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

on

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

VADOSE ZONE HYDROLOGY AND RADIONUCLIDE RETARDATION

ANSTO Environment Division
CSIRO Land & Water

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AUSTRALIAN NUCLEAR SCIENCE

AND TECHNOLOGY ORGANISATION

LUCAS HEIGHTS SCIENCE AND TECHNOLOGY CENTRE

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4. VADOSE ZONE HYDROLOGY AND RADIONUCLIDE RETARDATION

by

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SUMMARY

The site for the radioactive waste repository must be selected to minimise the likelihood that inadvertent release of radionuclides could 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 (CNSA) region 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 CNSA 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 CNSA 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

4.1 INTRODUCTION

This component of the study considers water flow and radionuclide movement and their impact on site selection for a radioactive waste near surface repository in the Central Northern South Australia (CNSA) region identified in BRS (1997).

The Australian repository 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 is required to have long-term stability, and provide adequate isolation so that there is no unacceptable health risk to humans and no long-term detriment to other biota. A safety assessment is required to clearly demonstrate that the protection of humans is optimised, and that the potential radiation exposure to a member of the public will not exceed the values, currently, of 1 mSv per year, recommended by the NHMRC. This dose limit must be met at all times — both during operation and after closure.

The Code also specifies a number of criteria for site selection. The criteria that relate to water flow and radionuclide movement are:

- the water table should be at sufficient depth to ensure that groundwater is unlikely to rise within five metres of the waste, and large fluctuations in water table should be unlikely (section 2.4.2b);.
- the geological structure and hydrogeological conditions should permit modelling of ground water gradients and movement, and allow prediction of radionuclide migration times and patterns (section 2.4.2c); and
- ground water in the vicinity which may be affected by the presence of the facility should ideally not be suitable for human consumption, pastoral or agricultural use.

These requirements set limits on the release of radionuclides to the accessible environment in both the short term and the long term. In the short term, engineered barriers and operational procedures must ensure that releases are within acceptable limits. In the long term, the geosphere should provide a barrier to the release of radionuclides from the site.

This study of hydrology and radionuclide retardation will:

a) describe relevant aspects of the environment of CNSA;

b) review methods used to estimate unsaturated water movement in the arid zone and identify the soil properties that affect flux and storage of water and which would influence selection of the repository site;

c) list and characterise radionuclides of importance for an Australian repository;

d) review information on the movement of radionuclides in the vadose zone in arid zone soils;

e) identify limitations of data on water flow and radionuclide retardation and identify site specific data needed to resolve issues of importance for assessing safety of repository.

4.2 ENVIRONMENT OF CENTRAL NORTHERN SOUTH AUSTRALIA

The hydrology of potential repository sites depends on rainfall and evaporation, unsteady unsaturated movement of soil water, and extraction of water by plants. Its definition therefore requires information on the climate, the soils and the vegetation.

4.2.1 Climate

The climate of CNSA is arid and characterised by irregular low rainfall, low relative humidity, high evaporation and high summer temperatures. Climate data has been collected at the Woomera Aerodrome since the late 1940s, and they are representative of the whole CNSA region. Other less complete data sets are available from Cooper Pedy, Andamooka and Roxby Downs.

Figures 4.1, **4.2** and **4.3** illustrate, respectively, the average (a) and monthly historical (b) rainfall, evaporation and air temperature data over the past decade for the Woomera Airport. Over this period, the average rainfall is 198 mm/annum, the average relative humidity is 43% and the pan evaporation average is 1886 mm/year. For completeness, relative humidity and long term solar radiation data are presented in **Figures 4.4** and **4.5**.

The climate of the CNSA region exhibits a very strong periodicity in evaporation and temperature. This permits use of long term monthly, or daily, averages in calculations. Rainfall, by contrast, is most irregular and any form of average must be used with caution. Furthermore, the consequences of storm intensity, duration and frequency of occurrence differ depending upon whether we seek to estimate deep drainage or run-off.

For the purpose of assessing the groundwater transport of radionuclides from the repository, it is preferable to overestimate rather than underestimate deep drainage. Hence, it is reasonable to use daily rainfall information in this study to calculating deep drainage because it will overestimate infiltration and underestimate runoff. For predicting erosion and runoff, it would be more appropriate to use the rainfall and runoff data of Pilgrim (1987), which is generally used for flood estimation.

4.2.2 Soils

The soils and landscapes of the CNSA region are well described (Jackson, 1956; Jessup, 1951, 1960a, b, 1961a, b, c). However, the hydraulic and other physical characteristics of the soils are poorly known. An exception is the work by Graetz and Tongway (1980) in the vicinity of Roxby Downs. In general, the soil hydraulic behaviour must be inferred from experience elsewhere.

The Handbook of Australian Soils (Stace et al., 1968) identifies three major soil groups within the CNSA region. It is convenient, because of the classification of profile descriptions within the Handbook, to retain the now superceded Great Soil Group names. Within that nomenclature these are:

i) Grey brown and red calcareous soils [Map Code 7]

ii) Desert loams [Map Code 8], and

iii) Solonized brown soils [Map Code 19]

