Contaminant transport from proposed Jabiluka mine uranium tailings paste repositories - model analyses

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Abstract: In 1999 the Australian Government commissioned a number of scientific studies in response to some objections to a proposal to mine uranium and store tailings underground at a mineral lease at Jabiluka in Northern Australia. Kakadu National Park, a listed World Heritage Area surrounds the lease. This paper describes a hybrid numerical/analytical modelling investigation to determine the possible movement of potential contaminants from the tailings repositories towards wetlands adjoining the mining lease. Because of the uncertainty in the model parameters a Monte Carlo approach was employed to generate a large number of possible concentration profiles. The results show that there will be no significant impacts on groundwater in the wetlands.

1 INTRODUCTION

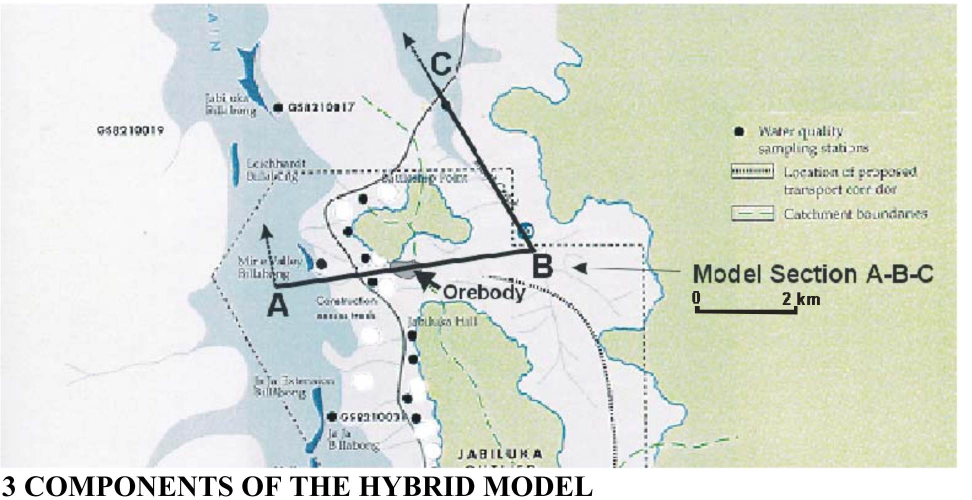
The preceding paper titled "Contaminant transport from proposed Jabiluka mine uranium tailings paste repositories - conceptual description" by C.R.Dudgeon and F.R.P.Kalf describes the geographic, geologic and hydrogeological conditions and tailings properties which would influence the movement of contaminants leached by groundwater from underground tailings repositories at the proposed Jabiluka uranium mine. Groundwater flow could potentially carry the contaminants towards nearby wetlands. These wetlands occur on the floodplain of Magela Creek, a tributary of the East Alligator River, Northern Territory, Australia and are part of the Kakadu National Park, a listed World Heritage Area.

This paper describes model analyses used to predict the movement and concentration levels away from the tailings repositories. Selected results are presented in graphical form and discussed in relation to the risk of the stored tailings having an impact on the wetlands. A full description of the modelling, and results and a list of references can be found in the report by Kalf & Dudgeon (1999).

2 MODELLING APPROACH

In hard rock aquifers, fractures usually provide the main flow paths for groundwater that has the potential to transport contaminants away from a mine. Provided the scale of the fracture network is small compared with that of the region of flow, a fractured rock aquifer or aquitard can be represented as an equivalent porous medium on a regional scale. In general this assumption is often also required because of the lack of knowledge about the fracture distribution characteristics in the rock formation. Geological conditions at Jabiluka and the scale of the site area meet the above modelling criterion as a good approximation. Also, the data available to describe the hydraulic characteristics of the aquifer do not justify, at this stage, a fully three-dimensional model to represent both flow and contaminant transport. Data are available to allow modelling of flow along the main flow paths and potential contaminant transport routes east and west from the mine towards the Magela floodplain (Figure 1). Consequently, modelling has been carried out to first determine flow velocities in these directions, then to estimate the amount of leaching from the repositories and finally to determine the movement of these leached substances along these groundwater flow paths. The overall model(s) can therefore be described as hybrid.

