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A REPORT TO THE
DEPARTMENT OF PRIMARY INDUSTRIES AND ENERGY
BUREAU OF RURAL SCIENCES

on

TECHNICAL STUDIES FOR SITE SELECTION OF A NATIONAL LOW-LEVEL RADIOACTIVE WASTE REPOSITORY

VADOSE ZONE HYDROLOGY AND RADIONUCLIDE RETENTION

SUPPLEMENTARY STUDY

ANSTO Environment Division
CSIRO Land and Water

February 1999

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VADOSE ZONE HYDROLOGY AND RADIONUCLIDE RETENTION

SUPPLEMENTARY STUDY

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1. INTRODUCTION

Australia intends to establish a National Low-Level Radioactive Waste Repository. This will be a near-surface facility that will meet the requirements of the "Code of Practice for the Near-Surface Disposal of Radioactive Waste in Australia 1992" [NHMRC 1992]. Under this Code, the site selected for the repository must be geotechnically stable in the long term and be sufficiently isolated to prevent unacceptable health risk to humans and long-term danger to other biota. A safety assessment will be required to demonstrate that safety of the facility and that potential radiation exposures, both during operation and after closure will not exceed the values recommended by the National Health and Medical Research Council.

The criteria for site selection in the Code include a requirement that no unacceptable radiation dose accompanies inadvertent release of radionuclides. In this context, the hydrology and chemistry of the site is of central concern because water is the medium most likely to mobilise the nuclides and the surface chemistry (particularly of the colloidal material) determines how much the radionuclides are retarded. The hydrology of potential repository sites depends on rainfall and evaporation, unsteady unsaturated movement of soil water, and extraction of water by plants. Site selection and repository design therefore require information on the climate, the soils and the vegetation.

An area of approximately 67,000 km^2 in Central Northern South Australia (CNSA) has been identified as having generally desirable geographical, geological and social attributes.

Harries *et al*. [1998a] reported on a study of vadose zone hydrology and radionuclide retardation in this area. The report was commissioned as a desk study, however, and with the exception of climatic data, it was based on idealised field information of uncertain reliability, although considerable effort was taken to ensure it was based on the best information available. The Summary of this report is in Appendix 1.

This subsidiary study reports results of measurements on soil samples collected from two sites in the CNSA region. The study was commissioned to collect some critical field parameters in order to confirm key conclusions of the desk study. This field data will permit more efficient measurement on a small number of preferred sites before the finally repository site is identified.

2. EXPERIMENTAL PROCEDURES

Soil water balance and the retardation of nuclides in the soil are key attributes of a site where inadvertent release of nuclides is to be minimised. In the desk studies, both these attributes were necessarily based on inferred data as set out in Harries *et al*.[1998a]. Samples from two similar sites in CNSA were therefore taken to

(a) confirm general intuitions about soils of the area as well as to

(b) provide a preliminary order-of-magnitude check on the illustrative calculation in Harries *et al*. [1998].

Dr DE Smiles and Mr TW Green of CSIRO Land and Water visited the south eastern sector of the preferred area of CNSA on 3rd September 1998. Two sites, "characteristic" of the area, were sampled to depths of 1.3-1.5 m. The sites are close to the township of Pimba in this sector, and the profiles are representative of the soil tentatively termed the Pimba soil in the Harries report.

Photographs of the sites are shown as Figure 1. The vegetation and characteristic surface layer of gibbers are evident in both sites.

Auger samples of disturbed soil, small “undisturbed” cores for bulk density and water content and larger cores for hydraulic conductivity were taken. Samples were packed in polythene bags to prevent water loss in transit to the laboratory.

The following measurements were made on the collected samples:

1. Water content:
   Soil water content was measured by oven drying augered samples at 105ºC.

2. Water content and bulk density:
   Cylindrical core samples of “undisturbed” soil 37.5 mm long and 48 mm internal diameter were taken at a range of depths in the profile. Excess soil protruding from these cores was trimmed and the remaining contents transferred to weighing tins which were weighed, oven dried at 105ºC and reweighed. The field bulk density, the gravimetric and the volumetric water contents were calculated. The method and calculations are similar to those described in Black [1965].

3. Hydraulic conductivity:
   Undisturbed cylindrical cores 80 mm in diameter and 80 mm long were trimmed to length, mounted vertically and water applied at a small suction (3 cm) to the upper surface. The soils swelled as they wet. They were therefore trimmed to length (80 mm) and measurements made on the wet material. The saturated hydraulic conductivity was determined from the long term steady flow rate assuming that the hydraulic potential gradient was unity.

4. Soil moisture characteristic:
   These data were determined by standard procedures [Black 1965] using tension plate and pressure membrane equipment. They represent points on the draining scanning curves of the hysteresis loop.

5. Particle size analysis:
   These selected data were determined using methods described in Loveday [1974]

6. Coefficient of linear shrinkage:
   Shrinkage was measured using the method of McKenzie *et al.* [1994]. This method uses soil crushed to pass a 2 mm sieve and gives results that correlate well with observed shrink-swell behaviour of field soils.