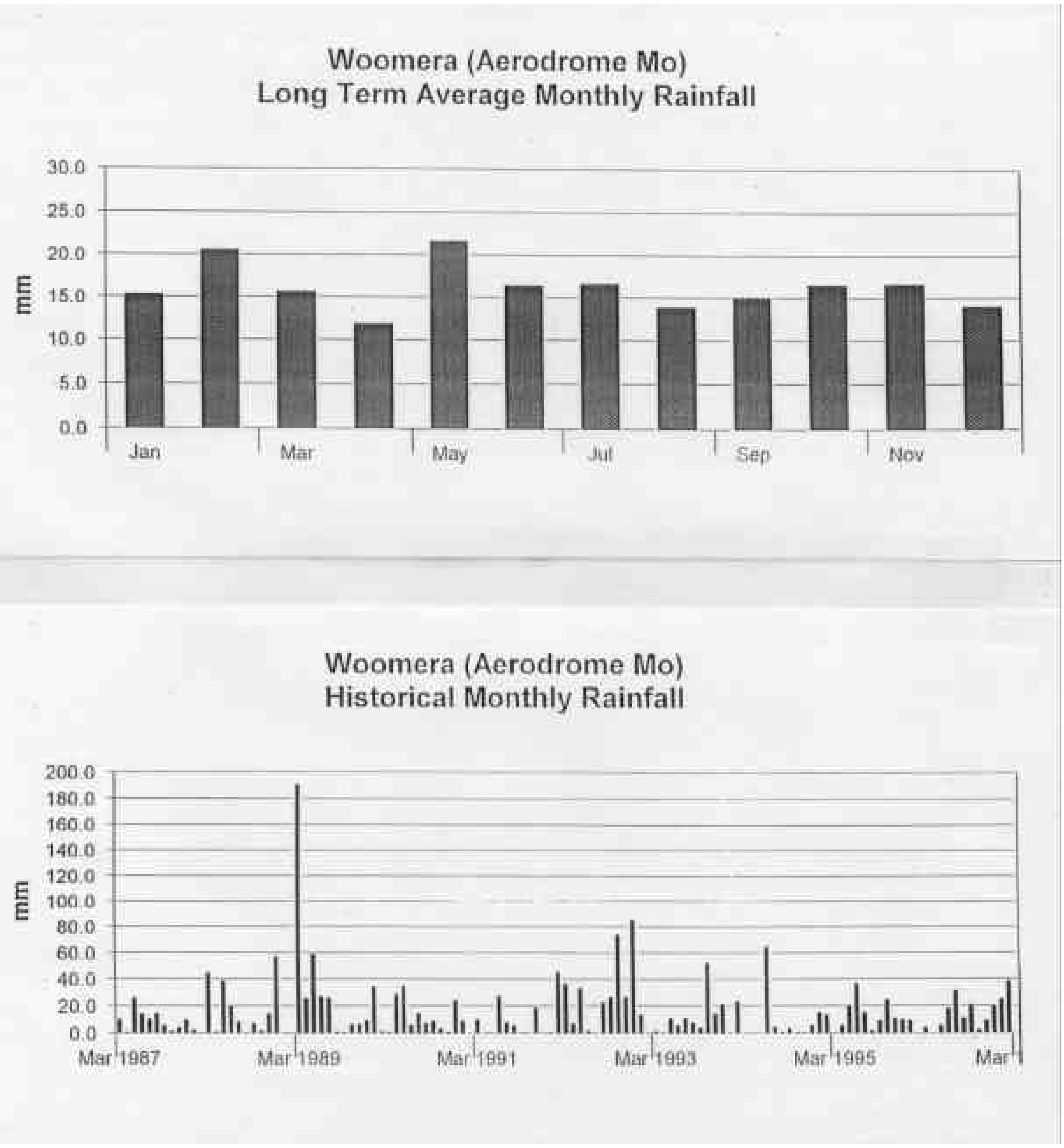

Figure 4.1 Rainfall measured at Woomera Aerodrome

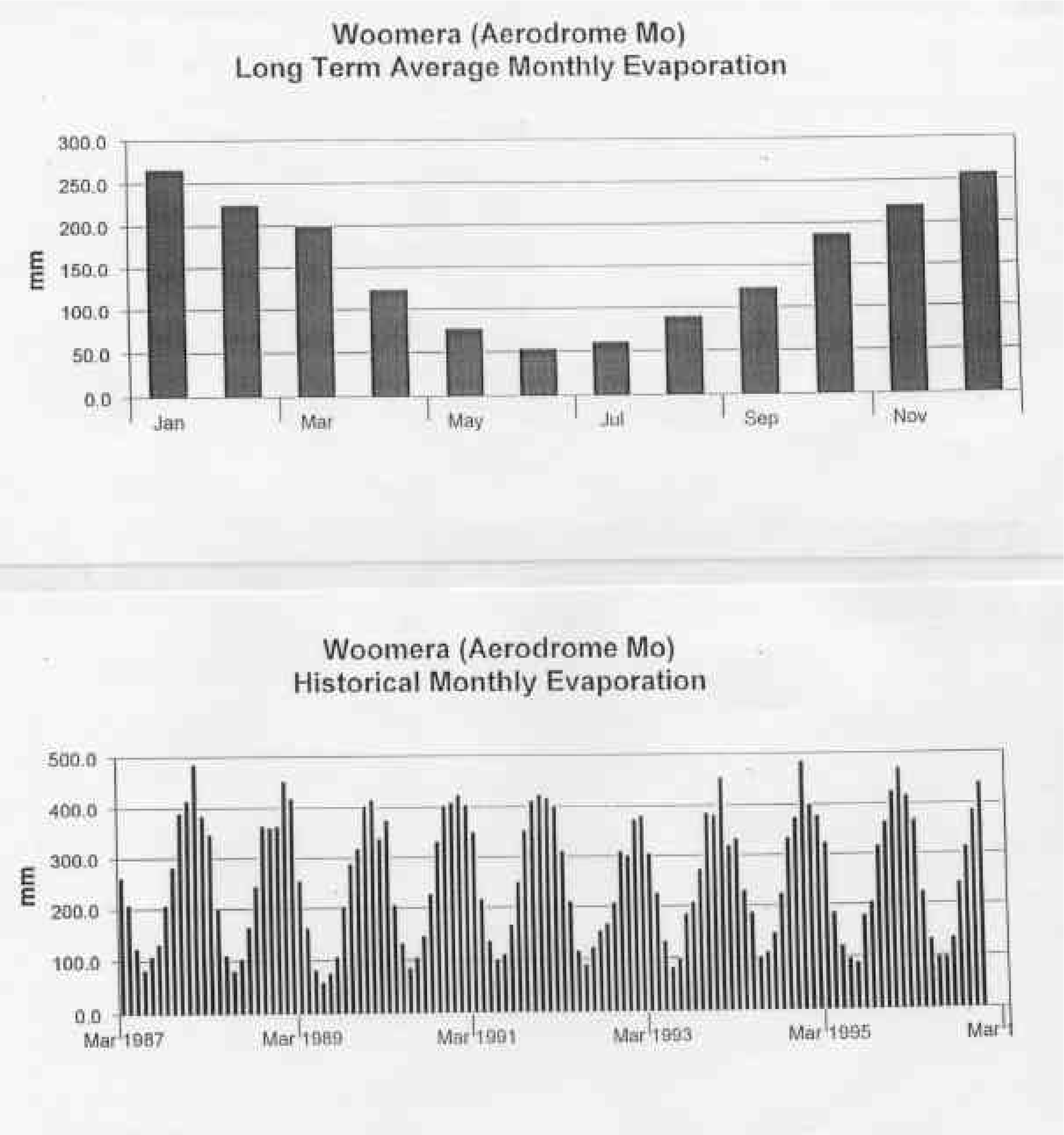

Figure 4.2 Evaporation measured at Woomera Aerodrome

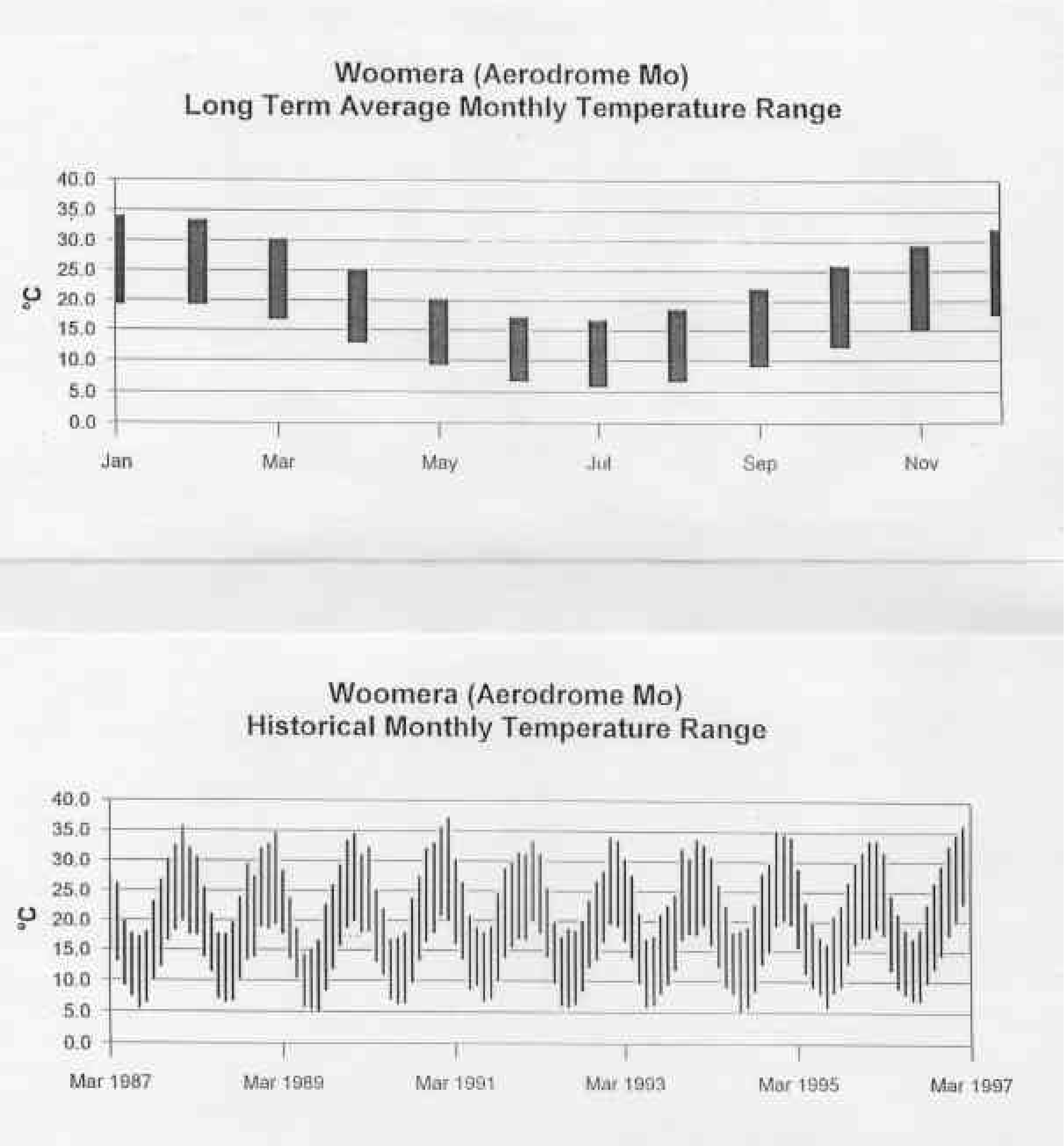

Figure 4.3 Air temperature measured at Woomera Aerodrome

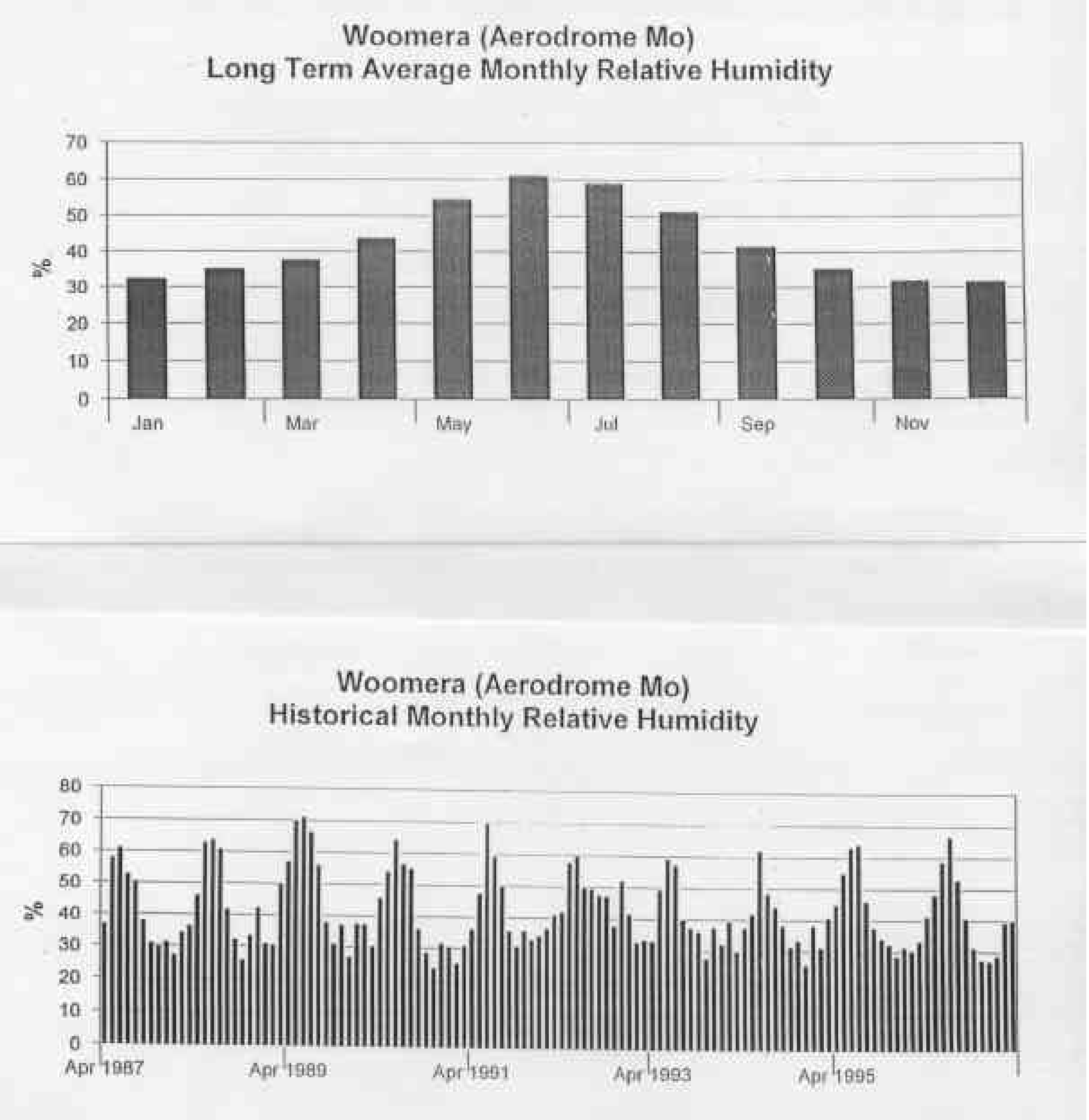

Figure 4.4 Relative humidity measured at Woomera Aerodrome

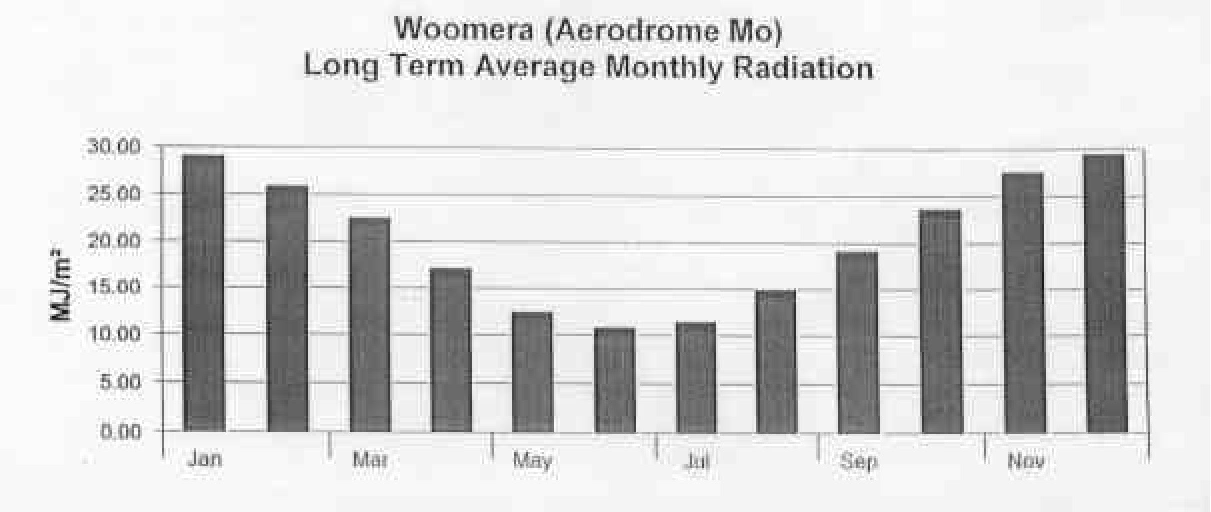

Figure 4.5 Solar radiation measured at Woomera Aerodrome

Exemplary profile descriptions are provided in the Handbook. "Soils, an Australian Viewpoint" (CSIRO, 1983) also offers comment on the soils and geomorphology of the area.