Figure 1 Plan of Jabiluka site showing location of two-dimensional flow model section.



3 COMPONENTS OF THE HYBRID MODEL

The models used were:

1. A regional scale two dimensional (2D) section finite element section model (SEEP/W) to determine head distributions, flow directions and the range of Darcy velocities along Section A-B-C (Figure 1) parallel to the groundwater flow lines.
2. A local scale three-dimensional (3D) finite difference solute transport model (MODFLOW-SURFACT) applied to a 1m thick horizontal layer of

horizontal flow through and around a repository to determine the concentrations of contaminants leached from the tailings.

3. An analytical contaminant transport model to determine concentrations along the flow paths represented by the finite element flow model. The effects of advection, dispersion in three co-ordinate directions and retardation are accounted for. The model uses as input the flow velocities determined from model 1 above and source concentrations determined from model 2 above. This model was combined with a Monte Carlo simulations to determine concentration profiles for a large number of parameter values within selected ranges.The models have been chosen to provide levels of approximation, which match that of the available data. The numerical flow model and solute transport leaching model provide data of appropriate accuracy to use in the analytical contaminant transport model.

4 CONTAMINANT CHARACTERISTICS

The contaminants considered in the modelling were magnesium sulfate, manganese, uranium and radium 226. Conservative dispersion and retardation characteristics of these materials listed in Table 1 were chosen from data available in the literature and the results of analysis of measurements at the nearby Ranger Uranium Mine tailings dam.

Table 1 Parameter Ranges used in the Monte Carlo Analysis

Parameter		**Range**
Longitudinal Dispersivity	α_L	1m to 10m
Transverse Dispersivity	α_T	0.1m to 1m
Vertical Dispersivity	α_V	0.01 to 0.1m
Darcy Velocity	v_D	5×10^{-5} to 5×10^{-6}m/day east of silo bank 5×10^{-4} to 5×10^{-5}m/day west of mine void
Effective Porosity	P_a	0.005 to 0.10
Retardation Factor	R_f	1 for magnesium sulfate and manganese 20 for uranium and 100 for radium 226
Decay Constant	λ	0 (i.e.negligible) for uranium 1.186×10^{-6}day^{-1} for radium 226

5 GROUNDWATER FLOW SYSTEM – NUMERICAL 2D MODEL

Model Mesh and Boundary Conditions

Figure 2 shows the finite element mesh used. It is comprised of quadrilateral and triangular elements which both incorporate secondary nodes. To remove the ‘no flow’ edges of the model, ‘infinite’ elements were used to allow the model to behave as though the section extended to a very large distances beyond each of these edges.

For simulating long-term response it is valid to consider the potentiometric surface to be at steady state since the influence of seasonal fluctuations on groundwater flow will tend to cancel out below and above a mean potentiometric level. Constant heads at the elevation of the measured mean water table shown in Figure 2 were therefore set as constant heads in the model.

