NABARLEK PIT DECOMMISSIONING

MIGRATION OF SULPHATE, NITRATE AND RADION IONS IN GROUNDWATER - PRELIMINARY MODELLING

"WORKING DISCUSSION PAPER"
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S Appleyard
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1. INTRODUCTION

1.1 Objectives of the Modelling Exercise

The Nabarlek mine pit contains water which has high concentrations of the ions calcium, magnesium, ammonium, radium, sulphate and nitrate, and high levels of manganese. Queensland Mines Limited have requested that their authorisation be amended such that the water level in the pit be allowed to rise to RL 70m, a level where groundwater outflows from the pit will take place. It is envisaged that this high pit water level will be maintained for a period of four years, after which time water will be removed and the pit will be rehabilitated. This discussion paper will examine the possible impact of contaminants in groundwater outflows from the pit on Cooper Creek which is situated about 1 km to the south-east.

1.2 Identification of Major Pollutants

Fresh and weathered rock possess a natural capacity to remove many cations from solution through the processes of irreversible adsorption and ion exchange. Observations from uranium mines in America (see e.g. Rouse and Williams, 1983) have indicated that heavy metals and ammonium ion are totally removed from seeping mine waste water within a few metres of the seepage source, and this is also expected to be the case for water discharging from the Nabarlek pit. The major pollutants that will reach Cooper Creek are those that will not be adsorbed by mineral surfaces. The most important pollutants reaching Cooper Creek are therefore expected to be the anions nitrate and sulphate. Another possible contaminant that could reach Cooper Creek is radium ion; radium is extremely toxic in low concentrations and can be concentrated to a large extent by organisms such as freshwater shellfish.
2. HYDROGEOLOGICAL SETTING OF THE NABARLEK PIT

Mineralisation at Nabarlek is hosted within a sequence of Proterozoic micaceous and chloritic schists (the Nourlangie Schist) adjacent to a large differentiated dolerite sill (the Oenpelli Dolerite) (Anthony, 1975). The transmissivity of rock near the pit lies in the range 0.1 to 10 m$^3$/day/m, whereas schistose rock 500m to the south east of the pit has a transmissivity in excess of 100 m$^3$/day/m. Recent geological evidence (Noakes, Q.M.L., pers. comm 1984) suggests that the low transmissivities close to the pit are due to the presence of a well developed chlorite alteration halo that encircled the original orebody. The approximate boundary of this low transmissivity zone is shown in a schematic cross section (Fig 2.1).

The main aquifer in the area between Cooper Creek and the Nabarlek pit consists of fracture zones within schistose rocks. Most water is found in partially weathered schist (10 to 20m thickness) and this is overlain by a 10m thick confining layer of clay (Fig 2.1).

If the pit water level is raised to RL 70m, groundwater outflow will possibly occur at a rate of 35 m$^3$/day (AGC, 1984) and pore water velocities are expected to be in the range 0.02 - 0.6 m/day. The great range in estimated pore water velocities is due to the fact that the extent to which a hydraulic connection between the chlorite halo and surrounding rock exists is not known. Geophysical and pump testing work will be carried out by ABC to try to resolve this problem.
3. LONG TERM MODEL FOR RADIIUM

3.1 Development of an Analytical Solution

Groundwater movement near the pit at Nabarlek takes place within discrete fractures in schistose rocks. These fractures can be envisaged as consisting of an indeterminate number of tubes which connect a source of pollution (the pit) to a discharge point (Cooper Creek). Water enters these tubes containing high concentrations of radium, and radium is progressively lost by rock adsorption and radioactive decay with distance along each tube. The question is, what will the radium concentration in groundwater be as a function of time and distance from the pit, and will significant levels of radium be discharged into Cooper Creek?

To simplify the solution to this problem, all water leaving the pit will be considered to pass through a single tube.