The soils are old and deeply weathered, and tend to be sodic at the surface with accumulations of divalent cations, e.g. calcrete, at depth. The surface sodicity results in structural instability during rainfall, which substantially restricts infiltration. The soils range from uniform profiles to gradational ones of medium texture. The desert loams tend to have texture contrast features with sandy loam overlying medium clay. There are significant areas of soil with relatively high amounts of smectite relative to kaolinite. This results, even in this environment, in shrink/swell behaviour and areas of gilgai. Such areas would need to be identified and perhaps should be avoided in site selection.

The general distribution of these soils appears to be well-illustrated in 1:100 000 and 1:250 000 colour enhanced LANDSAT TM maps (Wilford, ibid.) and in particular the 1:100,000 sheets he titles Woomera/ Koolymilka and Bon Bon/ Eba. The former lies within [136.30°E; 31.30°S] and [137.15°E; 30.30°S]. The latter lies within [135.00°E; 30.30°S] and [136.00°E; 29.45°S]. Enhanced LANDSAT TM images over these sheets purport to provide soil surface texture information. If this is the case then it can be inferred from them that the Woomera / Koolymilka region has quite extensive and relatively uniform areas of similar soils. The Bon Bon region, for geologic and geomorphological reasons appears much more complicated. Field checking of the LANDSAT TM imagery is required to validate the relationship between soil type and image response.

For illustrative purposes, and on the presumption that the remotely sensed data does permit us to identify soil type differences, we focus attention on the Woomera / Koolymilka sheet. This stretches north and west of Woomera and Pimba. It is bounded in the south by a scarp which borders the large salt Lakes Gairdner, Hart and Island Lagoon. The landscapes north of this scarp are characterised by soils with clay and oxides of iron in the surface. This "plateau" drains sharply to the south and more gently to the north. Approximately 50 km north of Woomera this surface gives way to soils characterised by broadly spaced, linear, wind deposited sand dunes, low, broadly spaced rolling stony rises and some small salinas. Soils here are characterised by hardpans, silcrete and calcrete. Some detail on these landscapes is provided by Graetz and Tongway (1980). The soils tend to show texture contrast features and may have hydraulic behaviour similar to that in the Victorian and South Australian Mallee [for which area Allison and co-workers [see reference list] offer hydrological experience relevant to this study].

Soil surfaces throughout tend to be sodic and structurally unstable. In the south, surfaces are protected by stones [gibbers]. The "dune country" is subject to significant sheet erosion by both water and wind. Milnes and Wright (1993) describe features of the landscape. An early description of the landscape, soils and vegetation is given by Jessup (1951). Two "characteristic" profiles from Pimba [136.9^{o}E, 31.4^{o}S] and further north and west [135.0^{o}E, 29.0^{o}S;] are attached in **Appendix A**.

Thickness of the soils and subsoils is around 2m on the plateau west and northwest of Woomera. It gradually increases to about 5m toward the "dune country. Preliminary landform data also developed by Wilford (ibid.) from remotely sensed information suggest that these soils overlie saprolite of unknown thickness which grades into the Arcoona quartzite. The regional ground water tables lie 30-50m below the ground surface. In the topographically lower areas of Island Lagoon and Lake Hart the water table is closer to the surface (Kellet, ibid.). The unconfined regional aquifer is fractured Arcoona quartzite which appears to be relatively permeable. The "saprolite" overlying the quartzite permits various interpretations. It my consist of several metres of silcrete or calcrete immediately beneath the solum. This in turn may overlie up to 10m of a kaolinitosed Cretaceous shale [Bulldog shale]. In other cases, the saprolite may consist of silcrete directly overlying weathered quartzite. silts and siltstone. The weathering characteristics of the Arcoona quartzite are unknown.

These soils are much older and more deeply weathered than are arid zone soils in the United States where the majority of arid soil nuclide studies have been conducted. Conclusions about radionuclide movement developed for the radioactive waste disposal facilities in the United States are therefore not necessarily applicable to the CNSA region.

4.2.3 Vegetation

An ecological survey by Graetz et al. (1982) of the south Simpson Desert, together with comments on the soils and vegetation in the vicinity of Roxby Downs, offers some indication of the current and native vegetation. It appears that much of the native vegetation has altered in response to opportunistic grazing and fire over nearly 120 years. The original vegetation included myall [*Acacia pendula* and *A. papyrocarpa*] and bluebush [*Maireana spp*] in the swales of dunes, and mulga [*Acacia aneura*] on the flanks and crests. Some *Casuarina* is present on drainage lines together with *Eucalyptus spp*. Some of the higher surfaces are stony and treeless although saltbush [*Atriplex sp*] is common in some areas.

Some hydrological consequences of the native vegetation were discussed by Graetz and Tongway (1986) who examined the effects of surface cover on infiltration under realistic imposed rainfall on relatively sandy soils of the area. They found that ungrazed soils with a well-established cover of *Atriplex vesicaria* and a well-developed surface cryptogam crust permitted sustained infiltration rates of less than 10 mm/hour and tended to pond in 2-10 minutes, depending on the rainfall rate. Infiltration in disturbed grazed areas, without the lichen crust, ponded in about the same time, but the steady infiltration rates were almost an order of magnitude greater. These data were for deep medium sands. The saturated hydraulic conductivity of the generally sodic medium clay soils is expected to be at least an order of magnitude less that the sandy soils examined by Graetz and Tongway (1986).

Sharma and Tongway (1973) showed that both *Atriplex vesicaria* and *A. nummularia* remove significant amounts of water soluble salts from a depth of 40-60 cm in clay soils in the arid zone profiles. These salts return to the soil surface in leaf fall and litter decomposition.

A. vesicaria is said to be relatively shallow rooted. For example, Sharma (1978) found more than 90% of the roots within the top 20 cm of a profile at Deniliquin in NSW. The depth of penetration of roots accords with speculation that the roots are found where 90% of the extractable water is to be found (Carrodus and Specht, 1965; Jackson, 1958).

Old man salt bush, *A. nummularia,* is deep rooted, with tap roots to be found at depths greater than of 3 m. Both species are said to do well where precipitation is less than 200 mm/year. At the same time, both species appear vigorously to extract water from at least 60 cm of the profile and their influence might be expect to extend to at least 100 cm. These observations are used in the illustrative water balance calculations performed below, but they should be confirmed by field measurement.

4.3 HYDROLOGIC ISSUES

The possible transport by infiltrating water of radionuclides from the repository to the water table is one of the most important pathways that might lead to the release of radionuclides into the environment. Thus, preferred sites are located in relatively arid regions where the water contents in soil profiles are low and fluxes and pore water velocities are very small. This section reviews conventional approaches to the issues of water movement. Two distinct, but complementary, approaches are considered:

i) prediction based on solving the water balance equation;

ii) measurement based on movement of natural or artificial tracers in water.

4.3.1 Water Balance Equation

The water balance equation formally accounts for all sources and sinks for water in the soil hydrological cycle. In the present context, two significant concerns arise: the first relates to the way radionuclides move relatively close to the repository, the second relates to estimation of nuclide transfer deep into the profile towards the water table. Both must be considered in terms of the soil water balance equation as it is applied to the vadose zone. This equation may be stated as follows:

$$D = P - O - E + S_w \qquad (1)$$

in which D is the deep drainage term, P is the rainfall, O is overland flow that might occur during rainfall, E is loss of water to the atmosphere via plants and directly from the soil surface, and S_w is the change in water stored in the soil. The solution of this equation has been much studied over the past century. Generally these solutions are based on Richards' equation which describes transfer of water in the soil with P and estimates of E providing "boundary" conditions for its solution. Richards' equation combines a continuity equation for the water with Darcy's law, which describes the water flux, v, in response to the space gradient of the total potential, F, of the soil water.

Darcy's law, in 1-dimension, is written:

$$u = -k(y)\left(\text{¦}\,\Phi / \text{¦}\,z\right) \qquad (2)$$

In this equation, u is the Darcy flux, and $k(y)$ is the hydraulic conductivity of the soil. The necessary and sufficient conditions on the use of this approach are that the water content, q_w, and k be well-defined functions of the water potential y. We define water content, q_w, here as the volume fraction of the water. y is a result of the interaction of the water with the solid surfaces and their geometry in the generally unsaturated soil. In general, $q_w(y)$ and $k(y)$ are not easily predicted but are readily measured. In Equation 2, z is the vertical space coordinate, +ve upwards, and in its simplest form$F$ is given by:

$$\Phi = y + z \qquad (3)$$

where the potential is defined as work per unit weight of water with convenient dimensions Land units, m of water.

These issues are set out in detail in texts such as Hillel (1971), Jury et al. (1991) and Marshall et al. (1996); their application to unsaturated groundwater flow in the present context is reviewed, for example, by Allison et al. (1994) and recently by Scanlon et al. (1997). A useful Australian survey is offered by Allison et al. (1983).