Aquifer-Aquitard Properties

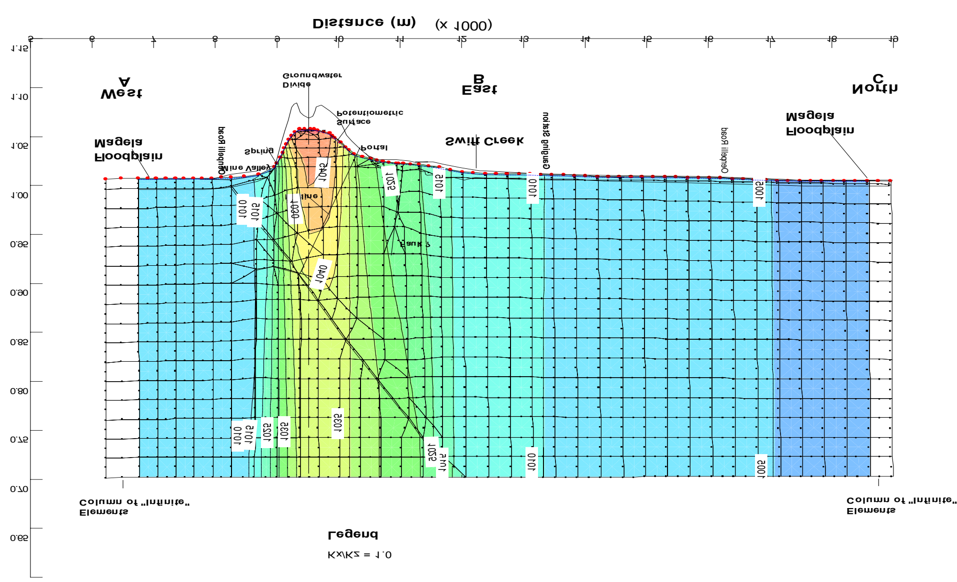
The model was set up with a permeability of 10^{-2} m/day in the sandstone east of the divide and 5 x 10^{-2} m/day in the sandstone west of the divide. The schist/carbonate in the west was assigned a permeability of 2 x 10^{-1} m/day.

Figure 2 Finite element mesh and steady state potentiometric heads in the section A-B-C two dimensional flow model

Alluvial sediments were assigned a permeability of 10^{-1} m/day and the floodplain sediments 10^{-2} m/day. These data were obtained and assessed from the results of the hydrogeological investigations conducted by ERA.

Tailings Repositories

The fill in the mine void was assigned a permeability of 10^{-4} m/day. For the



regional flow model the permeability in the silo bank area was not reduced below that of the surrounding sandstone (10^{-2} m/day) since introducing a lower permeability here would violate the ability of the groundwater to flow in the third dimension around the silo repositories.

Model Results

The results of the steady state simulation are presented in Figure 2. Potentiometric heads in terms of mine RL(m) are marked at the upper and lower ends of constant head lines shown in the figure. The results indicate essentially horizontal flow with a slight upward component developing with distance from the topographic divide to the west. Darcy velocities east of the divide range from 5×10^{-5} to 5×10^{-6} m/day. To the west the range is 5×10^{-4} to 5×10^{-5} m/day.

6 LOCAL SCALE SOLUTE TRANSPORT/LEACHING MODEL

This model was set up to simulate leaching of the assumed non-reactive substances (magnesium sulfate and manganese)and also radionuclides from the paste fill in the proposed Jabiluka silo bank and mine void. Groundwater flow through and past the tailings repositories will be nearly horizontal so two dimensional (2D) flow in a 1m thick horizontal slice was adopted.

For these simulations a 3D saturated/unsaturated flow and solute transport model code MODFLOW-SURFACT (MS) developed in the USA by Hydrogeologic Inc. was used. MS is an enhanced and much advanced version of the standard USGS MODFLOW saturated groundwater flow code.

The MS code was set up to examine flow for both a single silo and a bank of silos. The mine void case was approximated by a large diameter single silo. A finite difference mesh of cells, each 1 m x 1 m in plan, was used to represent the horizontal layer of saturated flow.

Constant heads were applied at each end of the model to achieve a constant hydraulic gradient of 0.03 (based on actual monitoring bore water levels) for all simulations. Two values of tailings paste permeability, 10-4 and 10-5 m/day, were used in the computations.

A discussion of the range of these relative concentrations is given in section 8. The 1000-year uranium concentration profile through two silos in a bank is presented in Figure 3. The concentrations determined from such profiles immediately along the downgradient edge of the silo bank to the east and mine filled void to the west were used as the source input concentrations to the regional analytical contaminant transport model. This model was then used in turn to predict the far field concentrations levels assuming the leach concentrations to be the source plane.

