mg/l or normalized in the range $0 < m_J < 1$ ).
$\hat{m}_J$	: Mass concentration at the source/sink location (same as for $m_J$ ).
$n$	: Porosity (dimensionless).
$S_c$	: Specific storage coefficient (dimensionless).
$S_t$	: Saturated thickness (L).
$t$	: Time (T).
$U_i$	: Fluid particle velocity (L/T).
$\hat{U}, \hat{V}$	: x - and y - direction components of the generalized Darcy velocity (LxL/T).
$x, y$	: Cartesian coordinates (L).
$Z$	: True vertical coordinate, positive upwards (L).
$\alpha_{xx}, \alpha_{yy}$	: Dispersivities in the x - and y - directions (L).
$\mu$	: Fluid viscosity (M/LxT).
$\rho_0$	: Fluid density (M/LxLxL).
$\rho_s$	: Density of formation particles (M/LxLxL).