There are several well-established models that solve equation 1. A model called SWIM [Soil water infiltration and movement] is generally available in Australia and has been extensively tested across the continent. Richards' equation is solved using measured or inferred soil hydraulic properties. SWIM can deal with by-pass flow and vapour transfer and takes account of soil surface evaporation, surface sealing and run-off. It accounts for plant water uptake using conventional root distribution-uptake models and predicts solute movement presuming that so-called "piston flow" occurs. This model assumes that packets of soil water containing soluble salts are displaced in their entirety by succeeding packets with the solute redistributed within and between packets according to a diffusion model. SWIM also permits estimation of exchange reaction using a Freundlich-type exchange isotherm. It may be used at many levels of precision depending on the precision with which material, climatic and vegetation properties are known. SWIM is fully documented by Verburg et al. (1996). We use SWIM below in an illustrative calculation of recharge in the Central Northern South Australia soil in Section 4.4 below.

A model similar to SWIM but with some ability to deal with 3-dimensional flow, called HYDRUS, is also available from the US Salinity Laboratory at Riverside, CA. It requires exactly the same material properties that SWIM requires and its output is very similar to SWIM. The ability of HYDRUS to deal with multi-dimensional flow will be useful in calculating the flows around the actual repository.

It is important to point out that both SWIM and HYDRUS formally solve Richards' equation. They specifically determine the deep drainage term in Equation (1), as well as E and S_w, as part of that solution. Because material balance is central the derivation of Richards' equation, its solutions do not determine any term in Equation (1) as the difference of others. Thus D is effectively calculated using Eq (2) for the potential gradient and hydraulic conductivity estimated sufficiently deep in the profile.

A more complete review of models is provide by Hook (1996). That review confirms that SWIM and HYDRUS, because they incorporate Richards' equation, represent the most advanced approaches to the problem, differing only from others in their class in algorithms used for calculation and parameterization.

4.3.2 Tracer Studies

Scanlon et al. (1997) and Allison et al. (1983) review the use of tracers to infer water flow and recharge rates in arid environments. Allison's group in Adelaide conducted extensive field experiments using tracers, particularly in the Victorian and South Australian Mallee, to estimate recharge in that environment (Allison and Hughes, 1978 and 1983; Allison et al., 1985; Cook et al., 1989, 1994). A report to the Department of Primary Industries and Energy by Harries et al. (1998) offers a well-focused and practical guide to the use of radioactive tracers to predict the long term transport of nuclides in the arid zone.

These approaches are based on the notion that a detectable tracer (such as tritium, chloride or chlorine-36) will be concentrated when the rain containing it is concentrated by evaporation in the soil profile. The subsequent movement of that local concentration in a relatively dry soil will be affected by hydrodynamic dispersion but will, overall, obey a piston-like transfer with its velocity, V, reflecting the flux of the water according to the equation

$$V = u / q_w \tag{4}$$

The concentration of each years "peak" will differ from that of its neighbours, because of annual variation of the tracer and because of seasonal variation in evaporation. While such analyses remain somewhat contentious because of assumptions about past climate, useful order-of-magnitude site estimates of water flux and water velocity are obtained.

The tracer studies in South Australia and Victoria indicate that the rates of recharge (fluxes) in the Mallee are of order 1-10 mm/yr with rates in the arid zone of Alice Springs an order of magnitude less. The rates in the Mallee appear to be significantly reduced in areas where natural vegetation remained, although deep rooted vegetation caused some confusion in the interpretation of measurements.

4.4 WATER BALANCE CALCULATIONS

This section provides the water balance calculations for conditions expected in the CNSA region. Three sets of calculations are performed using data and properties inferred in relation to the two soil profiles set out in the Attachments. Weather data were taken from MetAccess files as illustrated in **Figures 4.1-4.3**. The water relations of the soils were inferred from the soil texture profiles using methods discussed by Verburg et al (1996). Some values were estimated from infiltrometer studies at Roxby Downs by Tongway and Graetz (1989), and they were supported by infiltration detail published by Jackson (1956) for soils 100 km south of Woomera. The effect of vegetation on these systems is simulated using data on *A. vesicaria*.

Representative profile and vegetation properties necessary to model the soil water regime are set out in the **Tables 1, 2** and **3**. For illustrative purposes the soils are considered to have, at most, two identifiable layers together with a surface crust. These are not restrictions imposed by the water flow model. A catenary sequence across an idealised sand-dune system encapsulates the widest range of profile behaviour.

The calculations are also restricted to a maximum depth of 100 cm on the grounds that existing vegetation cannot extract water from below this depth so water below this depth can only move downwards as deep drainage. Again, this is not a restriction imposed by the water flow model. In passing we note that extreme diurnal soil surface temperature variation might also transfer water vapour. The effect will generally be of second order, however, and probably of greatest influence during the winter. It will result in some diminution in the soil water store.

SWIM was run for each of the exemplary soils in **Tables 1-3** using

a) monthly average rainfall and evaporation data over 13 months shown in Figs 4.1 and 4.2;

b) historical daily rainfall and evaporation data for the 27 year period 1969-1996

For each type of climatic data input we investigated the effect of:

a) the presence or absence of vegetation; and

b) the presence or absence of a cryptogam crust.

TABLE 1
Sand Dune Profile

	Presence and depth	Comments
General		This profile represents the relatively deep sand profiles found on the crests of the parallel dunes in the north and west of Central Northern South Australia. It is assumed the profile has a stable cryptogam crust as described by Graetz and Tongway(1979), and is colonised by *Atriplex vesicaria*. No account is taken of annual or perennial grasses/forbs.
Surface		Surface structure is stable, stores~10mm of water before run-off.
Vegetation	Yes	*A. vesicaria* model; xylem potential=-150m; root depth constant=200mm; root length density=LD 3.5
Surface crust	0-10 mm	Cryptogam; k_{sat}=7mm/h; maximum conductance=0.7/h; [=minimum conductance].
Topsoil	10 mm –200 mm	Medium sand, k_{sat}=70 mm/h; porosity=0.35; θ_{sat}=0.33;
Subsoil	200 mm-2000 mm	Medium sand, k_{sat}=70 mm/h; porosity=0.35; θ_{sat}=0.33;

TABLE 2
Solonetz Soil (E.A.Jackson, 1956)

	Presence and depth	Comments
General		This profile represents the texture contrast soil [Subnatric sodosol] with a stable cryptogam crust as described by Graetz and Tongway(1979). It is "undisturbed" and is colonised by *Atriplex vesicaria*. At this stage no account is taken of annual or perennial grasses/forbs. It is on the lower slopes of the dune.
Surface		Surface structure is stable, stores~10mm of water before run-off.
Vegetation	Yes	*A. vesicaria* model; xylem potential=-150m; root depth constant=200mm; root length density=LD 3.5
Surface crust	0-10 mm	Cryptogam; k_{sat}=7mm/h; maximum conductance=0.7/h; [=minimum conductance],
Topsoil	10 mm –200 mm	Medium sand, k_{sat}=70 mm/h; porosity=0.35; θ_{sat}=0.33;
Subsoil	200 mm-2000 mm	Sodic and alkaline medium clay, k_{sat}=0.1 mm/h; porosity=0.45; θ_{sat}=0.43

TABLE 3
"Pimba" Soil (C.G. Stephens, 1962)

	Presence and depth	Comments
General		This profile represents the uniform soil [Sodic, mesotrophic dermosol] with a structurally unstable surface. It is "undisturbed" although it has been grazed by "hoofed" animals and is colonised by *Atriplex vesicaria*. At this stage no account is taken of annual or perennial grasses/forbs. This soil is characteristic of the profiles found in the swale of the dune system, although the actual profile was described near Pimba.
Surface		Surface structure is unstable because of sodicity, stores~10mm of water before run-off
Vegetation	Yes	*A. vesicaria* model; xylem potential=-150m; root depth constant=400mm; root length density=LD 3.5
Surface crust	0-20 mm	Structure is unstable and a crust forms in proportion to the rainfall; k_{sat}=1 mm/h decreases to 0.01 mm/h as structure falls apart; maximum conductance=0.5h^{-1} decreasing to minimum conductance =0 0005 h^{-1};
Soil	20 mm-2000 mm	Sodic and alkaline medium clay, k_{sat}=0.1 mm/h; porosity=0.45; θ_{sat}=0.43;

4.4.1 Water Balance Results

Table 4 lists the results of the SWIM calculations of water balance. The data for the solonetz soil are most illuminating and we examine these data in the sets characterised by the different climatic period first.

a) Monthly average rainfall and evaporation data over 13 months. These data exemplify the problem with using monthly averages. In these circumstances models deal with rainfall intensity within each month as an average. The results then grossly underestimate runoff associated with intense storms which often occur in the Central Northern South Australia area. The results exemplify this and no runoff is predicted by the calculations based on monthly averages, or rests, for even the most impermeable soil [the medium clay with an impermeable crust]. The approach is used no further.

b) Historical daily rainfall and evaporation data for the 20 year period 1969-1996. Daily data provide the finest resolution of climatic information generally available. These data sets retain some of the averaging difficulties in calculating the effects of severe storm events, although evaporation data are probably relatively reliably treated as daily averages. Neglect of intense storms within a day overestimates infiltration and underestimates runoff so the model inevitably sets a worst case scenario by overestimating deep drainage.

Using these climatic data on the Solonetz soil, we found that of the total precipitation of 586 cm, about 9 cm ran off, 577 cm evaporated and, in the presence of vegetation 0.004 cm drained from the profile. In the absence of vegetation 2.9 cm drained from the profile. Even this latter number is still small since it is the cumulative amount over 27 years; it corresponds to an average recharge rate of 0.11 cm/year.

TABLE 4

Calculated water balances based on SWIM calculations for the period 1969-1996

During this period a total of 586 cm of rain fell, and the total evaporation
from a free water surface was approximately 51 m.

	Soil	Deep drainage	Runoff
Vegetation	Solonetz soil	0.0042 cm/27 years = 0.00016 cm/yr	8.75 cm /27 years. =0.324 cm/yr
	Sandy soil of dune crest	3.52 cm/27 years = 0.13 cm/yr	Zero
	Medium clay soils	0.0041 cm/27 years = 0.0005 cm/yr	0.44 cm/27 years =1.63 cm/yr
No Vegetation	Solonetz soil	2.92 cm/27 years =0.108 cm/yr	9.915 cm/27 years =0.37 cm/yr
	Sandy soil of dune crest	18.33 cm/27year =0.68 cm/yr	Zero
	Medium clay soils	0.0041 cm/27 years 0.00015 cm/yr	0.4427 cm/27years =1.64 cm/yr

By contrast, the sandy soil of the dune crest, during the same 27 year period, produced no run-off and contributed about 18 cm in deep drainage in the absence of vegetation but only 3 cm in the presence of vegetation. The vegetated dune data exceed by an order of magnitude the results obtained by Allison et al. (1985) based on isotope measurements on well-vegetated dunes in the Murray mallee of South Australia. In that case however the vegetation was deep rooted mallee rather than the very shallow rooted *A. vesicaria*. Interestingly, Allison's estimates of deep drainage in the cleared dunes corresponds almost exactly with ours of ~0.7 cm/year for cleared dunes. It is rather less than the **maximum** rates estimated, using chlorine-36, for soils in the vicinity of Broken Hill by Harries et al. (1998). The climate there is similar but a little wetter than that in the CNSA region. These correspondences are encouraging.