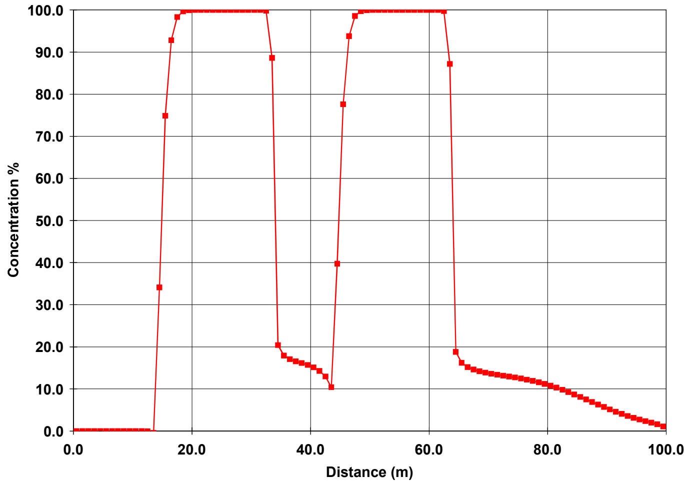


Figure 3 1000 year relative uranium concentration profile through two silos – groundwater flow from left to right.

7 REGIONAL SCALE TRANSPORT – ANALYTICAL MODEL

A solute transport analytical equation (Domenico and Schwartz 1998, Kalf and Dudgeon 1999), was used to determine contaminant concentrations along the flow paths represented by the finite element regional flow model described previously.

The transport model is based on an analytical solution to the advection-dispersion equation and assumes uniform conditions throughout the flow field. It also assumes one co-ordinate direction for advection along the vertical planes in section A-B-C and three co-ordinate directions for dispersion.

For all simulations, concentrations were computed along the axis of symmetry of the contaminant plumes emanating from the source.

Monte-Carlo Simulation

Monte Carlo simulation refers to the technique of repeatedly re-running a model using various model parameters selected randomly within a given range. Provided a sufficient number of computer runs is chosen, the results are an approximate representation of the results of all the possible combinations of the given parameters within each range.

No particular probability distribution of parameter values within each range of values was assumed in any of the simulations; all parameter values had equal probability of occurrence as determined by the computer program random number generator. This uniform distribution approach is conservative.

Simulations were conducted using 255, 500 and 1000 runs or realisations. It was found that there was little difference between the results of these simulations so the results for 255 runs were used to determine median relative concentration versus distance plots for the contaminants studied.

Model Parameters

Solute transport model parameters used in the Monte Carlo simulations are given in Table 1.

Source planes were 100 m high x 600 m wide for the silo bank and 100 m high x 500 m for the mine void.

Results

A typical set of Monte Carlo concentration profiles for uranium from the silos to the east using 255 realisations and a simulation period of 1000 years is given in Figure 4. A plot of median relative concentration against distance for the two flow directions east and west for uranium, radium 226 and sulfate is given in Figure 5. The curves in this composite plot were obtained by determining the median location of each concentration value for 255 Monte Carlo realisations for each of the three contaminants considered. Note that the results for sulfate can also be used for manganese since both were assumed to be non-reactive.