7. Structural stability:
   Using the method of Emerson (AS 1289.c8.1-1980) as described in Loveday [1974]

8. Soil water chemistry:
   The specific conductivity and pH of the 1:5 soil water extract were also measured.

9. Radionuclide absorption studies:
   Sorption properties of representative soil samples [0–10 cm from Site 1 and 40–50 cm from Site 2) were measured for uranium-238 and caesium-137. These are radionuclides of importance for assessing the safety of the repository. The soil samples were dried at 40ºC, and then dry sieved to remove material above 1 mm. Sorption properties were measured in

batch experiments using the radionuclides caesium-137 and uranium-238 (separately) over the pH range from 7 to 10.

Results and observations for all experiments are tabulated below.

3. RESULTS AND DISCUSSION

3.1 Soil Properties

TABLE 1
Soil profile attributes at sampling on 3rd September 1998

Site location Latitude /longitude	Depth (cm)	Water content (g/g)	pH	EC (dS/m)	Colour	Bulk density (g.cm^{-3})
Site 1						
31^{o}.09’.57” S	0-5	0.13	7.89	4.17	5YR 4/6	
136^{o}.35’.31” E	5-10	0.19	7.40	6.34	2.5YR 4/6	1.15*
	10-15	0.16	7.42	6.54	2.5YR 4/6	
	15-20	0.18		6.64	2.5YR 4/6	
	20-30	0.18	7.69	6.75	2.5YR 4/6	1.28*
	30-40	0.20	7.82	6.73	2.5YR 4/6	
	40-50	0.20	7.94	6.61	2.5YR 4/6	
	50-60	0.20	7.83	7.66	2.5YR 4/6	
	60-70	0.19	7.83	7.68	2.5YR 4/6	
	70-80	0.19	7.98	6.45	2.5YR 4/8	
	110-120	0.20	7.81	6.83	2.5YR 4/6	
Site 2						
31^{o}.18’.26” S	0-10	0.20	7.41	9.91	5YR 5/6	
136^{o}.50’.40” E	10-20	0.18	7.32	10.67	5YR 4/6	1.01*
	20-30	0.18	7.43	9.69	5YR 4/6	
	30-40	0.20	7.54	8.29	5YR 5/6	1.31*
	40-50	0.23	7.66	8.25	5YR 4/6	
	50-60	0.23	7.83	8.14	5YR 4/6	
	60-70	0.23	7.81	7.68	5YR 4/6	
	70-80	0.25	7.79	8.81	5YR 5/6	
	80-100	0.23	7.79	8.63	5YR 5/6	
	100-120	0.23	7.96	6.75	5YR 5/6	
	150	0.22	7.74	7.72	5YR 5/6	

Notes:
Colours were determined on air dry samples
Bulk densities are geometric means of 3.

Observations:

1. pH is consistent with mild sodicity as was envisaged in Harries *et al*. [1998a].
2. Specific conductivity on a 1/5 soil water extract is quite high and soils would be classified as saline. This is consistent with perceptions of the original report.
3. Soils are “whole coloured” red (desert loams) (Red pedaric dermosol, [Isbell 1996])
4. Field texture is consistent with desert loams [Stace *et al*. 1968]

5. Emerson (AS 1289.C8.1-1980) dispersion tests were also performed on these samples. All remoulded samples were stable although the near-surface natural samples showed some dispersion. We attribute this behaviour to presence of $CaSO_4$ nodules which do not affect the natural aggregate test because of their low solubility, but which are distributed through the soil during remoulding and confer stability on the remoulded samples.

3.2 Moisture Characteristics

TABLE 2

Soil profile moisture characteristic and particle size attributes

Site location	Depth (cm)	Field water content (g/g)	1/3 Bar water content	15 Bar water content	Sand (g/g)	Silt (g/g)	Clay (g/g)
Site 1 31^{o}.09’.57” S 136^{o}.35’.31” E	0-5	0.13	0.230	0.155	0.53	0.29	0.18
	5-10	0.19	0.324	0.202	0.48	0.29	0.23
	10-15	0.16	0.328	0.206	0.48	0.30	0.22
	15-20	0.18	0.342	0.217			
	20-30	0.18	0.358	0.224			
	30-40	0.20	0.387	0.242	0.37	0.19	0.44
	40-50	0.20	0.386	0.242			
	50-60	0.20	0.375	0.236			
	60-70	0.19	0.357	0.231			
	70-80	0.19	0.344	0.228	0.32	0.23	0.45
	110-120	0.20	0.328	0.248	0.32	0.37	0.31
Site 2 31^{o}.18’.26” S 136^{o}.50’.40” E	0-10	0.20	0.329	0.201	0.57	0.26	0.16
	10-20	0.18	0.334	0.207	0.61	0.26	0.16
	20-30	0.18	0.340	0.215			
	30-40	0.20	0.382	0.228	0.51	0.28	0.22
	40-50	0.23	0.421	0.244			
	50-60	0.23	0.418	0.266	0.53	0.28	0.19
	60-70	0.23	0.412	0.264			
	70-80	0.25	0.426	0.274			
	80-100	0.23	0.392	0.259	0.34	0.38	0.28
	100-120	0.23	0.386	0.253	0.35	0.39	0.25
	150	0.22	0.379	0.245			

Observations

Throughout each profile, soil water contents at sampling are somewhat drier than the wilting point water content (in equilibrium with 15 bar water potential) shown in Fig. 2.

