Prediction of Solute Transport from Gold Mine Wastes, Coromandel, New Zealand

By C. H. KIDD

GCNZ Consultants Ltd
PO Box 8441, Auckland 3, New Zealand

ABSTRACT

This paper describes a case history of using an integrated geochemical and hydrogeological approach to predicting solute transport from gold mine tailings in highly fractured volcanic terrain. Two modes of transport are identified, namely discrete fissure flow and diffuse seepage through the intervening weathered rock. A simple mass balance approach is used to predict concentrations at points of emergence because most of the seepage migration will be by way of the discrete fissures where advective transport will predominate. The mass balance method has been modified to allow for natural degradation of weak acid dissociable cyanide. The long term effects of diffuse seepage are also examined.

INTRODUCTION

The recent resurgence in the gold mining industry has focused exploration activity on the Coromandel Peninsula in the North Island of New Zealand. This area, which was extensively worked for gold and silver from the 1890's to the 1930's, is presently an important recreational area. Therefore, the community places a high value on the water resources and the local regulatory authorities have set stringent water quality criteria on receiving waters. These are generally based on the United States Environmental Protection Agency criteria to protect aquatic life.

It is necessary therefore, for the mine developers to demonstrate that seepage from the mining wastes, particularly the cyanided tailings, will not cause the receiving water quality criteria to be exceeded. Since there was no recent experience with gold mine tailings in the Coromandel or elsewhere in New Zealand, predictions of the impact of the tailings seepage on receiving water chemistry has had to rely on the results of laboratory geochemical studies and defensible methods of predicting solute transport.

Reliable prediction of solute transport is difficult at the new mine sites, because they are located in fractured volcanics, which are often crossed by faults that provide potential preferred flow paths for seepage migration. The approach taken at two of these new projects, namely the Martha Hill Mine and the Golden Cross Project, has been to use a simple mass balance method for calculating concentrations in springs and streams. The method takes into account natural degradation of cyanide and allowance has been made for attenuation processes accompanying diffuse transport in the weathered volcanics. The method is simple and can be understood by members of the public.

This paper illustrates this approach with reference to the Golden Cross Project.

GOLDEN CROSS PROJECT

The Golden Cross Project, which is being developed by Cyprus Gold (NZ) Ltd, is situated in the headwaters of the Waitekauri River,in the Coromandel Range about 9 km to the northwest of Waihi. The ore body is a classical epi-thermal deposit with quartz-calcite lode/stockwork type mineralisation associated with hydrothermally altered andesites of late Tertiary Age. It is planned to mine the stockwork zone by an open pit and the deeper feeder veins by underground methods. The mine will produce approximately 600,000 tonnes of tailings annually from a carbon-in-leach process. Most of the tailings will be deposited in a valley-fill type storage in the catchment of Union Stream located 750 m north of the open pit (Figure 1). The remainder will be placed in the open pit, which will be mined out three years before the underground operation is completed.

There are two main rock units at the site:- namely, the Older Andesite, or Coromandel Group, which is a hydrothermally altered andesite that hosts the mineralisation; and the Omahia Andesite, which is a dark non-mineralised andesite that partly overlies the mine area and underlies the Union Tailings Storage. The latter is generally highly weathered to a depth of about 20 m. Two prominent fault sets have been mapped, one which trends north-northeast and the other west-southwest. The locations of the faults with respect to the tailings impoundment are shown in Figure 1 and the subsurface relationship of the main geological units is shown schematically on Figure 2.

The Omahia Andesite averages about 100 m thick under the tailings storage. It is highly fractured, has an average hydraulic conductivity of 3×10^{-6} m/sec and is considered to be a significant local aquifer. Between 10% and 20% of the annual rainfall (2900 mm) recharges and circulates through this aquifer to discharge in numerous springs associated with the faults or the contact with the underlying Older Andesite. The hydrothermal alteration of the Older Andesite has filled many of the fissures with clay and its average hydraulic conductivity is about 1×10^{-8} m/sec. Very little water circulates through this unit. The quartz-calcite veins of the ore body are highly fractured and have an average hydraulic conductivity of about 5×10^{-5} m/sec. They will require continuous dewatering during the mining.