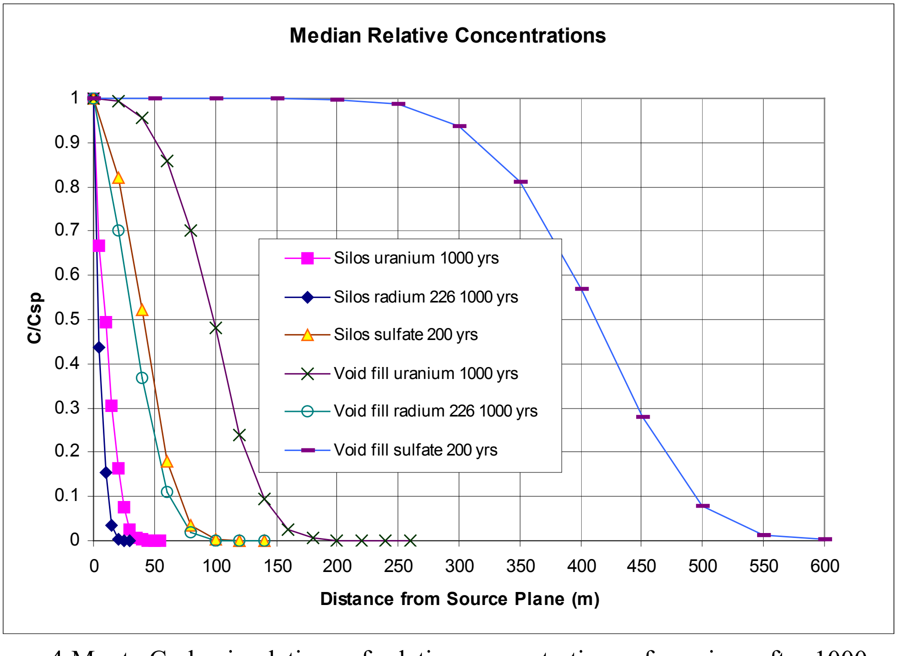


Figure 4 Monte Carlo simulations of relative concentrations of uranium after 1000 years from silos in an easterly direction.

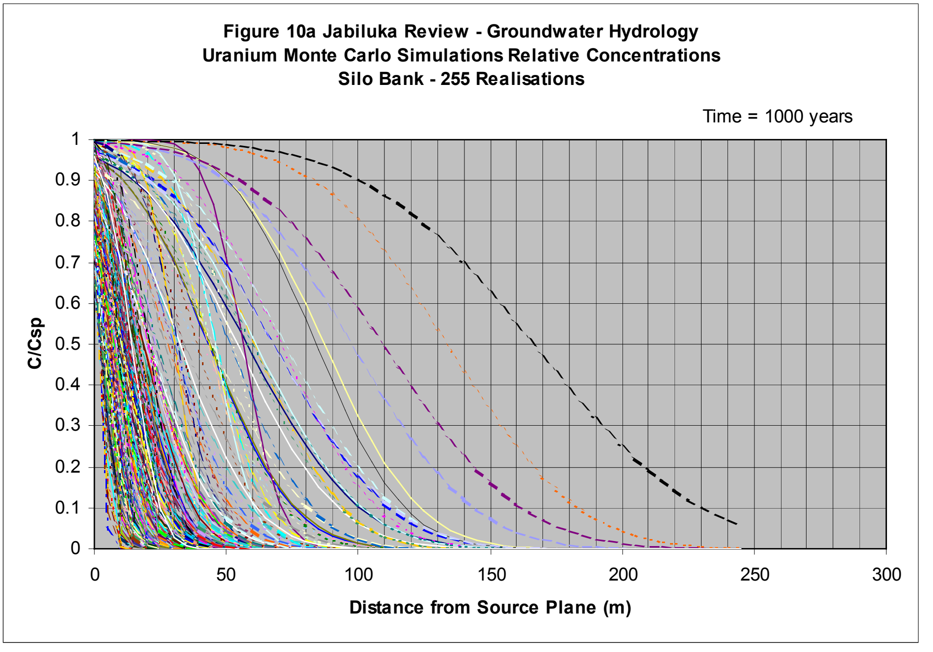


Figure 5 Median relative concentrations down gradient from the silo bank and mine filled void.

Absolute values of contaminant concentrations

If the absolute concentration of a contaminant in the tailings is known, absolute concentrations of the contaminant in the plume downstream from the source can then be determined from the relative concentrations given by the regional contaminant transport model.

Conservative estimates of Jabiluka tailings paste properties have been used to convert the relative contaminant concentration figures determined by modelling to conservative estimates of absolute concentrations between the Jabiluka tailings repositories and the Magela wetlands.

The conservative value used for expected paste permeability is 10^{-4} m/day although it should be possible to achieve 10^{-5} m/day.