In relation to the particle size distribution, the clay content appears surprisingly low. This may be a consequence of inadequate dispersion because of the presence of significant amounts of $CaSO_4$ and $CaCO_3$. In relation to the figures in the Table, we note that 90% of the sand fraction passes a 250 μm sieve. The material therefore contains a high fraction of material in the silt - very fine sand range. It swells with increasing in water content but the cation exchange capacity tends to be low because of the relatively modest clay content.

In view of the importance of the clay content and mineralogy in relation to nuclide retention [Willett *et al*. 1992] this uncertainty needs clarification.

TABLE 3
Hydraulic properties of soil samples

Site location Latitude /longitude	Depth (cm)	30cm water content (cm^3/cm^3)	100cm water content (cm^3/cm^3)	340cm water content (cm^3/cm^3)	600cm water content (cm^3/cm^3)	1 Bar water content (cm^3/cm^3)	15 Bar water content (cm^3/cm^3)	Saturated Hydraulic conductivity (cm/h)
Site 1 31°.09’.57” S 136°.35’.31” E	15	0.532	0.474	0.404	0.384	0.380	0.257	0.13
	15	0.566	0.511	0.440	0.418	0.417	0.279	0.09
	15	0.575	0.528	0.465	0.443	0.426	0.292	0.08
	40	0.595	0.544	0.459	0.431	0.415	0.290	0.07
	40	0.5545	0.503	0.425	0.402	0.382	0.284	0.06
	40	0.532	0.492	0.431	0.409	0.401	0.286	0.10
Site 2 31°.18’.26” S 136°.50’.40” E	10	0.486	0.431	0.369	0.348	0.339	0.241	0.18
	10	0.495	0.440	0.379	0.363	0.344	0.253	0.20
	10	0.491	0.435	0.378	0.359	0.349	0.226	0.15
	38	0.523	0.479	0.405	0.384	0.390	0.266	0.09
	38	0.534	0.490	0.416	0.389	0.409	0.272	0.08
	38	0.529	0.487	0.427	0.405	0.405	0.284	0.07

Comments

Measured saturated hydraulic conductivity is greater than that previously inferred for the Pimba soil. Furthermore the surface soil structure is stable and we have no reason to expect a decrease in conductivity with time as was envisaged in Harries *et al*. [1998a].

The subsoil conductivity is slightly less than that at the surface. This is consistent with the observed increase in bulk density and clay content with depth. The slightly higher surface conductivity of the soil from SE of Pimba is consistent with both texture and bulk density measurements. The subsoil structure also appears to be stable.

The moisture characteristic is shown as Figure 2. It should be noted that at this stage it is sufficient to fit a Brooks and Corey [1964] model to the total data set. When specific sites are selected then more specific curve fitting will be warranted.

3.3 Shrinkage properties

Shrinkage was measured using the method of McKenzie *et al*. [1994]. This method uses soil crushed to pass a 2 mm sieve and gives results that correlate well with observed field soil observation.

Figure 3 shows the results of length change /water content measurements. These soils appear quite reactive and while it is, again, unnecessary to explore these data in detail, the general trends are evident across all samples. The profiles are strongly pedal (pedaric) but do not show strong shear surfaces often characteristic of shrink/swell soils. This feature may be the result of their salinity together with the presence of calcic deposits. At the same time, the volume change is effectively 3-dimensional and "normal" in the sense that aggregates are effectively revealing unit volume change per unit change in water content. The slope of the profile shrinkage curve (relating profile hight to water content change) is approximately 1/3. These observations confirm predictions in the desk study but field observation outside the area of sampling near Pimba suggests that the behaviour may be more general than the desk study anticipated. The apparent relatively low clay content compared with the fine sand silt fraction requires more careful examination: it may be a consequence of difficulty dispersing the clay mineral in these soils because of cation type or the presence of oxidic and/or siliceous cements.

The shrink/swell behaviour may affect site engineering and the long term integrity of structures; it merits further study.

3.4 Effect on measured field data on previous estimations of soil water balance

The water balance model SWIM [Verburg *et al*. 1996] was run using the measured hydraulic data derived here. Specifically, the moisture characteristic and the saturated hydraulic conductivity data were used to predict the water content/hydraulic conductivity data using the Brooks and Corey [1964] model. In addition, climatic data, provided by the Meteorological Office from December 1996 to the present were included. Previous calculations were based on data from 1976 to 1996, so this additional information permitted us to extend the calculations to 29 continuous years of data. We are thus able to compare these estimations with observed field measurements of 3-4 September 1998, identified above.

Table 4 sets out the results of these calculations.

The cumulative deep drainage estimation is based on drainage from the surface 1-1.4m. It presumes that the deep soil profile is at a quasi-steady state established over many centuries of flow in equilibrium with a reasonable stable climate, and that no storage of water occurs there. The starred numbers were incorrectly reported in Harries *et al*. [1998a].