Deep drainage in the medium clay soils was insignificant under all circumstances.

SWIM also offers an opportunity to explore the consequence of particular historical climatic sequences and their outcomes in terms of deep drainage and runoff. Two contrasting periods within the 27 year run of data are examined here using the data for the Solonetz soil.

a) 1974 was the wettest year in the sequence. In that year, 49.3 cm of rain fell, with 10 cm falling in May, the wettest month. The rainfall run for the year is shown in **Figure 4.6**. As this Figure shows, the rain in May was preceded by significant rain earlier in the year. SWIM indicates that the soil profile was relatively wet and while almost 50% of the May rain (3.4 cm) ran off, the wet profile transferred most of the remainder (1.5 cm) to deep drainage. This deep drainage represents more than 50% of the 27 year total. The runoff represents about 30% of the 27 year total.

b) In early March 1989, following an extended dry period, 19.2 cm of rain fell with the wettest daily total 13.8 cm on 14 March 1989 (**Figure 4.7**). The profile at the beginning of this event was very dry. The soil effectively stored, close to the soil surface, all the rain that infiltrated.

> Subsequent drainage following redistribution and evaporation from the soil and through the vegetation was minimal. The intensity of rain however was such, even on daily rests, that almost 5 cm of rain ran off. This was more that 50% of the 27 year total runoff from the site.

Thus the wettest single day in 1989 resulted in much runoff, and the rest of the rain merely filled dry soil and, in time, was evaporated. In the wettest year (1974), a period of more modest rain resulted in some runoff and the rest of the rain added to already moist soil from which a small proportion drained, but this drainage was more than 50% of the total drainage in the whole 27 years.

4.4.2 Discussion of Water Balance Results

The low recharge derived using the illustrative calculations, discussed above, supports the likelihood that suitable repository sites will be found in the CNSA region. The water flow model, using profile and vegetation data inferred from field reports, predicts recharge rates which are consistent with some field observations. The results indicate that there will be very little deep drainage on soils with sodic heavy clay subsoils and well established *A. vesicaria* cover.

These observations require qualification:

a) Firstly, the illustrative calculations are based on reasonable, but estimated, soil profile properties. These properties should be confirmed with careful measurements from specific sites.

b) The medium clays are sodic and may have columnar structure below about 40 cm. There may then be flow in preferred channels separating the columns of soil. This is only likely to be important for short periods of time and it is unlikely that preferred channel flow will penetrate to a significant depth. In addition, some clay soils, which have gilgai micro relief, may still be active. This implies that infiltration in the depressions may be locally significant and soil movement may affect building foundations and repository seals.

c) While these estimates demonstrate the suitability of some soil types of the area, the operation of the repository and the design of the covers will be critically important. After burial of waste, the soil surface should be managed to at least re-establish the conditions which existed before pits are opened. This would ensure that any radionuclides released from the waste would be expected, in the worst case, to move with water in the vadose zone towards the water table. The most mobile nuclide will be tritium or tritiated water which will move at the same rate as the water. All other radionuclides will be retarded to an extent depending on their reaction with the surface of the soil solid (see section 4.5).

The data offer an estimate of the transit time of water moving from the repository at a depth of [say] 5m to a depth of say 50 m in a soil where $\theta_v \approx 0.1$ [this seems a common figure for these landscapes]. If the recharge rate is of order 1.5×10^{-4} cm/year in a profiles with medium clay, the velocity of the water will be of order 1.5×10^{-3} cm/year and the transit time to 50 m will be of order 10^6 years. On the other hand, the highest rates of recharge in the cleared sand soils of 0.68 cm/yr, yields a transit time of approximately 660 years.

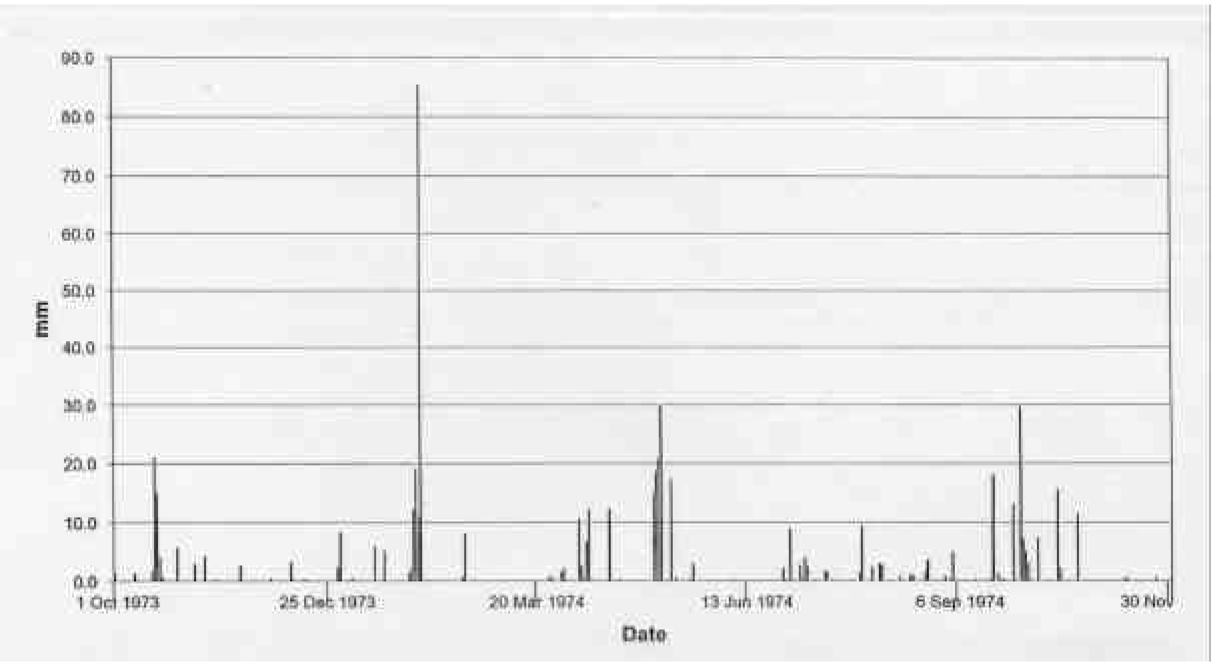

Figure 4.6 Daily rainfall for 1973/74 measured at Woomera Aerodrome

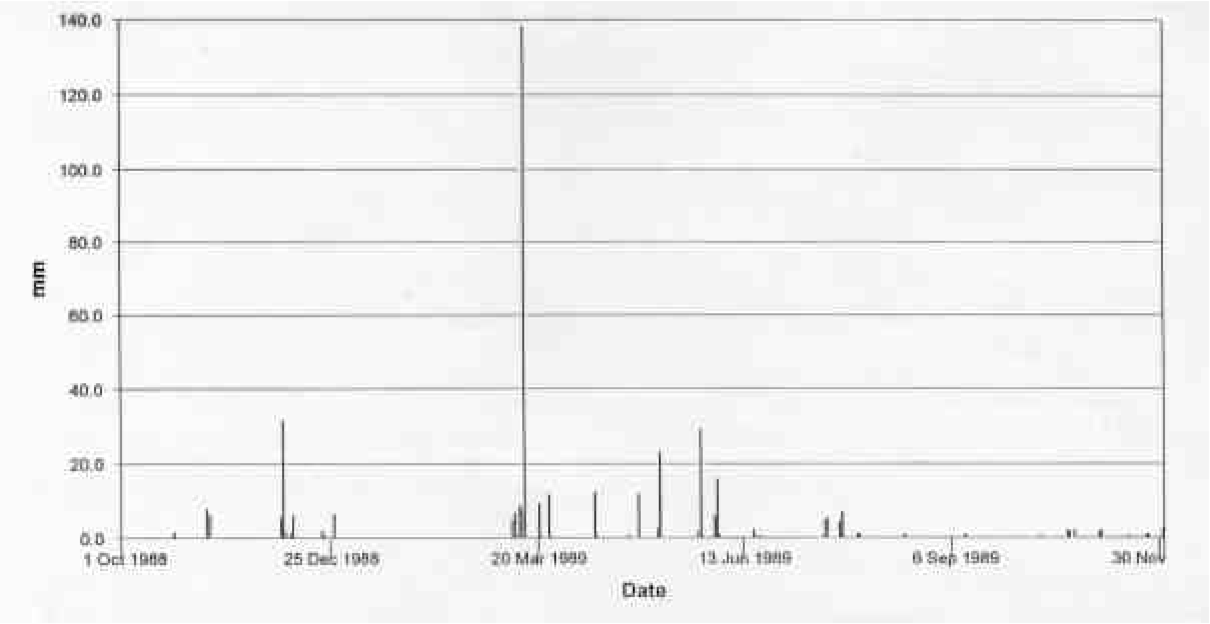

Figure 4.7 Daily rainfall for 1988/89 measured at Woomera Aerodrome

4.5 RADIONUCLIDE MOVEMENT

4.5.1 Radionuclides of importance

The material for disposal at the repository will contain many different radionuclides, with its composition depending on the source of the waste. In Australia, radioactive waste is generated by medical, research and industrial applications, the operation of research reactors, the production of radiopharmaceuticals. It might also include material derived from the clean-up of contaminated sites and mineral processing wastes (but not from uranium mines).

Nuclides which are important in assessing the safety of the repository are listed in **Table 5**. This list includes radionuclides that are responsible for most of the radioactivity in a repository, as well as the long-lived radionuclides that are important in the assessment of the long-term safety of the repository after closure. The relatively short lived radionuclides tritium and cobalt-60 are included because they are likely to contribute a significant proportion of the total radioactivity in the repository. Tritium and technetium move with water in the soil and reveal little retardation.

The amount of each of these radionuclides in the Australian repository is uncertain. The composition of Australian radioactive wastes will be quite different from the waste composition in countries with nuclear power systems. Column 3 in **Table 6** lists a nominal inventory of the radionuclides in 10,000 m^3 of radioactive waste assumed to be in the repository at closure. This inventory is based partly on estimates of the Australian inventory by Camilleri (1992) and on Talbott and Gelhar (1994), who provided a nominal inventory for a much bigger generic US repository designed for 10^6 m^3 of waste. The Talbott and Gelhar inventory was based on the assumption that 75% of its waste was received from non-fuel aspects of the nuclear power industry and 25% from industrial, medical and academic sources. We assume that 1 % of this inventory would approximate Australia’s inventory. In addition, the inventories of fission products Sr-90, Tc-99 and I-129 are based on the 20 TBq inventory of Cs-137, assuming that these radionuclides are present in the same ratios as they as produced in the thermal fission of uranium. The relative inventory of the activation products Ni-59 and Ni-63 is based on differences in half-lives and neutron activation cross-sections.