Absolute paste pore water concentration values that are based on data obtained from ERA's nearby Ranger mine and the literature are:

sulfate	20 000mg/L
magnesium	5 000mg/L
manganese	500mg/L
uranium	15Bq/L
radium 226	15Bq/L

8 DISCUSSION

The parameter values and method of analysis given above are considered to be conservative and should provide a conservative assessment of the impact of the tailings repositories on the quality of water in wetlands on the floodplain.

Non-reactive contaminants

The model simulations show that for a paste permeability of 10^{-4} m/day, non-reactive contaminants would be at a concentration generally 10 to 12% of the source concentration as they leach out immediately down-gradient (i.e. to the east) of the silos.

The simulations indicate that concentrations immediately down-gradient (i.e. to the west) of the mine void fill would probably be less than 5% of the source concentration for a paste permeability of 10^{-5} m/day and less than 30% for a paste permeability of 10^{-4} m/day. For a paste permeability of 10^{-3} m/day, the immediate down-gradient concentration could be 80% or more.

The modelling results show that over a period of 200 years the non-reactive contaminant fronts from the silos would migrate a probable distance of less than 100 m in a easterly direction. Beyond this distance concentrations would be negligible. The maximum computed distance (of very low probability) for this case is 800 m.

The simulations conducted for a non-reactive contaminant emanating from the mine fill void indicate a probable contaminant migration distance in a westerly direction of 550 m after 200 years although greater migration distances are possible. However, the large migration distances indicated in the Monte Carlo simulations can be ignored because the gradients beneath the Magela floodplain would be much smaller than those assumed in the simulations so velocities would be lower. The groundwater would also be entering an area of already poor water quality with high sulfate concentrations (1500 to 6850 mg/L - see the accompanying paper by Dudgeon and Kalf at this conference) so therefore would not have a significant impact on the water quality over time.

Absolute concentrations based on the curves provided can be derived as shown in the following example. Should, for example, the concentration of sulfate in the silos be 20 000 mg/L, the concentrations immediately down-gradient of the silo would be say 10%. Based on the leaching model, (that is 2000 mg/L) then at 100 m the concentration would be a further 1% of this value (i.e. 20 mg/L). Concentrations of sulfate as well as being affected by dispersion will also be affected by dilution due to the influence of rainfall infiltration at shallow depths. Hence there would be a further dilution for that part of the plume extending upward into shallow alluvial or weathered rock aquifers. It is concluded that there would be negligible potential for contamination of surface streams to the east. The probability of a continuous high permeability fracture system extending to the east over long distances is considered to be low. Even with a fracture system extending some one to two hundred metres, the final concentration due to both dispersion and dilution would be low and probably negligible compared to the high sulfate levels in the Magela floodplain created by natural oxidation processes. Similar arguments are valid for concentrations extending in a westerly direction from the mine filled void even though these concentrations would be higher.

Radioactive contaminants

The simulations conducted for radium and uranium over a period of 1000 years indicate that they would migrate respectively a probable distance of less than 50 m and 100 m in an easterly direction and 100 m to 200 m in a westerly direction.

It is possible to provide a measure of the likelihood that a given level of concentration will lie within a selected travel distance. This is shown for example in Figure 6 based on the Monte Carlo simulations for uranium shown in Figure 4.

Figure 6 shows the cumulative probability of for example the far field 10% relative source concentration of uranium against travel distance. This figure shows that there is a 95% probability that the 10% relative concentration will lie within 100 m of the source plane at the silos.

9 POTENTIAL FOR CONTAMINATION OF THE WET LANDS

Simulations conducted for radionuclides uranium and radium 226 indicate that that these contaminants are restricted in their movement. Provided that adequate low permeability can be achieved in the tailings paste the concentrations will remain at background levels within the wetlands. This situation would also apply to manganese.

Sulfate will be the most mobile contaminant but concentrations emanating from the tailings paste would be low if tailings paste permeability is 10^{-4} m/day or lower. Sulfate concentrations in the wetlands currently occur at high levels due to naturally occurring processes in the acid sulfate soils of the floodplain. Some sulfate from the tailings will reach the floodplain to the west, but concentrations are predicted to be less than those that occur naturally in this area.