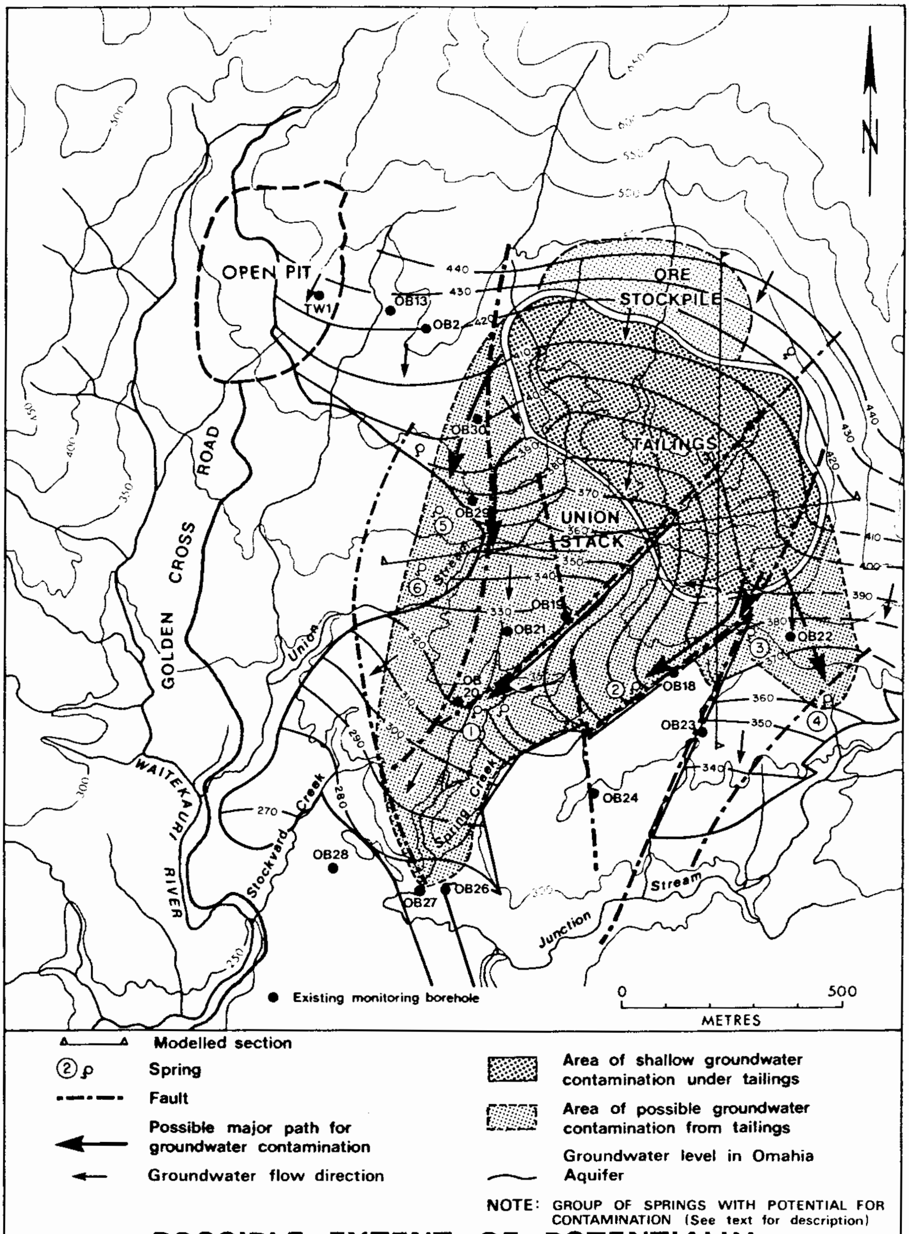
The potentiometric surface in the Omahia Andesite generally reflects the topography and groundwater flows in a southwesterly direction from the higher ground north of the tailings impoundment (Figure 1). There is evidence that there is a direct hydraulic connection under the southwest abutment via a series of faults between the Union Catchment and the adjoining Junction Catchment (Figure 1). The most prominent of these faults, trends from the southwest to the northeast through the center of the tailings storage; this is referred to as the Southwest fault.