Consider a single tube:

\[
P \quad Q
\]

\[
G \rightarrow \frac{dV}{y \quad y+dy}
\]

A given concentration flow rate, \( G \), of radium enters the groundwater flow tube from the pit. At point \( P \), fraction \( y \) of radium has been lost from solution by adsorption and radioactive decay. After a small volume increment, \( dV \), fraction \( y+dy \) of radium has been lost from solution. If \( r \) is the rate at which radium ions are lost from solution per unit volume increment, then
under steady state conditions the following mass balance results for the volume contained between points P and Q:

radium lost up to point Q = radium lost at P + radium lost in \( dV \).

ie. \( G(y+dy) = Gy + rdV \)

ie. \( rdV = Gdy \)

\( V = \int_{0}^{1} dy \)

ie. \( V = G \int_{y}^{1} dy \)  \hspace{1cm} (1)

The volume of tube required to remove fraction \( X \) of the original radium is given by:

\( V = G \int_{y}^{1} dy \)  \hspace{1cm} (2)

The sorption of radium is a first order rate process. The term \( r \) can also incorporate radioactive decay, since this is also a first order rate process.

ie. \( r = k [Ra] \)  \hspace{1cm} (3)

where \( k \) = a combined rate constant for the adsorption and decay of radium

\([Ra]=\) concentration of radium in solution

Rearranging:

\( r = k (1-y) \)  \hspace{1cm} (4)

Substituting into (2):

\( V = G \int_{y}^{1} \frac{dy}{1-y} \)

ie. \( \ln \frac{1}{1-X} = \frac{Vk}{G} \)  \hspace{1cm} (5)
If the cross sectional area, $A$, of each fracture is known, concentrations of radium can be determined as a function of length, $l$, along a given fracture:

\[
\ln \frac{1}{1-X} = k A \frac{G}{l} \tag{6}
\]

The amount of radium remaining in solution, $C$, is related to the fraction adsorbed, $X$, by:

\[
\frac{C}{C_0} = 1-X \tag{7}
\]

Substituting into (6):

\[
\ln \frac{C}{C_0} = k A \frac{G}{l} \tag{8}
\]

where $k$, $A$ and $G$ are constants that have to be estimated here. Australian Groundwater Consultants (1984) have estimated that the maximum seepage rate from the pit will be of the order of 35 m$^3$/day. Radium concentrations in pit water at this time will be in the order of 100 Bq/L. Therefore, the radium flux, $G$, for the model is given by:

\[
G = 100 \text{ Bq/L} \times 1000 \text{ L/m}^3 \times 35 \text{ m}^3/\text{day} = 3.5 \times 10^6 \text{ Bq/day}
\]

Darcy's Law can be expressed as:

\[
Q = vA \tag{9}
\]

where $Q$ = discharge volume

$v$ = pore water velocity

$A$ = cross sectional area

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AGC (1984) estimated that groundwater velocities out of the pit are likely to be in the range 0.02 to 0.6 m/day. Assuming a discharge volume of 35 m$^3$/day, gives values of ranging from 60 m$^2$ to 2000 m$^2$ for the tube in the model.

The constant which is subject to the greatest uncertainty is the combined rate constant, $k$. This was determined by fitting a curve to the observed distribution of radium concentrations in groundwater near the pit. The Nabarlek orebody acted as a source of radionuclides for millions of years prior to mining, and so the distribution of radium in groundwater near the pit should have attained a state of equilibrium with aquifer host rocks. This equilibrium state should still exist in groundwater here despite the fact that the orebody has been removed, because of the slow nature of groundwater-rock interactions. Values of $C/C_0$ for several bores as a function of distance from the pit are plotted in Fig 3.1, where:

where $C =$ long term average radium concentration in the bore

$C_0 =$ concentration of radium in the original orebody, or about 1 to 2 Bq/L (see AGC, 1984)

The curve of best fit has a value for the combined constant (incorporates $k$, $A$ and $G$) of $3 \times 10^{-2}$. Assuming values for $A$ and $G$ derived above gives values for $k$ in the range 50 to 2000 Bq day/m$^3$.

3.2 Sensitivity Analysis

Since equation (8) contains three constant terms which are not accurately known, it is necessary to carry out a sensitivity analysis to test the effect of varying one
or more of these parameters. If the curve shown in Fig 3.1 is assumed, the value of the ratio \( C/C_0 \) is about \( 10^{-13} \), which is equivalent to a discharge concentration of radium in Cooper Creek of about \( 10^{-13} \text{ Bq/L} \).