The following points emerge.

1. The hydraulic conductivity is greater than that estimated in Harries *et al*. [1998a], so the cumulative flux through each profile is greater.
2. The presence of vegetation greatly reduces recharge.
3. Overland flow is less than that predicted by Harries *et al*. [1998a] because we no longer assume that time dependent surface crusting occurs to reduce the infiltration rate.

On the basis of these data we can now, more reliably, estimate the transit time for water moving from the repository at a depth of (say) 5 m to a depth of (say) 50 m. If, as now seems the case, the minimum volumetric water content, $q_v \approx 0.2$, then the transit time will be of order:

- 6×10^4 years in the presence of vegetation; and
- 6×10^3 years in the absence of vegetation.

Also, a further check on the SWIM calculations is now provided by comparison with measured field water content profiles. Figure 4 compares measurements at the two sampled sites with the predictions of the “Pimba” profile with, and without, vegetation. The profile measurements were made on 3rd September, 1998. The calculations were based on rainfall and evaporation data for a period of 29 years up to that sampling date. Correspondence for the calculations that assume water extraction by plants is good and the deep profile approximates the wilting point water content for these soils. The profile calculated as if there were no vegetation is wetter than we measure. These data indicate that the model involving vegetation is both appropriate and relatively accurate.

TABLE 4
Results of SWIM calculation of cumulative deep drainage and runoff

		Cumulative deep drainage	Cumulative runoff
Vegetation present	Previous calculation	0.0041 cm/27 yrs =0.00015* cm/yr	44*cm/27yr =1.63 cm/yr
	Amended calculation	0.012 cm/29 yrs =0.00041 cm/yr	7.0 cm.29 yrs =0.24 cm/yr
Vegetation absent	Previous calculation	0.0041 cm/27 yrs =0.00015 cm/yr	44.27*cm/27 yrs =1.64 cm/yr
	Amended calculation	4.2 cm/29 yrs =0.14 cm/yr	7.9 cm/29 yrs =0.27 cm/yr

3.5 Radionuclide adsorption studies

The uranium and caesium sorption data are summarised in the following Table. For uranium, distribution coefficients (K_d values) were measured at pH values near 7, 8 and 9 and with total added U concentration (ΣU) of 1 µmol/L and 100 µmol/L. The sorption behaviour of the two soil samples for uranium was similar.

For comparison, generic K_d values for uranium in the compilations described in Harries *et al.* [1998a] are:

McKinley and Scholtis [1992]	20 to 1700 mL/g
Sheppard and Thibault [1990]	15 to 1600 mL/g

TABLE 5
Summary of K_d ranges for 9 experiments with uranium-238

Added Uranium (ΣU)	pH	Measured Range of Distribution Coefficient
ΣU = 1 µmol/L	pH ~7	2700 to > 10000 mL/g
ΣU = 1 µmol/L	pH ~8	50 to 260 mL/g
ΣU = 1 µmol/L	pH ~9	30 to 70 mL/g
ΣU = 100 µmol/L	various pH values	<10 to 1200 mL/g

The measured distribution coefficients for uranium decrease substantially as the pH increases from pH ~7 to a pH ~9. The K_d values decrease with higher total uranium, although the ΣU of 100 µmol/L used in these experiments is much higher than would be expected in normal ground waters. Typical uranium concentrations in ground water rarely exceed 1 µmol/L under most environmental conditions.

Referring to the caesium sorption data in the Table below: the amount of caesium-137 in the liquid and solid phases was measured using gamma spectroscopy, and the total Cs (ΣCs) was varied by adding non-radioactive caesium to the solution. Both soil samples had similar sorption properties for caesium-137.

TABLE 6
Summary of K_d ranges for 11 experiments with caesium-137

Total Caesium	pH	Measured Range of Distribution Coefficient
Trace Cs	pH ~7	4000 to 9000 mL/g
Trace Cs	pH ~8	2000 to >10000 mL/g
Trace Cs	pH ~9	3000 to >10000 mL/g
ΣCs = 1 mmol/L	various pH values	170 – 330 mL/g

For comparison, generic K_d values for caesium in the compilations described in Harries *et al.* [1998a] are:

McKinley and Scholtis [1992]	100 to 2000 mL/g
Sheppard and Thibault [1990]	280 to 4600 mL/g

The measured K_d values for caesium showed no significant pH dependence. Measured K_d values are extremely high for trace levels of caesium-137. However, there is a substantial dependence on caesium concentration. The K_d values for the experiments with ΣCs of 1 mmol/l were about an order of magnitude lower than the Kd for trace levels of caesium.

As indicated in Tables 5 and 6, the experimental K_d results (for both uranium and caesium) are in reasonable agreement with the general range of K_d values selected by previous workers and discussed and used by Harries *et al.* [1998a]. The wide ranges for K_d reported by McKinley and Scholtis [1992] and Sheppard and Thibault [1990] are due (at least in part) to the differing soil types, radionuclide concentrations and chemical conditions used in different studies on which their compilations are based.