4.5.2 Factors influencing radionuclide retardation in the geosphere

The migration of a radionuclide in groundwater is usually much slower than the rate of water movement. This is because mechanisms such as chemical precipitation or adsorption remove the radionuclide from the aqueous phase and deposit it on the matrix of the aquifer. Hydrodynamic dispersion [including diffusion] also affects transfer; they are discussed elsewhere.

If a radionuclide is present at concentrations exceeding the solubility of a solid phase, it will precipitate from solution. In this context, the word ‘precipitate’ has a distinct meaning, and refers to the formation of a solid phase from dissolved species, as represented in a reaction such as:

$$Ca^{2+} + 2\ UO_2^{2+} + 2PO_4^{3-} \Leftrightarrow Ca(UO_2)_2(PO_4)_2 \text{ (autunite)} \qquad (4)$$

This reaction expresses the formation of autunite from dissolved Ca, U and P species. Each precipitation reaction has an equilibrium constant, and the solubility of the mineral in contact with a given solution phase can be readily calculated. If this solubility is exceeded, the mineral will precipitate, and solubility therefore places an upper limit on dissolved radionuclide (in this case, dissolved U).

TABLE 5
Radionuclides of Importance for the Australian Repository

Nuclide	Half-life (years)	Nominal Inventory TBq	Production
H-3	12.3	1000	Produced by neutron activation of deuterium. Present in wastes from research reactors using heavy water and biological research.
C-14	5,730	1	Present in activated metals from reactors, sealed sources and animal carcasses used in research.
Ni-59	76,000	0.01	Produced by neutron activation of Ni-58 (68% of natural nickel) with cross-section = 4.6 b. Nickel is present in stainless steel (0 to 22 %) and structural steels in reactors.
Co-60	5.27	20	Produced by neutron activation of Co-59 (100% natural cobalt) with cross-section = 37 b. Cobalt is found in structural steels in reactors and widely used in sealed sources.
Ni-63	100	0.1	Produced by neutron activation of Ni-62 (3.6% of natural nickel) cross-section = 14.2 b. Nickel is found in stainless steel (0 to 22 %) and structural steels in reactors.
Sr-90	28.6	20	A fission product with a yield of 5.93% in thermal fission of U-235.
Nb-94	20,300	0.001	Produced by neutron activation of Nb-93 (100% of natural niobium) cross-section = 1.1 b. Niobium is present as a minor constituent in some stainless steels and as a trace constituent in nickel based alloys such as INCONEL. Not produced in fission.
Tc-99	213,000	0.01	A fission product with a yield of 6.1% in thermal fission of U-235.
I-129	1.57×10^7	0.0001	A fission product with a yield of 0.72% in thermal fission of U-235.
Cs-137	30.1	20	A fission product with a yield of 6.23% in thermal fission of U-235.
Ra-226	1600	1	A decay product of U-238 and a waste from early medical usage.
Th-232	1.41×10^{10}	10	A naturally occurring radionuclide, and a by-product of the mineral sands industry.
Np-237	2.14×10^6	0.001	Produced in reactors by neutron absorption on uranium. Mainly present as a decay product of Am-241 and Pu-241.
U-238	4.47×10^9	1	A naturally occurring radionuclide.
Pu-239	24,100	0.001	Produced by neutron absorption in U-238. Possibly present in very small amounts. Occurs in uranium irradiated in a reactor.
Am-241	432	2	Produced by neutron absorption in U-238 and Pu-239, and a decay product of Pu-241. Used in domestic smoke detectors.

Note: 10^6 Bq = 1 MBq, 10^9 Bq = 1 GBq, 10^{12} Bq = 1 TBq and 10^{15} Bq = 1 PBq

The likely solubility controls on releases from a high-level waste repository have been discussed by Langmuir (1997). While the geochemistry and waste composition of the low-level Australian repository will be different, it is instructive to review the conclusions which were derived. In one groundwater chemistry which was considered, (relatively oxidising at pH 7.4), it was concluded that the solubility of Am, Ra, Pu, and Th would be below 10^{-5} mol/L in all conceivable conditions. However, U and Np were relatively soluble, with limiting concentrations as high as of 10^{-2} mol/L. Finally, Tc was not limited by solubility under oxidising conditions. It must be emphasised that solubility only sets an upper limit on dissolved concentrations, and is therefore indicative of the worst-case scenario. Langmuir commented that concentrations of I-129 and Tc-99 would not be usefully limited by solubility in oxidised water. Other radionuclides such as Ra, Np and U may have potentially high solubility. Langmuir concluded that sorption reactions would significantly delay the escape of these isotopes and short-lived isotopes (e.g. Cs-137 and Sr-90) to the accessible environment.

As implied by the preceding discussion, chemical precipitation is only significant when concentrations exceed solubility limits. For most radionuclides, retardation occurs at lower concentrations, due to the mechanisms of adsorption and desorption. These are surface processes by which a solute is bound (adsorbed) or released (desorbed) by sites on the surfaces of minerals and organic matter in the soil. Generically these processes are referred to as sorption. Sorption causes most chemical species to be retarded relative to the water flow. The complex sorption interaction is simplified and expressed in terms of a distribution coefficient, K_d. K_d is a partition coefficient representing the relative amount of the radionuclide sorbed onto the soil and in the equilibrium solution.

The principles relating K_d and contaminant migration can be demonstrated with a simple one-dimensional case. Consider a water-saturated porous medium containing a contaminant. Provided that the partitioning of the contaminant between the solid and liquid can be adequately represented by sorption, the retardation factor R_f, is (Freeze and Cherry 1960):

$$R_f = 1 + \frac{r_b K_d}{q_w} \tag{5}$$

where ρ_b is the dry soil bulk density (kg/L), K_d is the distribution coefficient (mL/g i.e. (mg species/g of soil solid)/(mg species/mL soil solution)) and q_w is the volumetric moisture content. The term R_f is, in simple terms, the ratio of the speed of the moving water to that of the retarded constituent.

K_d therefore provides an estimate of the migration rate, and may have a range of values. The sorption effect depends on the chemical properties of the element, hence the K_d value is the same for all isotopes of an element. The value of K_d depends on the element in question, the chemical conditions of the groundwater, and properties of the solid (such as its surface area, mineralogy, surface charge etc). Typically some elements (such as iodine) have relatively low K_d in a range of geochemical environments, whereas others (such as thorium) have very high K_d values and are virtually immobile in most types of natural environments. However, the value of K_d for a single element may cover a range of orders of magnitude depending on the system in question.

4.5.3 Compilations of distribution coefficients

Several compilations of K_d values have been published. McKinley and Scholtis (1992) published lists of K_d values that have been used in safety assessments for a range of geological media. They note that the selection of K_d values for transport models is often ‘conservative’, in order to ensure that the models over-predict radiological consequences (err on the side of safety). A conservative K_d value would be lower than the expected or real K_d value. In their review, McKinley and Scholtis selected ‘best estimates’ (also described as ‘real’ or ‘mean’ values) when more than one K_d was given in each database. Their ‘best estimates’ for soil and surface sediments are listed in **Table 6**. These data are for studies in the UK, Switzerland, Canada and Belgium. Also listed in **Table 6** are data from a compilation by Sheppard and Thibault (1990) based on published K_d values for sand, loam and sand.

The order of elements in **Table 6** is based on the grouping developed by McKinley and Scholtis (1992). This grouping is further discussed below. Note that **Table 6** contains some elements, such as Se, Pd, Sn and Zr that are not important in assessing the safety of near surface repositories. These have been included here because they show the similarity of K_d values for elements with similar chemical properties. Some of the data from **Table 6** are presented in graphical form on **Figure 4.8**. This shows more readily the trends in the data-sets.

TABLE 6
Compilations of Representative K_d values (mL/g)

	Sand and Surface Media	Sand	Loam	Clay	Geom mean
source	McKinley and Scholtis (1992) 'best estimates'	Sheppard and Thibault (1990)			
Cs	100 to 2000 (n = 6)	280	4600	1900	660
Sr	10 to 100 (n = 5)	15	20	110	32
C (inorg)	0 to 100 (n = 5)	5	20	1	3.2
I	0 to 10 (n = 5)	1	5	1	1.2
Se	1 to 50 (n = 8)	150	500	740	28
Co	60 to 5000 (n = 3)	60	1300	550	440
Ni	10 to 1000 (n = 5)	400	300	650	140
Nb	30 to 5000 (n = 3)	60	500	900	180
Pd	4 to 100 (n = 5)	55	180	270	32
Sn	50 to 700 (n = 5)	130	450	670	190
Zr	10 to 8300 (n = 6)	600	2200	3300	660
Tc	0 to 5 (n = 6)	0.1	0.1	1	0.21
Am	100 to 8800 (n = 5)	1900	9600	8400	2500
Np	10 to 1000 (n = 6)	5	25	55	36
Pu	300 to 10000 (n = 6)	550	1200	5100	1400
Ra	10 to 100000 (n=11)	500	36000	9100	1400
Th	800 to 60000 (n = 6)	3200	3300	5800	4400
U	20 to 1700 (n = 6)	35	15	1600	98

Note: For the geometric mean, a value of zero was taken to be equivalent to 0.01.

Based on their K_d values for soil and surface sediments, the radionuclides of importance for assessing the performance of a near surface repository fall into the following six categories (based on the discussion in McKinley and Scholtis, 1992):

- Tritium is a special case because it occurs as tritiated water with no retardation relative to pore water movement, see also Smiles *et al.* (1995).
- The alkali/alkaline earth elements (caesium and strontium) show relatively narrow ranges (about an order of magnitude) with the midpoints of these ranges about 500 and 50 mL/g respectively. The K_d for strontium tends to be less than that of caesium by a factor of 2-10.
- The anionic non-metals (p-group elements) (inorganic carbon (i.e. carbonate), iodine and selenium) generally have low sorption (around 10 mL/g) because they tend to be repelled by

the predominantly net negative surface charge characteristic of soil minerals. The NRPB assumed zero sorption for this group of elements.

- The transition metals (cobalt, nickel, niobium, palladium, zirconium and tin) tend to have K_d values that lie in the range of 10 - 1000 mL/g with the higher values for zirconium.
- Technetium is treated separately because of its importance and its very low sorption in oxidising systems. The value of K_d varies from 0 in oxidising systems to 250 mL/g in reducing systems. Soils are generally oxygenated and very low or zero sorption of technetium is assumed.
- The actinides (americium, neptunium, plutonium, radium, thorium and uranium) are generally strongly sorbed. Americium, plutonium and thorium have with K_d values from 100 to 100,000 mL/g. The sorption for uranium and neptunium is significantly lower with K_d from 10 to 100 mL/g.