The above ratio applies only as \( t \to \infty \), i.e. radium is given ample time to reach the creek. If the flow rate is increased by an order of magnitude or if the rate constant or cross-sectional area is decreased by an order of magnitude, the value of the ratio \( C/C_0 \) will be approximately 0.1, i.e. the discharge concentration of radium in Cooper Creek will be one tenth that contained in the pit after rehabilitation. Similarly, if the flow rate of radium ions is decreased by an order of magnitude, or if the cross sectional area or rate constant is increased by an order of magnitude, effectively no radium will reach Cooper Creek. The family of curves that result if the bulked constant term, \( K \), is varied by an order of magnitude is shown in Fig 3.2.

The terms \( G \), \( A \) and \( k \) in equation (6) are all imprecisely known largely because of lack of detailed knowledge about the degree to which a hydraulic connection exists between poorly transmissive rock near the pit and highly transmissive rock to the south-east. Geophysical work test pumping will be carried out in the area to the south east of the pit by AGC this year, and data obtained from these studies may lead to better estimates of fracture density in this area, which in turn will lead to better estimates of the terms \( k \), \( A \) and \( G \) being made. However, it must be stressed again that the above analytical solution was derived for \( t = \infty \). AGC (1984) laboratory tests place the groundwater velocity of radium ions at Nabarlek in the range \( 5 \times 10^{-6} \) to \( 2 \times 10^{-7} \text{ m/s} \), which suggests that \( Ra \) will not appear at Cooper Creek for about \( 5 \times 10^5 \) years.
4. FINITE ELEMENT MODELLING

Due to a lack of hydraulic data for the fractured rock aquifer near the pit, finite element modelling was only carried out on a highly transmissive zone some 350m to the South east of the pit. Modelling was carried out on a 1150 x 600 m² consisting of 276 elements, each of dimensions 50 x 50 m² (Fig 2.1). Standing water level data in this area indicate that the hydraulic gradient here is very low (<2x10⁻³) and so initial potentiometric levels in the model were set to zero. Cooper Creek was represented as a line of nodes with fixed potentiometric heads (Om) and seepage at a rate of 35 m³/day (A.G.C., 1984) was assumed to be evenly distributed across five nodes. Pump testing in the area has indicated that the aquifer in this highly transmissive zone is confined and isotropic in nature. A value of 140 m³/day/m is assumed for transmissivity and storativity is assumed to be 8 x 10⁻⁴. Modelling was carried out using the finite element programme SEFTRAN.

Potentiometric contours for the model after 273 days of seepage are shown in Fig 2.2. The model assumes no vertical recharge, and so the time period above was selected to give a stable solution which would represent the groundwater potentiometric surface after a single dry season of seepage.

The average pore water velocity of groundwater moving towards the creek after 273 days of seepage was 0.03 m/day, and if water consistently flowed at this rate it would take approximately 55 years for conservative solutes (such as sulphate ions) to travel across the gridded area. The extent of a hypothetical seepage plume 273 days after seepage is first detected in the modelled area is shown in Fig 4.3. Note that this is not the time elapsed since seepage from the pit commenced; AGC (1984) estimated groundwater velocities near the pit to be in the range 0.02 to 0.6 m/day, and so seepage from the pit would take from 1 to 34 years to reach the modelled area.

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The model described above assumed that groundwater velocities prior to seepage commencing were zero. This is not the case, so actual groundwater velocities are likely to be higher than that calculated above. The probable upper limit for groundwater flow rates towards the creek in the highly transmissive zone, is the AGC (1984) estimate of 2m/day. The maximum extent of a groundwater seepage plume at $t = 273$ days assuming $v = 2m/day$ is also shown in Fig 4.3.
5. ESTIMATES OF NITRATE AND SULPHATE LOADS IN COOPER CREEK

Unlike the situation for radium, sulphate and nitrate ions are not adsorbed by mineral surfaces to a significant extent and so the transport velocities of these ions are much higher than for Ra. Sulphate and nitrate ions probably move at the same rate as groundwater here. AGC (1984) have estimated that 35 m$^3$/day of water will seep from the pit during rehabilitation, and that groundwater will have a velocity of about 0.02 - 0.6 m/day to the south east. Therefore, the time required for sulphate and nitrate ions to reach Cooper Creek via groundwater transport from the pit will be in the order of 5-140 years.

In order to assess the effect of nitrate and sulphate ions seeping into Cooper Creek from the pit, background levels of these ions in Cooper must be known. Total loads of nitrogen (nitrate, nitrite ammonia and organic nitrogen) and sulphate in loads for the wet seasons between 1978 and 1981 are tabulated below, together with loads carried in the first month of flow.