We conclude that there is reasonable agreement between our measured sorption data and that used in the illustrative calculations of Harries *et al*. [1998a]. Measurement on samples from the preferred site(s) remain necessary to provide detailed and specific information relevant to the conditions expected at the locations and depth of the repository.

4. DISCUSSION

The results of analysis of the soil samples continues the general soil profile forms anticipated by Harries *et al*. [1998a] are confirmed. However, the hydraulic conductivity and the profile water contents, inferred from published data, were underestimated.

The measured soil hydraulic conductivity means that the residence time of water in a 50 m profile was overestimated in Harries [1998a] by approximately an order of magnitude. Minimum residence time is now estimated at about 6,000 years while the residence time in a vegetated soil is estimated to be of order 60,000 years. These remain very long times compared with the half-lives of typical wastes.

The longer residence time under vegetation suggests it would be desirable to maintain vegetation during operation, and to ensure any cleared areas are revegetated after closure.

The SWIM model using the measured soil profile data and recorded rainfall and evaporation data, predicts the measured water content profiles relatively accurately.

The soil in the region swells with increased water content as was anticipated, but the clay contents appear to be relatively low. The apparent inconsistency implicit in these observations indicates a need to ensure that particle size analysis on the preferred sites is based on samples as completely dispersed as possible. Problems arise because effective dispersion of the clay mineral may be prejudiced by the presence of relatively large amounts of gypsum and perhaps calcium carbonate, possible oxides of iron and aluminium and the slightly alkaline pH. Ultrasonic dispersion should be used in conjunction with chemical treatment.

The clay mineralogy should also be determined because it will affect the mobility and absorption of nuclides. These aspects are critically important when the retardation of the nuclides is assessed. Clay mineral type and amount are also important if local material is required to provide effective “natural” barriers to water and nuclide transport from repository disposal trenches.

There is reasonable agreement between the measured sorption data and that used in the illustrative calculations of Harries *et al*. [1998a]. Since in general, the sorption and consequently the radionuclide retardation depends on pH, concentration, ionic strength, and redox potential, direct measurement on field samples can reduce the wide uncertainty in the sorption estimates.

5. FUTURE STUDIES

The safety assessment of the repository must consider the movement and ultimate fate of any nuclides inadvertent release from the repository. It is, therefore, important to establish reliable limits on the movement of these materials and their likely residence time above a water table. The following study program to provide this information uses material taken from, or representative of, the preferred site. It involves laboratory measurements of mineralogical, hydrological and physico-chemical properties. It should include properties that affect the structural stability of these soils, their mechanical properties and radionuclide distribution coefficients.

The following measurements are required.

1. Field measurement and sampling:
    - profile descriptions in local landscape context, including identification of gilgai (land surface shrink/swell topography);

- soil sampling for laboratory determinations. An indicative protocol envisages backhoe samples to a depth of approximately 2.5 m, and auger/drill samples from 10 m, 20 m, 30 m and 40 m if possible.

2. Laboratory measurements on soil samples from the selected sites:
    - clay mineralogy, exchangeable cations and water soluble salts;
    - mechanical properties and surface structural stability;
    - hydraulic properties and soil water content;
    - radionuclide distribution coefficients as a function of pH, ionic strength, redox potential and concentration;
    - measurement of radionuclide movement in small unsaturated soil columns.

We recommend that the hydrology of favoured sites be assessed using both water balance equation calculation and tracer methods, particularly chlorine-36. The tracer method using chlorine-36 was well-demonstrated by Harries *et al*. [1998b] in similar circumstances to those in the present study area. They established a practical protocol that should be followed here and they clearly demonstrate the rate of movement of a soluble radionuclide in the soils and thence an indication of the natural soil water recharge rate. The flow equation solution and the tracer methods are complementary.

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Attachment 1

SUMMARY OF VADOSE ZONE HYDROLOGY AND RADIONUCLIDE MIGRATION ISSUES

The site for the radioactive waste repository must be selected to minimise the prospect that the inadvertent release of radionuclides might lead to an unacceptable radiation dose. The geosphere can be an effective barrier that greatly limits the amount of radionuclides released from the site, in the long term. In this context, the hydrology and hydrogeology of the site is of central concern, because water is the medium most likely to mobilise the radionuclides.

The natural hydrology of potential repository sites depends on rainfall and evaporation, movement of soil water in the unsaturated zone and extraction of water by plants. Site selection and repository design therefore require consideration of the climate, the soils and the vegetation. The climate of Central Northern South Australia is characterised by low rainfall which averages about 200 mm/year, low relative humidity (about 43%), high evaporation (about 1900 mm/year) and high temperatures in summer. Evaporation and temperature data are strongly periodic but rainfall is very irregular.

Although the physical properties of the soils are poorly described in the literature, we infer that a physically based catenary sequence encompasses the range of soils likely to be encountered. Deep wind deposited sands, texture contrast sand over medium clay, and uniform medium clay soils occur in much of the region. Many of the soils are sodic with cryptogam ground cover and *Atriplex* spp as the dominant perennial shrub. Calcrete and sometimes silcrete hard pans commonly occur in the soils, and gilgai microrelief is common.