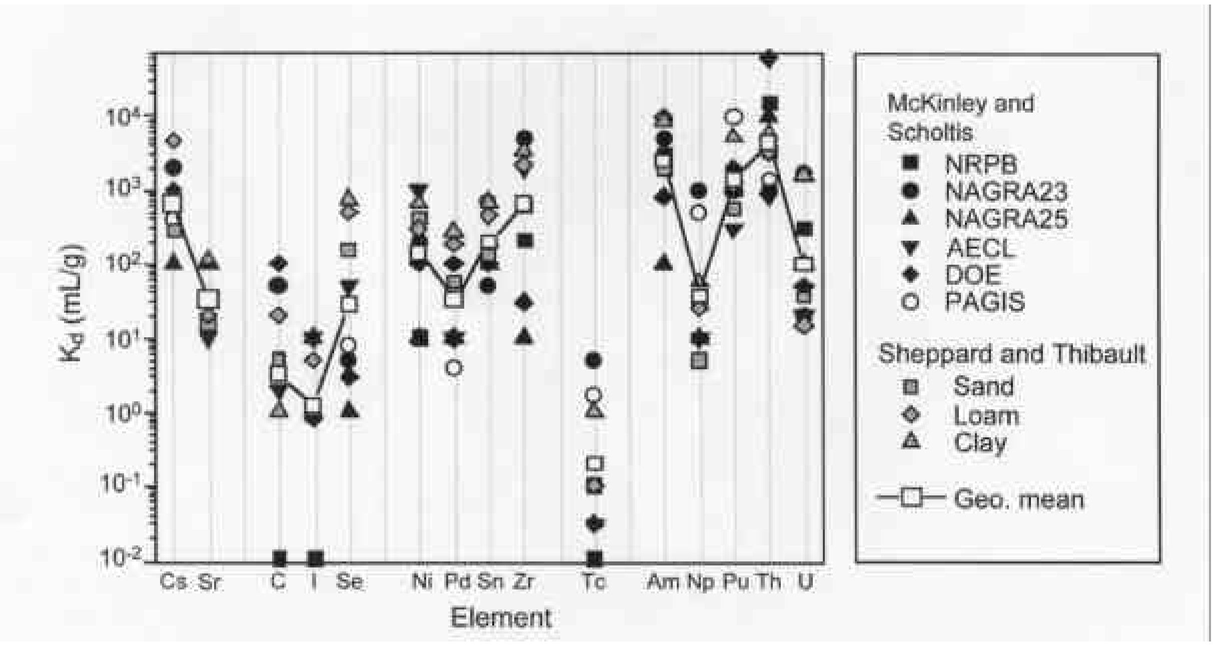

Figure 4.8 K_d values for sand and surface sediments

The wide range of K_d values for each element in these compilations probably reflects a diverse range of water chemistries and experimental conditions. Nevertheless, there are some systematic trends, such as the low K_d values for Tc and the high values for Pu or Th. Comparison of the geologic substrates surveyed by Sheppard and Thibault (1990) show that the K_d values for sand are lower than the K_d values for loam, clay or organic matter. This reflects the dependence of K_d on the character of the geologic substrate. These K_d values were measured under saturated conditions, but should also apply to transport in the unsaturated zone. The geometric means of the data in **Table 6** are used for the preliminary assessment to be discussed below.

In interpreting the compiled data for K_d values, the strong chemical dependence and site-specific nature of K_d values should be emphasised. Where an element is identified as being of concern, laboratory experiments will be able to provide site specific K_d values. It should be noted that even a low K_d value of 10 mL/g results in significant retardation of 50 to 100 times relative to the water flow.

4.5.4 Preliminary Model of Radionuclide Transport in Arid Soils

The first step in performance assessment is the development of scenarios that can lead to the radiation exposure of members of the public. A range of scenarios is needed to cover both normal operation and extreme events. The activity concentration limits listed in the NHMRC Code of Practice are based on an assessment of various intruder scenarios occurring after the institutional control period. After intruder scenarios, the most important scenarios are usually those based on the transport of radionuclides to the water table and use of contaminated water. For a repository in arid regions, the deep water table and the very low water flux in the vadose zone are important barriers to the release of radionuclides into the biosphere. The first stage of the groundwater exposure pathway is the release of radionuclides from the repository, followed by transport of radionuclides by infiltrating ground water to the water table.

This preliminary safety assessment estimates the likely transport process in the vadose zone of the regolith beneath the repository and above the water table. It includes effects of radionuclide decay, water fluxes, retardation and dispersivity. The transport is calculated using the one-dimensional advection-dispersion equation:

In one dimension, the equations are

$$\frac{\partial C_l}{\partial t} = -\frac{\bar{v}}{R_f}\frac{\partial C_l}{\partial x} + \alpha\frac{\bar{v}}{R_f}\frac{\partial^2 C_l}{\partial x^2} - \lambda C_l \tag{6}$$

where C_l is the radionuclide concentration in the liquid phase (Bq m^{-3}), $\bar{v}$ is the average linear water flux (m s^{-1}), R_f is the retardation, α is the dispersivity (m) and λ is the radioactive decay constant (s^{-1}).

In this preliminary safety assessment, any containment provided by the waste containers or the facility engineering is ignored. If the whole inventory of a particular radionuclide is released as a pulse into a previously uncontaminated soil, the solution of equation (6) is:

$$C_l(x,t) = \frac{I}{2A\sqrt{\pi\alpha\bar{v}R_f t}}\exp\left[-\left(\frac{\left(x-\left(\bar{v}/R_f\right)t\right)^2}{4\alpha\left(\bar{v}/R_f\right)t} + \lambda t\right)\right] \tag{7}$$

where I is the repository inventory of the radionuclide and A is the repository area. The area of the buries wastes at closure is assumed to be 2000 m^2 and the inventory of radionuclides listed in **Table 5** is assumed to be present at closure of the repository.

4.5.5 Calculated Radionuclide Concentrations

The advection-dispersion model, equation (6) has been used to estimate the concentrations of radionuclides in the pore water at a depth 50 m below the surface, which is taken to be 40 m below the repository. The illustrative calculation presented here is based on the geometric mean K_d values (**Table 6**), a volumetric water content of 0.15 and a water flux of 0.68 cm/y, which is for sandy soil of the dune crest with no vegetation (Section 4.4.2). **Figure 4.9** shows the calculated concentration of radionuclides in the pore water 40 m below the repository as a function of time. The model assumes that all radionuclides are released at time zero, that there is no precipitation of chemical species, that there is no significant lateral dispersion and that the soil hydraulic properties, and the same K_d values, extend to at least 40 m below the repository. This is one calculation of the many that would be required in the safety assessment for the repository.

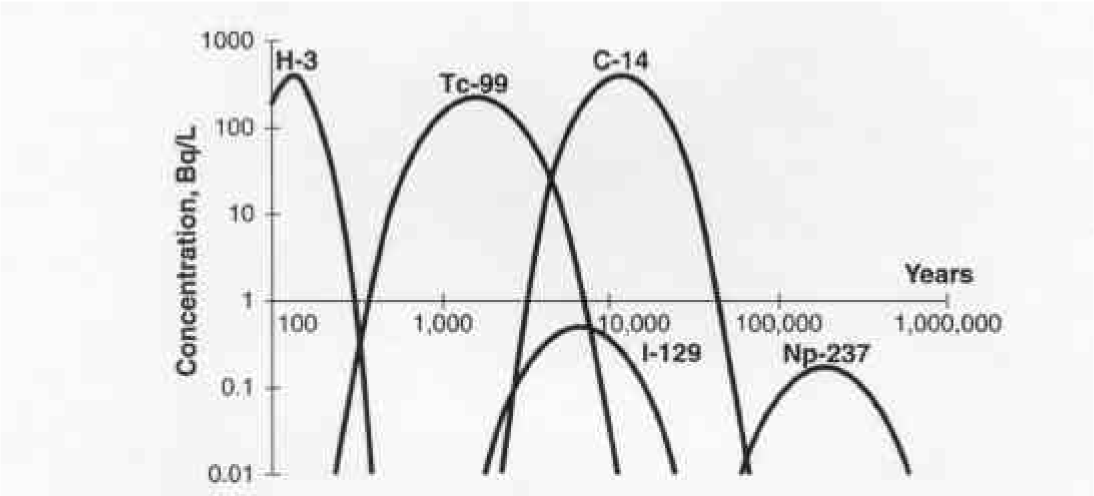

Figure 4.9 Calculated concentrations of radionuclides as a function of time at in vadose zone groundwater 40 m below the repository derived from the advection-dispersion model.

Only five of the radionuclides investigated, (H-3, C-14, Tc-99, I-129 and Np-237), have significant concentrations (greater than 0.01 Bq/L) at the depth of 40 m. Tritium arrives first due to its high mobility, but its short half-life results in its effective disappearance by 500 years. Tc-99, C-14 and I-129 arrive sequentially due to their greater retardation. Finally, Np-237, which has the highest retardation of these radionuclides, appears in the ground water. Most radionuclides are retarded in the soil column for long enough to ensure decay to very low levels.

Figure 4.10 shows the annual doses of radiation that would be received by individuals who drank 1000L/annum of the groundwater containing the concentrations of nuclides shown in **Fig. 4.9**. The public limit for annual dose is 1 mSv/y, so it is evident that at no stage would the groundwater present a threat to health. These calculated concentrations and doses are illustrative; they depend on a particular assumed inventory of radionuclides, estimates of distribution coefficients and assumed soil properties.

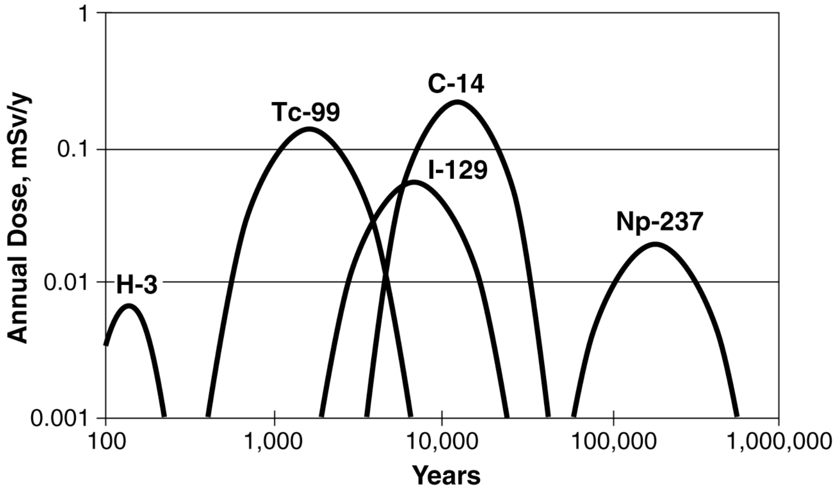

Figure 4.10 Illustrative annual doses received if a person drank 1000 litres of pore water containing the radionuclide concentrations shown in **Figure 4.9**.