A detailed description of the project can be found in the environmental impact report [1] and further information on the groundwater hydrology of the site is available in the technical appendix [2] which accompanies the EIR.

TAILINGS SEEPAGE

Laboratory testwork indicates that the Golden Cross Tailings will have a high clay content (40%) and that it will have an average hydraulic conductivity ranging from about 1×10^{-7} m/sec (when they are first deposited) to about 3×10^{-9} m/sec once they are consolidated. The seepage rate out the base of the tailings impoundment has been calculated to range between about 4 l/s and 14 l/s - most of which originates from the decant pond and the shallower, more permeable unconsolidated tailings around the periphery of the 23 ha impoundment. In the long term this rate should reduce to about 1 l/s as the tailings consolidate.

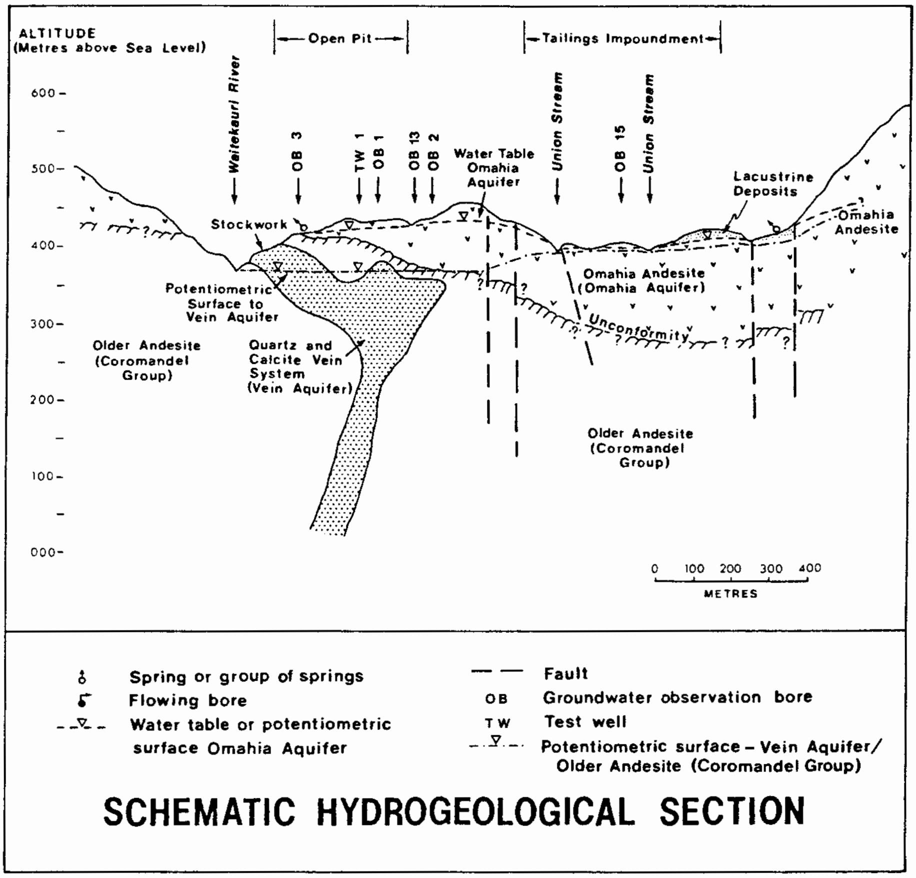
The chemistry of the tailings liquor and pore fluids, which are shown in Table 1, were determined from analysis of tailings samples prepared for metallurgical



POSSIBLE EXTENT OF POTENTIALLY CONTAMINATED GROUNDWATER AROUND UNION TAILINGS IMPOUNDMENT

GCNZ Consultants — Golden Cross Groundwater Hydrology FIGURE 1 testing and for evaluating tailings treatment processes. The estimated chemistry of the tailings pore fluids took into account the natural degradation of the weak acid dissociable cyanide (CN_{wad}) species within the tailings mass. This was determined by sealing samples of tailings in opaque containers and extracting samples of pore fluids for analysis at weekly intervals over a 12 week period [3].