Richard's equation was used for illustrative water balance calculations. The calculations were based on inferred profile properties, in the presence and absence of vegetation. They yield useful order-of-magnitude information that accords with experience in roughly similar though less arid environments. Specifically, they indicate that maximum recharge rates of about 7 mm/year (over the 27 years to 1996) occur on the deep sands in the absence of vegetation and a surface crust. *Atriplex vesicaria* and the presence of a stable cryptogam crust probably reduce this recharge rate by an order-of-magnitude. These estimates are in good accord with isotope studies in the Murray mallee of South Australia.

On texture contrast soils with much less permeable subsoils the maximum recharge rate was about 0.1 mm/year. The uniform, sodic, medium clay soil recharge rates were insignificant (< 0.002 mm/year). The maximum recharge rate under deep sands in the absence of vegetation was about 0.1 mm/yr. These calculations probably overestimate the deep drainage because the use of daily time steps means that the runoff from intense storms of duration less than a day is substantially underestimated.

The recharge rates provide an upper limit to the rate of migration of radionuclides. Most radionuclides move at rates that are orders of magnitude lower than the rate of water movement. This retardation is characteristic of the particular element and is due to mechanisms such as adsorption and chemical precipitation. For some of the longer lived radionuclides, particularly the actinides, the geochemical retardation mechanisms produce extremely low migration rates. A preliminary survey of the literature has identified typical retardation factors due to adsorption for the radionuclides of importance in assessing the safety of a near-surface repository.

The potential radiation exposure via the groundwater pathway from any release of radionuclides from the repository depends on many factors including the inventory of radionuclides, the flux of water, the geochemical retardation factors, the half-lives and the radiotoxicity of the radionuclides. A nominal inventory for radionuclides of importance is presented and is used in an advection-dispersion model to estimate the concentrations of radionuclides at a depth of 50 m in the unsaturated zone. Provided the water flux and retardation factors are representative of conditions in the field down to about 50 m, then the geosphere provides an effective barrier to the release of radionuclides. Although this modelling is preliminary, it identifies the site and soil properties that should be measured during site selection and characterisation.

The estimated low recharge rates and low radionuclide movement in the vadose zone confirm initial perceptions that much of the Central Northern South Australia region would contain suitable sites for a repository.

Illustrative estimates presented here must be refined when better information is available on soil hydraulic properties, radionuclide retardation factors and vegetation. Independent measurement of recharge rates using radioisotope tracers would be helpful.

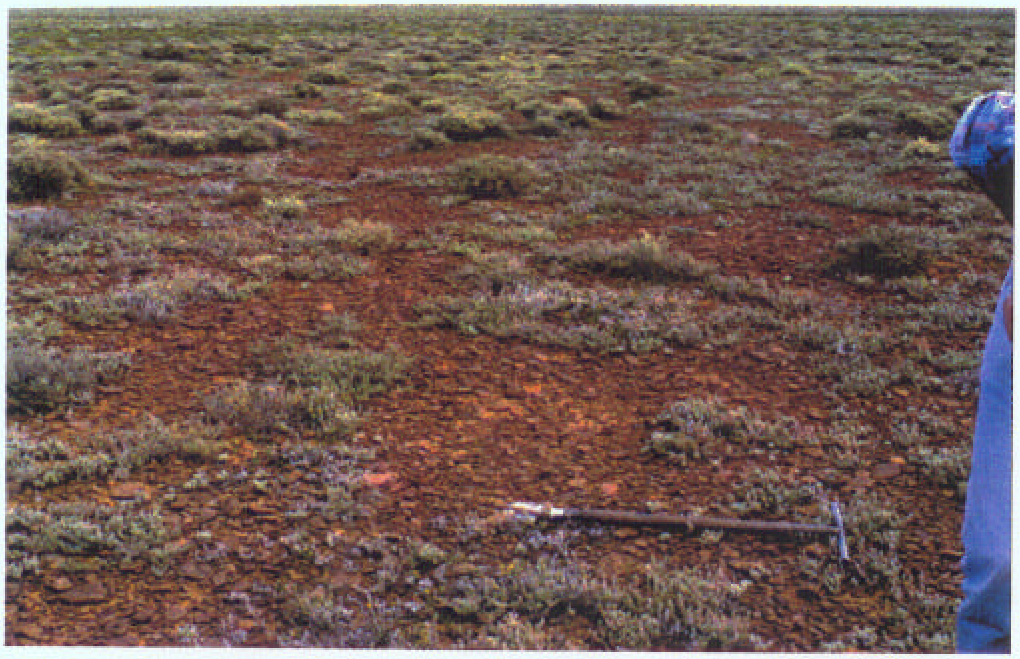
The combination of these insights with landform and geomorphic information which might be inferred from LANDSAT TM and radiometric data presented elsewhere in this study result in preliminary maps which could be used to identify areas suitable for the repository within the Central Northern South Australia region.

It is now necessary to correlate this remotely sensed data with "ground truth" and then to identify a small number of specific areas where field measurement of soil and land properties will permit better definition of local site properties.

The report concludes by recommending field and laboratory measurements that will facilitate selection and characterisation of a site for the repository.