It is significant that pre-mining sulfate levels currently in the Magela floodplain are substantially reduced by dilution and flushing during the annual wet seasons.

The probability of occurrence of linear and continuous major fracture systems extending for kilometres is unlikely, and it is not considered that these

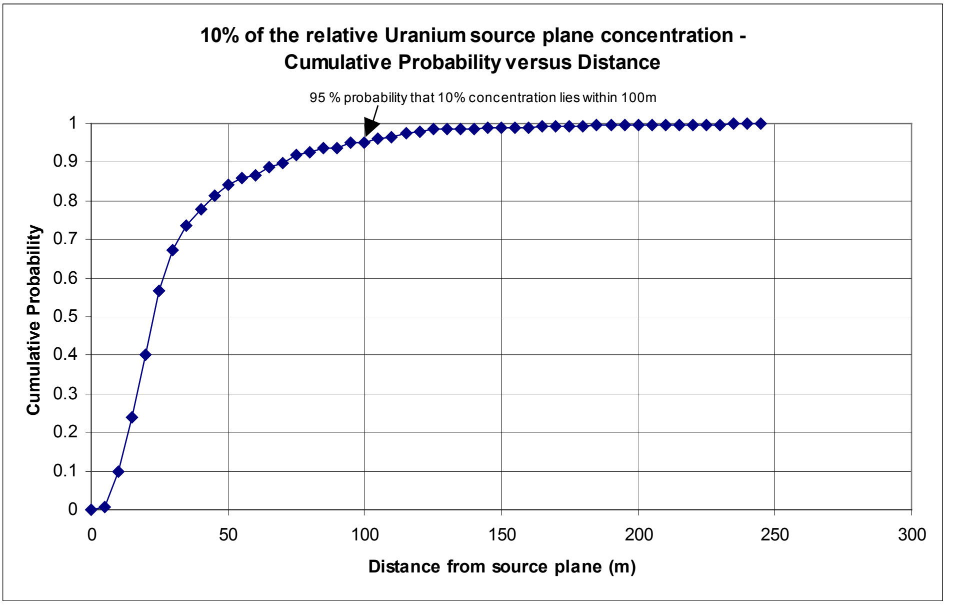


Figure 6 Cumulative probability of the 10% uranium relative concentration versus travel distance

structures would be sufficiently continuous to propagate contaminants beyond distances computed in this analysis.

UNESCO has reviewed the results of simulations given in Kalf and Dudgeon (1999) and they subsequently requested simulations for a time period of 10,000 years that were completed in mid 1999. In summary, the results do not change the conclusions given in this paper.

10 ACKNOWLEDGEMENTS

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REFERENCE

Kalf F.R.P. & Dudgeon C.R., 1999. *Analysis of long-term groundwater dispersal of contaminants from proposed Jabiluka Mine tailings repositories*. Supervising Scientist Report 143, Supervising Scientist, Environment Australia, Canberra.

Transport zanieczyszczeń z proponowanego składowiska odpadów kopalni uranu Jabiluka – analiza modelowa

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Streszczenie: W 1999 roku rząd Australii zlecił wykonanie badań naukowych w odpowiedzi na obiekcje dotyczące proponowanego wydobywania uranu i podziemnego składowania odpadów w złożu rudnym w Jabiluka w północnej Australii. Złoże otacza Park Narodowy Kakadu, znajdujący się na światowej liście obszarów chronionych. Artykuł opisuje hybrydowe numeryczno-analityczne badania modelowe dla określenia prawdopodobnego przemieszczania się potencjalnych zanieczyszczeń ze składowiska odpadów w kierunku terenów podmokłych otaczających obszar górniczy. Ze względu na niepewność wartości parametrów modelu zastosowano rozwiązanie Monte Carlo, aby stworzyć dużą ilości możliwych profili koncentracji. Wyniki wykazały, że eksploatacja i składowanie nie będą stanowić znaczącego zagrożenia dla wód podziemnych.