The partitioning of the cyanide between the solids and the solute and the leaching characteristics of the tailings were examined by a column leaching study of unconsolidated tailings. This indicated that a substantial amount of the cyanide was either bound to the solid phase or trapped in dead-end pore spaces. Approximately 5 pore volumes had to be flushed through the tailings before the concentrations of cyanide and metals dropped significantly. This compares with 2 to 3 pore volumes observed in tailings with a low clay content [4].



Golden Cross Groundwater Hydrology Figure 2

TABLE 1 EXPECTED CHEMISTRY OF TAILINGS LIQUOR AND SEEPAGE [5] (results in g/m3 unless indicated)

Parameter	TAILINGS LIQUOR		TAILINGS SEEPAGE	
	Without AVR	With AVR	Without AVR	With AVR
pH	10-11	9.5-10	9.5-10	8.0-9.5
Hardness (CaCO3)	750	2000	-	2000
Alkalinity (CaCO3)	1000	200	300-500	-
Sodium	400	-	300-400	-
Calcium	200-300	-	300-600	800
Sulphate	1000	2500	1000-2000	2500
Cyanide (Total)	150-220	25-30	50	25-30
CN wad	150-220	5-10	20-30	1-5
Arsenic	<1	<1	2-5	1.5-2.0
Cadmium	<1	0.1	<0.005	<0.01
Chromium	<0.02	<0.02	0.002-0.02	<0.02
Cobalt	0.1	0.3	0.1-0.5	0.25
Copper	1-5	5-8	5-10	0.5-1.0
Iron	1-5	5-10	5	8-10
Lead	0.001-0.1	<0.1	<0.001	<0.1
Manganese	0.05-0.1	<0.02	0.03-0.05	<0.1
Mercury	0.001-0.009	<0.0001	0.001-0.005	<0.0001
Nickel	0.01	0.5	0.1-0.2	0.5
Selenium	0.01-0.4	0.1	<0.05	-
Zinc	0.5-3.0	0.01-0.1	2-4	0.1
SCN	30-40	30-40	-	-
EC dS/m	-	-	-	

not estimated

The low hydraulic conductivity of the tailings and the significant partitioning from the solute to the solids, both reflect the high clay content of the tailings. These properties combine to indicate that the seepage from the tailings mass will continue to have a quality similar to the estimated pore fluid chemistry (Table 1) for at least 50 years. As a consequence, the company investigated treating the tailings with either the acid volatilisation reneutralisation (AVR) or hydrogen peroxide processes. The AVR process successfully reduced concentrations of both cyanide and metals as shown in Table 1. This process is described in more detail in another paper at this congress [6].

POTENTIAL SEEPAGE MIGRATION PATHS

From an initial assessment of the hydrogeology of the Union catchment it was concluded that tailings seepage could escape the proposed impoundment via:-

- the western ridge (or abutment) and migrate southwards along a fault zone to emerge in springs above Union Stream
- the tailings retention embankment to emerge in the filter drain; the embankment will be constructed from waste rock with an upstream low permeability zone of compacted argillic waste ($1x10^{-9}$ m/sec).
- the underlying shallow Omahia from which it will migrate to the nearest fault to discharge into former natural water courses under the tailings.

- the southern ridge (or abutment) to emerge at one of several groups of springs mapped on the southern side of the ridge in the adjoining catchment of Junction Stream.
- the southwest fault system, to emerge in major springs in Spring Creek a tributary of Junction Stream.