2 October 1998

(a)



(b)

Figure 1. The field sites near Pimba, SA at sampling on 3rd September 1998. These photographs show the vegetation at the sites and the characteristic gibber surface. The stones are confined to the soil surface; soil profile is not stony. (a) The site north west of Pimba [31.09.57 S; 136.35.31 E], (b) The site south east of Pimba [31.18.26 S; 136.50.40 E]

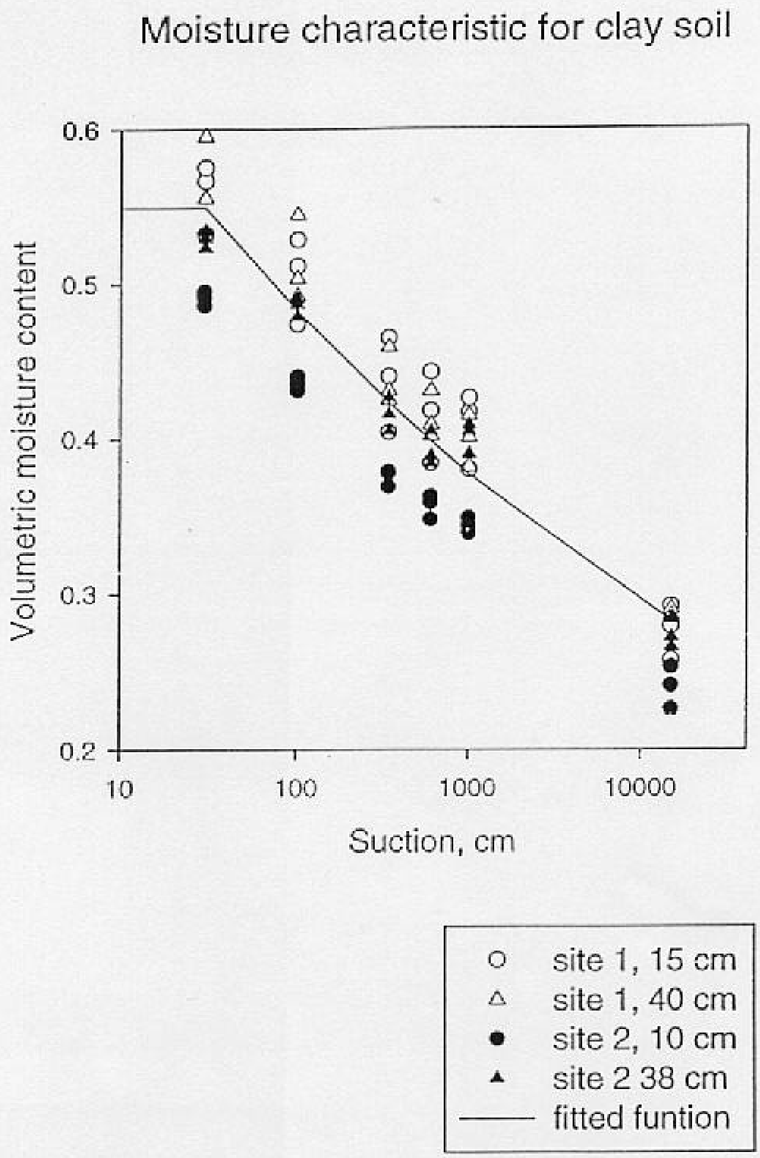


Figure 2 **Drainage soil moisture characteristics for the soils described herein. General patterns of behaviour are similar with the site 2 materials exhibiting general effects of modest increase of clay with depth. For the purposes of this study it is sufficient to fit these data, as shown, with a single Brooks and Corey [1964] model which is then used in water balance studies.**