<table>
<thead>
<tr>
<th>WET SEASON</th>
<th>FIRST MONTH</th>
<th>WHOLE SEASON</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TOTAL N (x10^3 Kg)</td>
<td>SULPHATE (x10^3 Kg)</td>
</tr>
<tr>
<td>1978/79</td>
<td>0.34</td>
<td>1.75</td>
</tr>
<tr>
<td>1979/80</td>
<td>2.84</td>
<td>16.3</td>
</tr>
<tr>
<td>1980/81</td>
<td>0.73</td>
<td>10.42</td>
</tr>
</tbody>
</table>

The greatest impact that water seeping from the pit could have on Cooper Creek, would be if evaporation during the dry season concentrated soluble nitrate and sulphate salts in creek sediments which were then flushed out in the first flow of the subsequent wet season.

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The concentration of nitrate ion could lie in the range 250-500 mg/L and sulphate ion in the range 9000-18000 mg/L during the rehabilitation if the pit. Assuming that water seeps from the pit at a rate of 35 m³/day and that water reaching Cooper Creek is evaporated for a period of seven months in the dry season then the total nitrate load deposited in Cooper Creek sediments as soluble salts is given by:

$$\text{NO}_3^- = 217 \text{ days} \times 35000 \text{ L/day} \times (250-500) \text{ mg/L}$$

$$= 1.90 \times 10^3 - 3.80 \times 10^3 \text{ Kg}$$

Converting to an equivalent nitrogen load:

$$\text{Total N} = (1.90 \times 10^3 - 3.80 \times 10^3) \times 14 \text{ Kg}$$

$$= 430 \text{ Kg} - 860 \text{ Kg}$$

Similarly for sulphate ion:

$$\text{SO}_4^{2-} = (9000-18000) \text{ mg/L} \times 35000 \text{ L/day} \times 217 \text{ days}$$

$$= 70 \times 10^3 \text{ Kg} - 140 \times 10^3 \text{ Kg}$$

A comparison of these results with total nitrogen and sulphate ion loads normally carried by Cooper Creek indicates that in a single dry season enough sulphate could accumulate in Cooper Creek sediments to equal the load normally carried by the creek in a year. Total nitrogen levels, by contrast, are much lower but are comparable with levels carried in the first month that Cooper Creek flows each wet season.

The above estimates for nitrate and sulphate ion loadings are probably much higher than will actually be observed in Cooper Creek for two main reasons:
(i) Most sulphate and nitrate ions will be discharged from the pit in one four-year pulse. Concentrations of these ions will be attenuated by dispersion before seepage water reaches this creek.

(ii) Large quantities of nitrate ions will probably be taken up by vegetation when the water table approaches the ground surface near Cooper Creek.

5.1 Concentration Distributions for Nitrate and Sulphate Ions

Solute transport in groundwater occurs due to the combined effects of convection (viscous movement of groundwater), diffusion (thermal motion of the solute within the water) and mechanical dispersion (solute mixing due to pore water velocity distributions). In an isotropic porous medium, one dimensional solute transport as a function of both time and space can be described by the expression:

$$\frac{D}{\partial x^2} \frac{\partial C}{\partial t} - \frac{\partial C}{\partial x} = \mu C - \gamma \quad (1)$$

(Van Genuchten, 1981)

where

- $D =$ dispersion coefficient ($L^2T^{-1}$)
- $C =$ solute concentration ($ML^{-3}$)
- $x =$ distance ($L$)
- $t =$ time ($T$)
- $v =$ pore water velocity ($LT^{-1}$)
- $R =$ retardation factor, a measure of the degree to which a solute is held by sorption processes
- $\mu, \gamma =$ rate constants ($T^{-1}$), ($ML^{-3}T^{-1}$)
During the remaining life of the Nabarlek mine, pit
water levels will be 10m higher than present levels, and
this will cause groundwater outflows from the pit to
take place. The duration of this initial seepage pulse
will be four years, as after this time water will be
pumped out of the pit as part of the mine rehabilitation
procedures.