PROPOSED ENGINEERING MEASURES TO MINIMISE SEEPAGE

Two vertical slice, steady-state, flow models of the tailings impoundment and adjoining areas were developed to examine the effectiveness of various engineering measures to control seepage. The modelling used a saturated-unsaturated, finite element modelling code known as TETFLOW [7]. The modelling indicated that by installing underdrains in the former water courses and by placing a blanket of low permeability (1 x 10^{-9} m/sec) material over the southern and western abutments of the tailings impoundments, the natural groundwater flow patterns would be maintained and no mounding would occur. Thus seepage from the tailings mass would follow the natural flow paths predominantly within the Omahia aquifer and emerge at existing well defined spring zones associated with faults or the contact between Omahia Andesite and the underlying Older Andesite. On this basis the possible extent of potentially contaminated groundwater was determined and is shown on Figure 1.

SOLUTE TRANSPORT

From consideration of the hydrogeology of the site two distinct modes of solute transport are likely to occur, namely discrete fissure flow, such as along the Southwest fault, and diffuse seepage through the weathered Omahia Andesite. The two types of flow are illustrated diagrammatically on Figure 3.

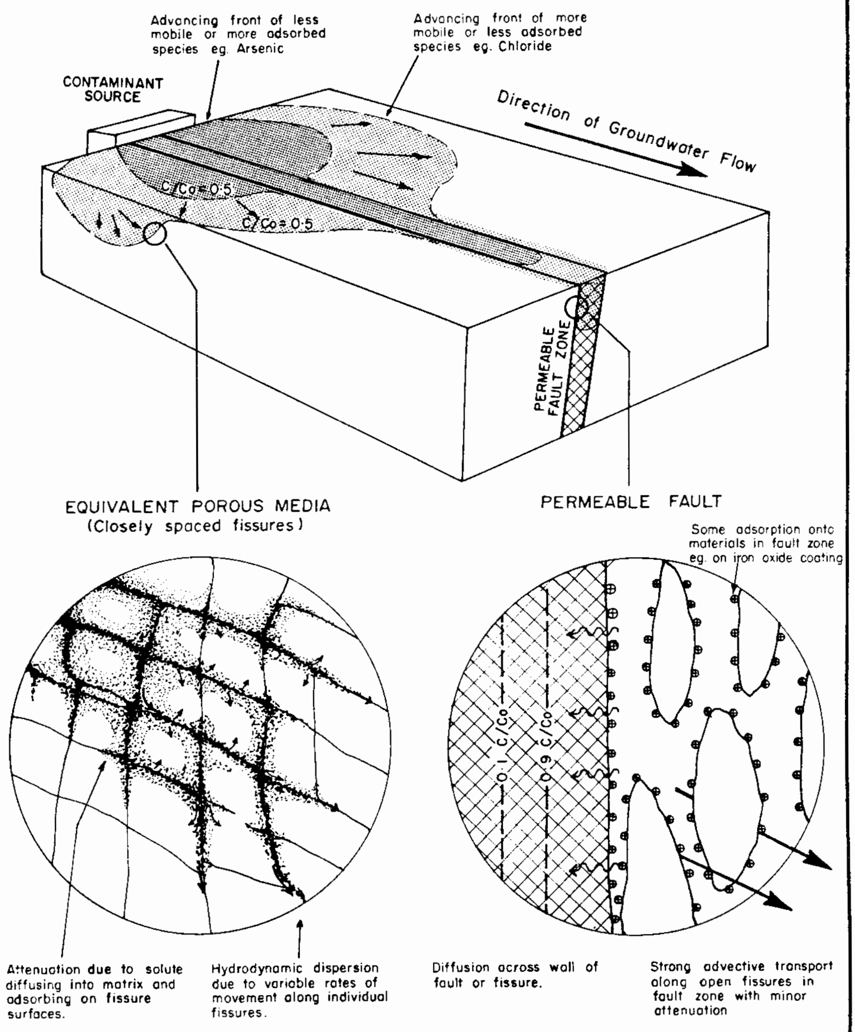
The discrete fissure flow is expected to be rapid with transit times ranging from 30 to 300 days. The transport will approximate plug flow with minor dispersion, except in the longitudinal direction, and little attenuation.