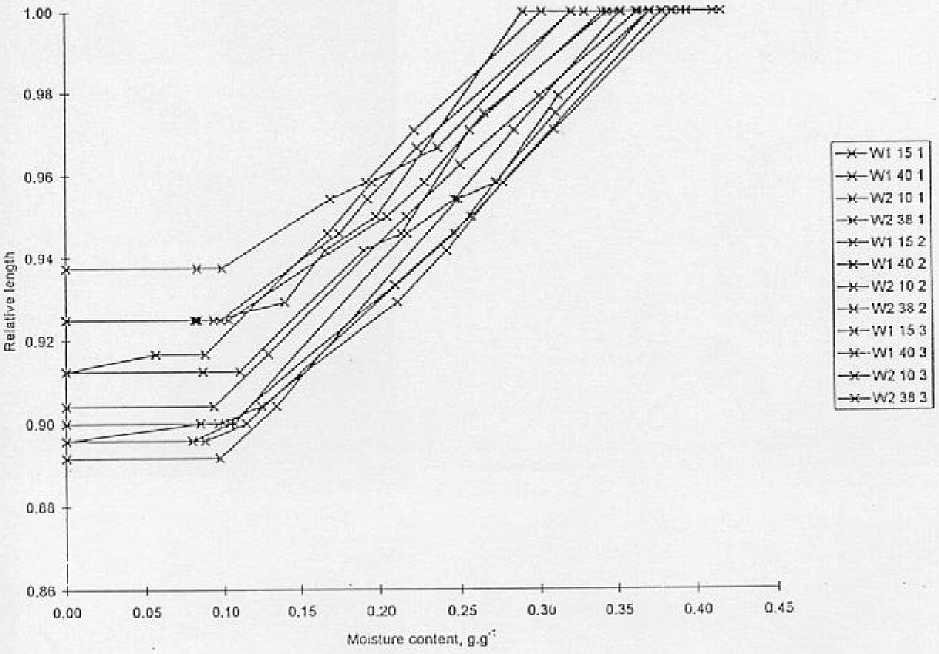


Figure 3 Linear shrinkage as a function of water content for the soils of this study. General patterns of behaviour are evident with all samples revealing effectively 3-dimensional (normal shrinkage) which will be revealed as in a profile shrinkage curve with a slope of about 1/3.

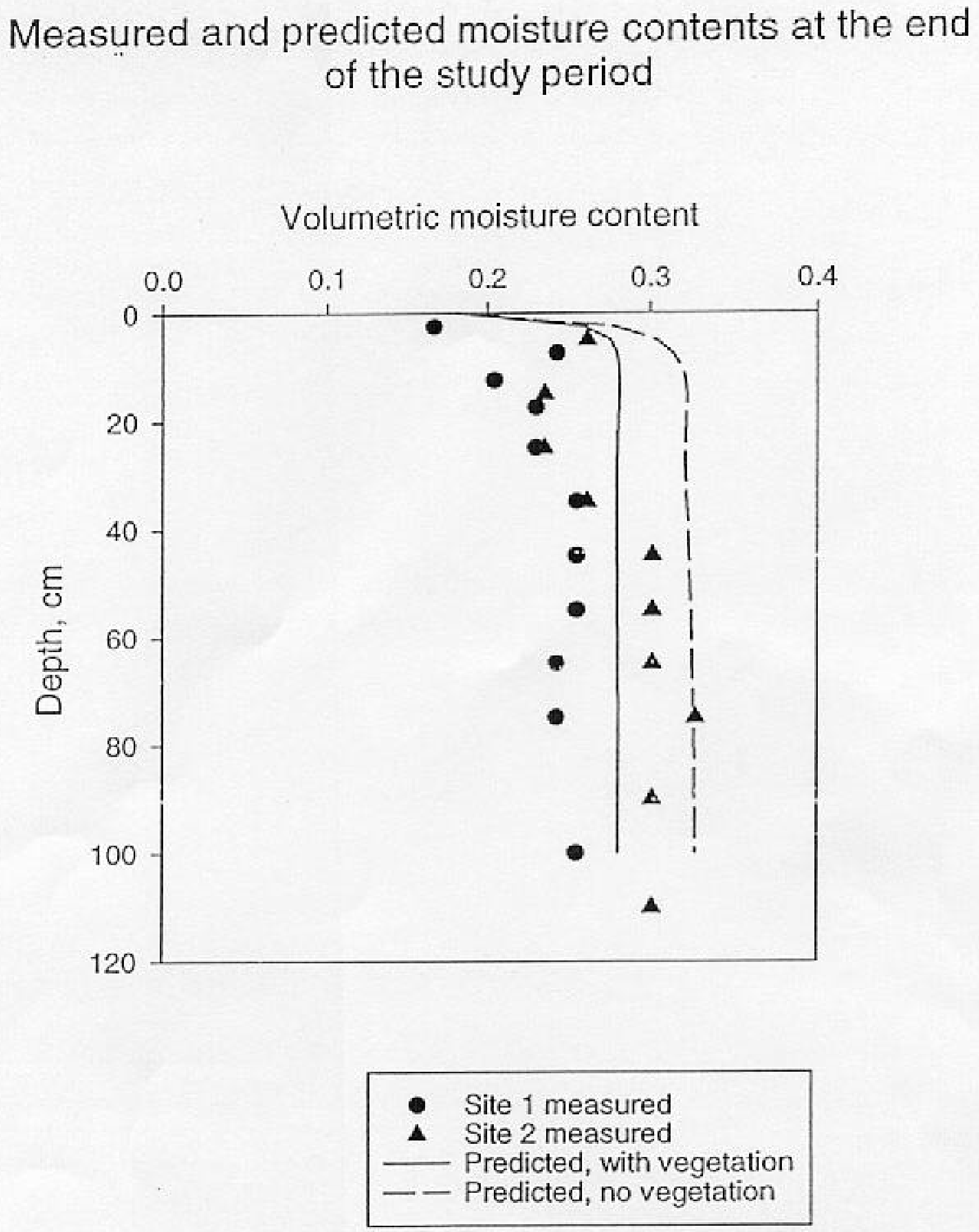


Figure 4 **Comparison of soil water content profiles observed on 3rd September 1998 with those predicted using the water balance model SWIM, the average soil material properties identified in the Report, and 29 years of daily rainfall and evaporation data up to that date. The solid line represents the prediction in the presence of vegetation, the dashed line is the prediction in the absence of vegetation. This level of agreement is excellent.**