An analytical solution to describe the motion of a
seepage pulse in an isotropic porous medium is given by
Van Genuchten (1981):

\[
C(x,t) = \begin{cases} 
C_0 A(x,t) + C_i Q(t) - C_i G(x,t) & 0 \leq t \leq t_o \\
C_0 A(x,t) + C_i Q(t) - C_i G(x,t) - C_0(x,t-t_o) & t > t_o 
\end{cases}
\]

where \(C(x,t)\) = concentration of a solute as a function
of time and space

\(C_0\) = initial concentration
\(C_i\) = background concentration in groundwater
\(t_o\) = duration of seepage pulse (assumed to
be 4 years here).

\(A(x,t), G(x,t), Q(t)\) are functions (see Appendix A).

An important parameter which has to be input into this
solute transport equation is a dispersion coefficient.
This was determined by assuming that the dispersion
coefficient for the fractured rock aquifer near the
water management ponds also applies to the area to the
south east of the pit. Seepage from the water
management ponds occurred in 1982 and 1983 and
breakthrough curves for sulphate ion at various times
(assuming the SPROP to be the seepage source) are shown
in Fig 5.1.
The longitudinal dispersion coefficient can be determined from a breakthrough curve by the expression (Fried, 1975):

\[ D_L = \left[ \frac{(x_{0.16} - x_{0.84})^2}{8t} \right] \]

where:
- \( D_L \) = longitudinal dispersion coefficient (m²/day)
- \( x_{0.16} \) = distance when \( C/C_0 = 0.16 \) (m)
- \( x_{0.84} \) = distance when \( C/C_0 = 0.84 \) (m)
- \( t \) = time (days)

For the breakthrough curve in Fig 5.1:

- \( x_{0.16} = 25 \) m
- \( x_{0.84} = 1 \) m
- \( t = 250 \) to \( 465 \) days (Treloar, 1982)

Assuming these values gives a dispersion coefficient in the range 0.15 to 0.3 m²/day. An average value of 0.2 m²/day is assumed to apply to the highly transmissive zone to the south east of the pit. The first order decay constant, \( \mu \), was assumed to be negligibly small.

Breakthrough curves for conservative ions (apply to both nitrate and sulphate ions) under a variety of groundwater flow conditions are shown in Fig 5.2 (a) to (c). If the groundwater velocity derived from the finite element model (0.03 m/day) is assumed, then the concentration distributions in Fig 5.2 (a) result. One year after a seepage plume containing sulphate and nitrate ions enters the highly transmissive zone, the boundary between seepage water and natural groundwater will still be clearly defined. The seepage pulse will take about 55 years to cross the highly transmissive zone and reach Cooper Creek, by which time maximum concentrations of sulphate and nitrate ions will be about 20% of initial values (at first entry into the highly transmissive zone, not from the pit).
If the groundwater velocity towards Cooper Creek is increased by a factor of ten (Fig 5.2(b)), a seepage pulse will take about 5.5 years to reach Cooper Creek and the seepage pulse will be much more clearly defined, having a width in the order of 200m. Maximum concentrations of sulphate and nitrate ions with about half of their initial values. At a groundwater velocity of 2m/day towards Cooper Creek, a seepage pulse from the pit will reach the creek in about 300 days as an unattenuated slug (Fig 5.2(c)).

Water levels in the Nabarlek mine pit will be raised above the present water level for a period of four years, after which time water will be pumped out to allow the pit to be rehabilitated. However, some time after rehabilitation of the pit is completed, groundwater throughflow will occur in this area and any remaining solutes in the pit will be subject to leaching. Breakthrough curves for nitrate and sulphate ions under these conditions will resemble that shown in Figure 5.2(c), except that seepage will be a continuous process, rather than lasting for four years. However, concentrations of these ions in the pit after rehabilitation will be much lower than at present, and so seepage in the long term will have a much lesser impact on Cooper Creek than seepage taking place in the near future.

5.2 Revised Estimates of Dry Season Nitrate and Sulphate Loads

Nitrate and sulphate loads can now be re-estimated in the light of the breakthrough curves described above.