By comparison the diffuse seepage through the fissured and weathered Omahia Andesite will be at least an order of magnitude slower. Solutes will be subject to strong hydrodynamic dispersion and will be strongly attenuated due to solute diffusion into the matrix and adsorption onto the surfaces (Figure 3). The fissured Omahia Andesite will approximate an equivalent porous media and the standard advective-dispersive-sorption transport equation can be used to predict solute transport [8].

In view of the apparent dominance of fissure flow in the natural hydrological regime beneath at the Union Tailings Storage, simple advective transport, or plug flow, will provide a reasonable approximation, albeit slightly conservative, of the concentrations of chemical constituents emerging at the springs. Where simple advective or plug flow occurs, the concentrations of chemical constituents at the springs can be determined using a mass balance approach.

MASS BALANCE APPROACH

The mass balance approach to calculating the concentrations of chemical constituents at the points of groundwater emergence (springs) involves estimating the seepage rates for each of the five major potential subsurface flow paths identified earlier in the paper and shown diagrammatically on Figure 4. The mass balance approach assumes conservation of mass and dilution applies only at the point of emergence. The seepage rate along each flow path



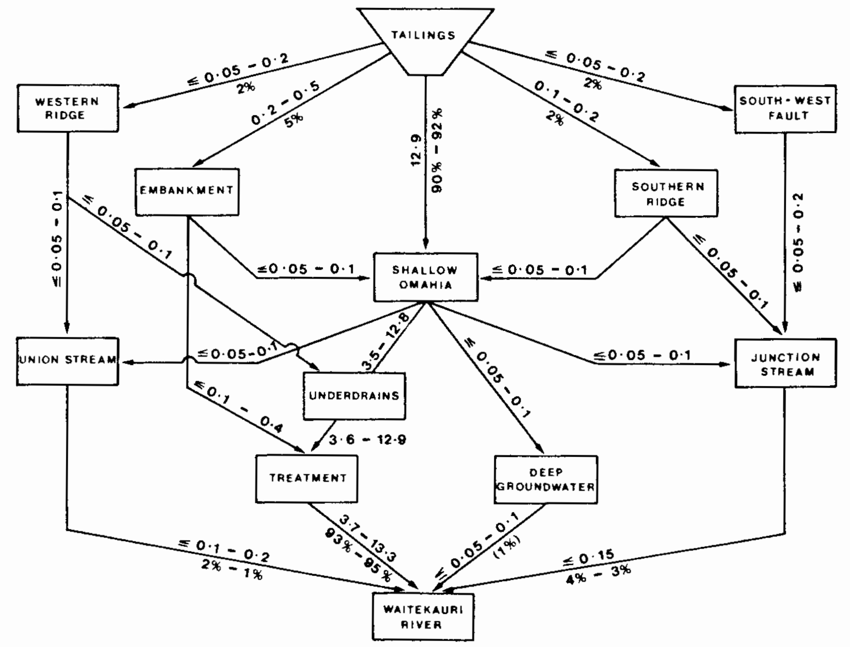
SOLUTE TRANSPORT PROCESSES IN FRACTURED ROCKS

GCNZ Consultants — Golden Cross Groundwater Hydrology FIGURE 3 was calculated using the Darcy equation and measured or assumed hydraulic parameters and gradients for the various materials along the flow path. Since the flow modelling indicated there would be little if any mounding under the tailings impoundment then the natural hydraulic gradients were used. The various seepage rates are expressed on Figure 4 as a flow in litres per second and as a percentage of the total seepage loss from the full tailings impoundment.

The concentrations at the springs were calculated using the following type of relationship

$$C = \frac{(C_T \times Q_T) + (C_s \times Q_s)}{Q_T + Q_s}$$

where C = concentration g/m^3)
C_T = concentration in tailings seepage (g/m^3)
Q_T = flow of tailings seepage entering the fissure (m^3/day)
C_s = natural concentration in spring water (g/m^3)
Q_s = natural range of spring flows (m^3/day)



SUBSURFACE FLOW PATHS AND SEEPAGE RATES
Litres per Second

FIGURE 4

The concentrations of sulphate and selected metals (present in the tailings seepage) estimated to emerge at the major spring fed by the Southwest fault (No 1, Figure 1) are given in Table 2.