4.6 DISCUSSION

This desk study has considered water flow in the soils of the CNSA region and radionuclide retardation for representative radionuclides. The study necessarily used published information to infer important soil and vegetation properties necessary for the calculations. The water recharge calculations appear reasonably reliable, because they are of similar magnitude to estimates based on radioactive tracer measurements made in other semi-arid environments in South Australia and in New South Wales.

The water balance calculations present a "worst-case" scenario because they overestimate deep drainage and underestimate runoff. This is because the time of 1 day over which rainfall is averaged overestimates infiltration and potential deep drainage. For site selection, where estimates of deep drainage are important, these errors are conservative. For engineering design, however, runoff and surface water control may be important. In that case tables of rainfall-run-off, which are available for the region (Pilgrim 1987), would need to be consulted.

Provided the site does not receive runoff from adjacent land surfaces, the recharge in the CNSA region based on the three soil types investigated is expected to be low and suitable for siting a low-level waste repository. There would be an advantage in selecting a site with some silt or clay in the soil under the repository to gain the benefit of the lower recharge rates.

The calculations of radionuclide retardation were also based on published data. In this desk study, we used retardation factors from the literature which might or might not be applicable to sites in CNSA region. There is still uncertainty about the retardation of nuclides in the soil/regolith profile below the repository, because of the wide range of distribution coefficients, K_d. Nevertheless, the data suggest that most radionuclides of importance are strongly retarded in the profile with respect to the movement of water. Silts and/or clays tend to have higher retardation factors than sands so heavier textured soils are more effective than sands in restricting transfer.

Calculations of the effectiveness of the geosphere barrier are based on a uniform and deep profile. The transit time from the release of a radionuclide to when it reaches the water table could be considerably reduced if the flow occurs through preferred pathways. Soils of the area have various surface and subsurface layers, such as calcrete and silcrete, which might channel water flow. While they are thin relative to the overall profile depth to the water table and while the soil water content is low, the effects of preferred pathways is expected to be small.

In general terms, we conclude that the soils and climate of CNSA region appear to be suitable for location of a repository. Clearly, it is important that the repository is on a locally elevated area so that no surface water flows towards the burial zone during extreme rainfall. There is also an advantage in ensuring that the soil/regolith under the repository zone contains some clays and silts to enhance radionuclide retardation, and that the water flow is not channelled into preferred paths.

These observations complement the regolith/landform information developed by Wilford (ibid.). Wilford uses LANDSAT TM data to develop landform maps and prepared images that relate to soil surface mineralogy. Since surface mineralogy is, to an extent, a defining feature of the soils, and since these maps also define local topography and drainage lines, they would permit, in principle, a synthesis of our insights across the landscape of Central Northern South Australia.

Land suitability maps incorporating these features, which also exclude areas closer than 200 m from streams lines, for the Woomera/Koolymilka, and Bon Bon/Eba areas have been prepared by Wilford (ibid.). These maps appear to indicate that the Woomera area is geomorphically relatively simple compared to the Bon Bon/Eba area. They also appear to indicate that a much greater area of continuous land meets these criteria in the Woomera/Koolymilka area.

These observations do not indicate any preference to one or other area, on the part of the authors. We simply observe that these observations offer a useful basis for preparing for field studies. It is also critically important to recognise that these inferences can only be accepted with confidence when the "ground truth" of the remotely sensed LANDSAT TM data is established. The correlation process necessary to establish ground truth must therefore be seen as a top priority for action.

In summary:

a. The climate of CNSA region is arid enough to ensure that it contains sites suitable for a repository.

b. Even permeable sandy profiles will retain the most mobile of solutes for more than 600 years if the water table is about 50 m deep and, with limited local exceptions, if the profile to this depth is uniformly permeable. Residence times for water in the sodic medium clays of the region may be a factor of 1000 times greater than this.

c. Clays will more effectively absorb nuclides, have higher retardation coefficients and generate greater runoff than will sands.

d. Some clay soils have gilgai micro-relief. These soils may still be active and present engineering difficulties. In addition, infiltration in the depressions may be locally significant.

e. Structural instability associated with sodicity may be advantageous because it results in a rapid reduction in infiltration capacity during and following rain.

f. Desirable natural features associated with minimal deep drainage include:

  - deep medium clay soils to reduce deep drainage and retard radionuclide movement;
  - local elevation high with defined drainage patterns to maximise runoff from repository site;
  - stable perennial vegetation and cryptogam surface and/or stony pavement to reduce infiltration, protect the surface from erosion and enhance extraction of water from below the surface.

g. The geology of the weathered zone at the site should be relatively simple so that water fluxes and radionuclide movement can be readily calculated and perhaps more easily managed. In particular, the depth to hard rock, e.g. the Arcoona quartzite, should be should at least 30 m, and preferably 50 m. The Arcoona quartzite is strongly fractured and water flow is channelled by the fractures, in which the radionuclide velocity is greater than might be the case in "unconsolidated" materials.

h. While many soil types of the area have properties that are consistent with repository requirements, the engineering of the repository and particularly the design of the covers will be critically important. After burial of waste, the cover and the soil surrounding the burial facilities will need to be managed to establish hydrological conditions which are as good as, or better than, those existing naturally.

i. The repository should be designed to enhance the desirable natural features. This will require construction of a soil cover of optimum shape to maximise runoff without erosion and to maintain vegetation that protects the surface and helps evaporate water that infiltrates. The cover might also have layers of varying hydraulic properties to ensure discharge of unsaturated flow to the periphery and a layer to reduce intrusion by plants or animals. We note that the water flow model HYDRUS identified above has the 3-dimensional capability needed to facilitate design in these circumstances.

4.6.1 Recommendations

a) Because of the paucity of data available to characterise the soil and land properties, local ground truth of inferences based on remotely sensed LANDSAT TM data and the reliability of LANDSAT TM -based suitability maps must be established. In this context, topographic issues are relatively unambiguous, but soil surface mineralogy needs to be confirmed and the ground significance of the colour enhanced images needs to be established. This will require a local survey, for which the time involved should be modest. With this information, Land Suitability Maps can be refined for the totality of the CNSA region, and a small number of suitable candidate sites selected for detailed investigation.

b) We recommend that representative soils of the CNSA region be collected from several sites of interest for laboratory measurements of mineralogical, hydrological and physico-chemical properties. This should include properties that affect the structural stability of these soils, their mechanical properties and radionuclide distribution coefficients. We suggest a sample initially be collected from 4 profiles and the following measurements be carried out.

Field measurement and sampling:

- profile descriptions in local landscape context, including identification of gilgai;
- soil sampling for laboratory determinations. An indicative protocol envisages backhoe samples to a depth of approximately 2.5m, and auger/drill samples from 10 m, 20 m, 30m and 40 m if possible.

Laboratory measurements on soil samples from the selected sites.

- clay mineralogy;
- exchangeable cations and water soluble salts
- surface structural stability;

- hydraulic properties;
- mechanical properties;
- pore water properties, including pH, redox potential and major solutes;
- soil water content;
- radionuclide distribution coefficients as a function of pH, redox potential and concentration;
- measurement of radionuclide movement in small unsaturated soil columns;

c) We recommend that the water balance approach be used to characterise a small number of candidate sites when appropriate field soil data have been collected. While the deep drainage D in the water balance equation is, in general, a small difference between large numbers in equation (1), the solution of this equation provides important insights into unsaturated flow in the vadose zone and critical information on properties of candidate sites.

d) 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. (1998) 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.

4.7 CONCLUSIONS

This desk study of hydrology and radionuclide movement indicates that the CNSA region offers ample opportunities to locate a national repository for low-level and short-lived intermediate-level radioactive wastes. The study merges environmental physical prediction, theory of nuclide movement in soil and remotely sensed landscape information to offer a strategy for identifying candidate areas and thence suitable sites where the repository could be sited. Because the approach has necessarily been based on inferred, rather than measured, data it is now necessary to provide ground truth for the remotely sensed data and obtain field data and samples to permit more authoritative calculations.

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APPENDIX A

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                    Agency Code : 499    Project Code : TR1          Site Id : A905         Obs. Id : 1

Elevation :                                                  State Name : SOUTH AUSTRALIA
Rainfall   : 170 mm                                          Desc By    : C.G. Stephens
Runoff     : Moderately rapid                                Date Desc  : 31/07/62
Drainage   :
Locality   : PIMBA                                           CLASSIFICATION :
Latitude   : 31.3639 S    Longitude : 136.8722 E             --------------
                                                             Principal Profile Form :
LANDFORM :                                                   Great Soil Group : Desert loam
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Relief Modal/                                                Australian Soil Classification :
Slope Class : Gently undulating plains <9m  1-3%                  SODIC, MESOTROPHIC, RED, Dermosol; (Confidence
                                                                  level 3)
Pattern Type : Plateau                                       Soil Taxonomy :
Element Type :
Relief       :                                               Taxonomic Unit :
Slope        : 0 %
Slope Category :                                             Mapping Unit :

GEOLOGY :                                                    LOCATION :
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Substrate Material :

Geological Reference :
Depth To Parent Material :                                   EROSION :
                                                             -------

SITE DISTURBANCE :
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 No effective disturbance other than
 grazing by hoofed animals
VEGETATION :
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St[illegible]um Form :
 [illegible] Shrub
 [illegible] Stratum Species:
  Atriplex vesicaria;

HORIZON        DEPTH            DESCRIPTION
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          0.00 to  0.12 m   5YR5/4d); Medium clay; Weak, Granular; ; 20-50%, Gravel gravel;

          0.12 to  0.35 m   2.5YR4/6d); Medium clay; , Angular blocky; ;

          0.35 to  0.86 m   2.5YR4/6d); Medium clay; , Angular blocky; ;

          0.86 to  1.09 m   2.5YR4/6d); Medium clay; , Angular blocky; ; 10-20%, Gypseous;

          1.09 to  1.24 m   2.5YR4/6d); Medium clay; ; 2-10%, Gypseous;

          1.24 to  1.62 m   2.5YR4/6d); Medium clay; ; 50-100%, Gypseous;

          1.62 to  1.90 m   5YR7/6d); Medium clay; ; 20-50%, Gypseous;

          1.90 to  2.23 m   5YR7/6d); Medium clay; ; 20-50%, 60-200mm, Gravel gravel; 2-10%, Gypseous;

          2.23 to  2.43 m   ;

          2.43 to  2.74 m   ;

NOTE : LAYER 7 HORIZON OF GYPSUM
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