A large unknown factor in estimating solute loads reaching Cooper Creek, is what values should be ascribed to initial sulphate and nitrate ion concentrations when...
seepage water reaches the highly transmissive zone to the south east of the pit. Diffusion and dispersion processes will reduce concentrations of sulphate and nitrate ions between the pit and this area. As a first approximation, it will be assumed that this effect is negligible and that initial nitrate ion concentrations lie in the range 250 - 500 g/m³ and initial sulphate ion concentrations lie in the range 9000 - 18000 g/m³. Sulphate and nitrate ion loads reaching Cooper Creek in a single dry season vary with groundwater velocity are equal to:

\[ L = A L_T \]

where

- \( L \) = dry season load of \( \text{NO}_3^- \) or \( \text{SO}_4^{2-} \)
- \( A \) = area under breakthrough curve for a time period corresponding to a dry season (assumed 200 days)
- \( L_T \) = non-dispersed dry season load of \( \text{NO}_3^- \) or \( \text{SO}_4^{2-} \)

At groundwater velocities of about 2m/day, dispersion is unimportant, and so nitrate and sulphate loads are as previously calculated, ie:

- Nitrate ion load (expressed as N) = 430 to 860 kg
- Sulphate ion load = \( 7.0 \times 10^4 \) kg to \( 1.40 \times 10^5 \) kg

However, if a velocity of 0.03 m/day is assumed, the situation is quite different. The breakthrough curve shown in Fig 3.2(a) is a normal distribution curve with a standard deviation equal to

\[ \sigma = (2 D_L t)^{1/2} \]  
(Fried, 1975)

\( t \) = arrival time at Cooper Creek = \( 2 \times 10^4 \) days

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and a mean at a distance of 600m. In 200 days, water will travel 6m at this velocity, and this corresponds to an area of 0.03. Solute loads are therefore:

Nitrate ion load (expressed as N) = 13 to 26 kg
Sulphate ion load = $2.1 \times 10^3$ to $4.20 \times 10^3$ kg

Although these loads are substantially lower than the non-dispersed case, sulphate levels are still significant in terms of first flush loads in Cooper Creek.
6. DISCUSSION

The above calculations suggest that the ion most likely to reach Cooper Creek at high levels in water seeping from the pit is sulphate ion. The greatest impact that sulphate ion could have on the Cooper Creek ecosystem would be if this anion was precipitated in creek sediments in soluble salts (probably as MgSO$_4$.7H$_2$O), and then redissolved in first flush waters. Sulphate ion is non-toxic, but high concentrations of this ion will increase the total dissolved salt load of a given water, and high TDS levels can interfere with fish breeding patterns, kill young waterfowl and wither plants (Train, 1979).

The U.S. Environmental Protection Agency recommend that TDS levels in water of the composition of Cooper Creek water (TDS = 10-50 mg/L) should not vary by more than 10% from the natural salinity range. At very low groundwater flow rates (i.e. dispersion of sulphate ion in groundwater is important), TDS level increases in first flush flows will be negligible. However, if groundwater flow is rapid and dispersion of sulphate ion in groundwater between the pit and Cooper Creek is negligible, then high TDS levels will occur in first flush flows in this creek for at least a four year period. A more accurate assessment of the impact of SO$_4^{2-}$ from pit seepage water on Cooper Creek cannot be made without more detailed knowledge of the nature of groundwater flow between the pit and Cooper Creek.
7. CONCLUSIONS

1. Preliminary modelling suggests that the long term radium distribution around the pit after rehabilitation will be similar to that already established in groundwater as a result of leaching of the original ore body. The arrival time for radium ions at Cooper Creek will be in the order of $5 \times 10^5$ years after rehabilitation.

2. Estimates of sulphate ion loads discharging into Cooper Creek neglecting dispersion are comparable with loads carried by this creek in a wet season. If a groundwater velocity of 0.03 m/day is assumed, groundwater will take approximately 90 years to reach Cooper Creek from the pit and dispersion will substantially reduce dry season loads of this ion. However, loading of $SO_4^{2-}$ will still be comparable with some first flush loadings for this ion in Cooper Creek.

3. Nitrate ion loads reaching Cooper Creek will only be comparable with first flush loads if dispersion is negligible. Dispersion of this ion in groundwater and uptake by plants are expected to substantially reduce the amount of nitrate ion that reaches Cooper Creek.