TABLE 2 PREDICTED RANGE OF CONCENTRATIONS OF SELECTED METALS IN SPRING No 1 ASSOCIATED WITH THE SOUTHWEST FAULT

Metal	Spring Concentrations (g/m^3)		
	Minimum	Likely Value	Maximum
Arsenic	0.15	0.5	0.7
Copper	0.01	0.03	0.3
Iron	0.80	3.00	3.3
Nickel	0.05	0.1	<0.2
Zinc	0.01	0.02	<0.03

MODIFICATION FOR CYANIDE DEGRADATION

The mass balance approach can be applied for most major ions and for metals, but it over-estimates the concentration of weak acid dissociable cyanide (CN_{wad}). This is the form of cyanide of most concern to regulatory authorities since it degrades with time, to form toxic free cyanide (HCN). It is therefore, essential that a reliable estimate of its concentration is obtained. The degradation of CN_{wad} is related to changes of pH and temperature, and to the presence of HCN. The degradation follows an exponential decay relationship of the following form [9]

$$C = C_o e^{-kt}$$

where C = concentration at time t
C_o = initial concentration at t=0 (g/m^3)
k = degradation coefficient (hrs^{-1})
t = time since degradation commenced (hrs)

The degradation constant (k) for exposed tailings liquors is normally in the range 0.001 to 0.008 hrs^{-1} [9], but laboratory testing indicates the constant may be about one order of magnitude lower within the tailings mass itself [10]. The degradation constant for a particular tailings liquor will decrease with time if the solution contains copper, zinc, nickel and iron complexes. In the early phase copper and zinc, both readily dissociable will degrade first leaving the more stable nickel and iron complexes to dominate the later phases.

In the natural ground the pH of the tailings seepage is expected to decrease due to mixing with the groundwater and the natural buffering capacity of the weathered rock. Therefore, a degradation contant of 0.001 hrs^{-1} was used to estimate the change in CN_{wad} concentration for estimated groundwater travel times between the bottom of the tailings mass and the point of emergence. The resulting new CNwad concentration was input into the mass-balance relationship to estimate the concentration in the spring after mixing.

The predicted concentrations of CN_{wad} for each of the main spring zones is shown in Table 3 for AVR treated tailings.

TABLE 3 PREDICTED RANGE OF CNwad CONCENTRATIONS IN SPRINGS AROUND UNION TAILINGS STORAGE DURING TYPICAL SUMMER LOW FLOWS

Spring No*	Length of flow path (m)	Estimated Travel Times (days)	Concentrate of CNwad in Springs (g/m^3) Minimum $C_0 = 1 g/m^3$	Likely Range $C_0 = 1 g/m^3$	Maximum $C_0 = 5 g/m^3$
1	650	34-340	<0.01	0.05-0.15	<0.75
2	400	200-2300	<0.01	<0.01	<0.01
3	150	43-430	<0.01	0.04-0.12	<0.60
4	350	65-650	<0.01	0.02-0.07	<0.35
5	400	83-830	<0.01	0.02-0.05	<0.25
6	350	60-600	<0.01	0.02-0.08	<0.04

* Refer to Figure 1 for location of springs.

EFFECTS OF DIFFUSE SEEPAGE

The main effect of attenuation during diffuse seepage through the weathered Omahia Andesite is to strongly retard the movement of chemical fronts for various metal species and hence, delay their arrival at the springs. However, since laboratory attenuation studies indicated that about 70 to 80% of the materials adsorbed by the weathered Omahia Andesite is irreversibly held on the solids, it is possible that some of the more strongly attenuated metals, e.g.arsenic) might never reach the points of emergence.