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REFERENCES


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APPENDIX A

SOLUTE TRANSPORT EQUATIONS

The concentration of a seepage pulse in an isotropic, porous medium varies with time and space according to the set of equations:

\[
C(x, t) = \begin{cases} 
C_0 A(x, t) + C_1 Q(t) - C_2 G(x, t) & 0 < t < t_0 \\
C_0 A(x, t) + C_1 Q(t) - C_2 G(x, t) - C_0 A(x, t-t_0) & t > t_0
\end{cases}
\]

(Van Genuchten, 1981)

The background sulphate and nitrate ion concentrations in groundwater at Nabarlek (C_j) were assumed to be zero. This equation set can then be simplified

\[
C(x, t) = \begin{cases} 
C_0 A(x, t) & 0 < t < t_0 \\
C_0 A(x, t) - C_0 A(x, t-t_0) & t > t_0
\end{cases}
\]

where \( A(x, t) \) is defined as:

\[
A(x, t) = \frac{r}{(r + u)} \exp \left[ \frac{r - u}{2D} \right] \text{erfc} \left[ \frac{Rx - ut}{2(DR^2)^{1/2}} \right] + \frac{r}{(r + u)} \exp \left[ \frac{r + u}{2D} \right] \text{erf} \left[ \frac{Rx + ut}{2(DR^2)^{1/2}} \right] 
\]

and \( u = \nu (1 + 4 \nu D/\nu^2)^{1/2} \).

The terms used in this expression are set out below:

<table>
<thead>
<tr>
<th>Terms</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_0 )</td>
<td>Initial concentration</td>
</tr>
<tr>
<td>( D )</td>
<td>Dispersion coefficient</td>
</tr>
<tr>
<td>( R )</td>
<td>Retardation factor</td>
</tr>
<tr>
<td>( t )</td>
<td>time</td>
</tr>
<tr>
<td>( u )</td>
<td>( \nu [1 + 4 \nu D/\nu^2]^{1/2} )</td>
</tr>
<tr>
<td>( \nu )</td>
<td>Pore water velocity</td>
</tr>
<tr>
<td>( x )</td>
<td>Distance</td>
</tr>
<tr>
<td>( \mu )</td>
<td>General first order decay constant</td>
</tr>
<tr>
<td>SA2/11:TJ</td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX B: COMPLEMENTARY ERROR FUNCTION (erfc)

\[
\text{erf}(\beta) = \frac{2}{\sqrt{\pi}} \int_{0}^{\beta} e^{-t^2} \, dt
\]

\[
\text{erf}(-\beta) = -\text{erf} \beta
\]

\[
\text{erfc}(\beta) = 1 - \text{erf}(\beta)
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CURVE OF BEST FIT TO THE OBSERVED DISTRIBUTION OF RADIUM concentrations
FAMILY OF CURVES THAT RESULT FROM VARYING $k = \frac{KA}{G}$ BY AN ORDER OF MAGNITUDE WHERE $K_0 = 3 \times 10^{-2}$
FINITE ELEMENT GRID
USED IN MODEL

Fig. 4.1
MODELLED HEADS AFTER 273 DAYS

SEEPAGE = 35 m³/day
TRANSMISSIVITY = 140 m³/day/m
STORATIVITY = 8 × 10⁻⁴
EXTENT OF SEEPAGE PLUME AFTER 273 DAYS ASSUMING VELOCITIES OF 0.03m/day AND 2m/day
FIG. 5.1

BREAKTHROUGH CURVES FOR SEEPAGE OF SULPHATE ION FROM THE SPROP

DISTANCE FROM SPROP (m)
FIG 5.2(a)

CALCULATED CONCENTRATION DISTRIBUTIONS FOR CONSERVATIVE SOLUTES

T = 1 YEAR

T = 55 YEARS

DISTANCE FROM TOP OF GRID (m)

COOPER CREEK

C/Co

T = 55 YEARS

\( D_L = 0.2 \text{m/day} \)

GROUNDWATER VELOCITY = 0.03\text{m/day}
CALCULATED CONCENTRATION DISTRIBUTIONS FOR CONSERVATIVE SOLUTES

\( D_L = 0.2 \text{m}^2/\text{day} \)  
GROUNDWATER VELOCITY = 0.3 m/day
CALCULATED CONCENTRATION DISTRIBUTIONS FOR CONSERVATIVE SOLUTES

\[ D_L = 0.2 \text{m/day} \quad \text{GROUNDWATER VELOCITY} = 2 \text{m/day} \]