A method developed by Griffin and others [11] was used to calculate the length of flow path required for adsorption to reduce the concentrations of selected chemical species in tailings seepage to the proposed water quality criteria. This method involves firstly determining the soil-effluent ratio, which is the weight of material (soil) required to reduce the concentrations of various chemical species in a unit volume of tailings seepage to a desired level, using a sequential batch reactor. The distance travelled is calculated by multiplying the soil-effluent ratio by the seepage flux and the period of time required to totally leach pore fluids and then dividing this by the soil bulk density. In view of the fissured nature of the weathered Omahia, the results were also divided by the estimated bulk porosity (0.05 to 0.1). This gives a conservative estimate of the lengths of flow path required to fully attenuate the solute as it does not allow for dilution and dispersion.

The calculated attenuation distances for various metals are shown in Table 4. Compared with the estimated length of the various flow paths it is evident that the diffuse seepage may eventually arrive at most of the springs.

However, using retardation factors estimated from the sequential batch reactor test results, the front for strongly attenuated species such as arsenic could take thousands of years to arrive at the springs, by which time the load from discrete fissure flow should be reduced dramatically. Thus, while the diffuse seepage may arrive much later than the discrete flow, it should not greatly increase the overall loading on the streams because the concentrations in the much larger discrete flows should be substantially reduced by this time.

TABLE 4 ESTIMATED TRAVEL DISTANCES IN WEATHERED OMAHIA ANDESITE BEFORE METAL CONCENTRATIONS ARE REDUCED TO RECEIVING WATER CRITERIA

Metal	Travel Distance (metres) Minimum	Maximum
Arsenic	40	180
Copper	80	400
Iron	160	800
Nickel	260	1300
Zinc	160	800

CONCLUSIONS

In a complex fractured rock environment such as at Golden Cross it is difficult to develop a defensible numerical solute transport model based on measured in-situ dispersion parameters, particularly where there is no full scale operational experience with which to calibrate the model. In these circumstances a defensible prediction of the impact of a proposed tailings storage on water quality can be made using an integrated geochemical and hydrogeological approach based on mass balance methods. However, for gold projects using cyanide leaching this method needs to be modified to account for the natural degradation of weak acid dissociable cyanide. The effects of diffuse seepage in weathered rock zones can also be assessed using simple manual methods.

REFERENCES

1. Cyprus Minerals (NZ) Ltd, 1987, Golden Cross Mining Project Environmental Impact Report.

2. GCNZ Consultants Ltd, 1987a, Golden Cross Mining Project, Groundwater Hydrology, E.I.R. Technical Report Series, No 7.

3. GCNZ Consultants Ltd and Stuart Miller & Associates Pty Ltd, 1987a, Golden Cross Mining Project, Geochemical Evaluation and Leaching Behaviour of Waste Rock and Tailings, E.I.R. Technical Report Series No 4.

4. GCNZ Consultants Ltd, 1988, Macraes Gold Mine Project, Water and Waste Management, E.I.A. Volume 2, Appendix 1.

5. Miller, Stuart, Technical Evidence Presented at Water Right Hearings for Golden Cross Mining Project, May 1988.

6. Williams M.P.A. & Goldstone A., 1988, Water Management and Water Treatment at Golden Cross, Proc. of the Third Int. Mine Water Congress, Melbourne.

7. Kalf, F.R., 1987, A Model for Three Dimensional Seepage Face Problems, Proc. Hydraulics in Civil Engineering Conf., Institute of Engineers, Australia.

8. Freeze, A. & Cheery, J., 1979, Groundwater, Prentice-Hall Inc.

9. Schmidt, J.W., Simovic, L. & Shannon, E., 1981, Natural Degradation of Cyanide Gold Milling Effluents. Proc. of Seminar "Cyanide in the Gold Mining Industry", Ontario, Canada.

10. Burden, R.J. & Kidd C.H., 1987, The Environmental Fate of Cyanide in Gold Process Tailings, Proc. of Annual Conf., Aust. Inst. of Mining and Metallurgy, Nelson, New Zealand.

11. Griffin, R, Schuller, R., Suloway J., Shimp, N., Childers, W., Ashley, R., 1980, Chemical and Biological Characterisation of Leachates from Coal Solid Wastes, Environ. Geology Notes No 89, Illinois State Geological Survey.