Technical Memorandum 34

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C.J. Chartres, P.H. Walker, I.R. Willett,
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ABSTRACT

Chartres, C.J., Walker, P.H., Willett, I.R., East, T.J., Cull, R.F., Talsma T. & Bond, W.J. (1991). Soils and hydrology of Ranger Uranium Mine sites in relation to application of retention water. Technical Memorandum 34, Supervising Scientist for the Alligator Rivers Region.

In 1986 surveys commenced of the soils and hydrology of the Ranger irrigation area and a nearby area which may be suitable for irrigation. The soil survey indicated three soil mapping units differentiated on the basis of soil colour, depth, drainage status and the presence or absence of ferricrete. The soils of all three units have high gravel fractions of quartz and ferruginous material, usually comprising between 20-50% of the soil mass. The quartz gravel is chemically inert and plays little or no part in immobilisation reactions, thereby reducing the effectiveness of the bulk soil as a contaminant repository. The soils are low in clay (mostly < 20%) and deficient in organic matter (mostly < 1%). Although clay contents increase slightly with depth, the clays are low-activity clay minerals (predominantly kaolinite). Consequently, the cation exchange capacities of the soils are extremely low (typically < 0.01 mol (p^+)/kg of the bulk soil) indicating a very limited potential for the assimilation of major cations.

Using conservative estimates of soil cation exchange capacity and total cation concentration of RP2 water, the time until the cation exchange complex of the upper 50 cm of soil comes into equilibrium with the irrigation water is calculated to be approximately 5 years. After this time the exchange-complex will be 100% saturated and any additional load of cations will pass through the soil profile (0-50 cm). The soils are also characterised by low soluble salt contents, acidic pH and low concentrations of secondary iron and manganese oxides. Field measurements of hydraulic conductivity indicate that the soils are highly permeable and that lateral flow of groundwater from the irrigation area to Magela Creek could take as little as 9 months. The survey of the alternative potential irrigation site indicated four mapping units with generally similar properties to the soils of the current irrigation area.

The capacity of these soils to assimilate the cations tested does not necessarily apply to other cations such as uranium and radium, present in minor or trace concentrations. In their cases, more specific adsorption reactions are likely, some of which may be effectively non-reversible. There is insufficient information available to enable any quantitative assessment of the likely significance of these mechanisms; however, the ferruginous gravels may play some part in specific adsorption reactions.

Laboratory water saturation experiments with soils from the irrigation area show that, with the exception of the 0-2 cm layer, there is negligible reductive dissolution of secondary iron and manganese oxides. It is therefore considered unlikely that mobilisation or immobilisation of pollutants (such as heavy metals) will be significantly influenced by soil oxidation-reduction cycles.

These soil assimilation results take no account of biological sinks or pathways, which may lead to temporary or longer term storage of applied ions within, or to removal of ions from, the irrigated area. Such biological factors will prolong the period estimated for saturation of the exchange complex of the soil, although their importance is diminished in the longer term. No data are available regarding sorption/desorption reactions that may take place in the weathered rock below the top 50 cm of soil.

1 INTRODUCTION

In 1985 Ranger commenced disposal of waste water from Retention Pond 2 by spray irrigation of a trial plot of 10.7 ha which later that year was expanded to 33 ha of highly weathered soils located between the mine and Magela Creek (Fig. 2). The adoption of spray irrigation as a method of disposal of waste water is based on the proposition that the soil will retain the ionic constituents of the applied water (dominant ions Mg^{2+}, Na^{+}, Ca^{2+}, Mn^{2+}, SO_4^{2-}; traces of UO_2^{2+} and Ra^{2+}) and so prevent their accession via groundwater to Magela Creek.

The data presented here were obtained as part of a continuing research project carried out by the Division of Soils, CSIRO in collaboration with the Alligator Rivers Region Research Institute of the Office of the Supervising Scientist, Jabiru, Northern Territory. The aims of the project are as follows.

Firstly, to assess the long term effects of the application of Retention Pond 2 (RP2) waste water from the Ranger Uranium Mine (RUM), Jabiru, N.T. to the soils of a c. 33 ha irrigation site, paying specific attention to:

a) the hydrologic properties of the site and its surrounds;
b) the adsorption capacity of the soils for solutes applied during irrigation (the near-neutral waste water is characterised by a sulphate anionic background containing magnesium and calcium as dominant cations, together with lower concentrations of inter alia manganese, uranium and radium);
c) the preferential adsorption/displacement of solutes as a consequence of both management and rainfall;
d) the seasonal and long term retentivity of adsorbed ions in the soils; and
e) the long term soil conditions after prolonged irrigation.

Secondly, to assess and advise on the presence of alternative sites within the Ranger Project Area, which have preferred soil and hydrological characteristics for water disposal by land application.

This study is concerned with characterisation of the soils and hydrology of the site; it is part of ongoing research to determine processes controlling adsorption and retention of the applied solutes in the soils. Biological sinks are not being considered as they only temporarily store ionic water constituents.

Figure 1 shows the Alligator Rivers Region and the location of Ranger Uranium Mine. The primary focus of the study reported here is an area of 33 ha of eucalypt woodland near Ranger's RP2 (Site 1, Fig. 2) located adjacent to Magela Creek. This area was adopted by RUM as its 'Magela Creek Water Management Site 1' in 1985; at the time of the field work (September 1986) it was being sprinkler-irrigated for the second Dry season in succession.

Although soil survey information was available for this locality (Wells 1979), the scale (1:10,000) was considered too small for the needs of the present investigation. Descriptive data for the soils of Site 1 were also available from the Conservation Commission of the Northern Territory (White & McLeod 1985) and the Office of the Supervising Scientist (East & Cull, pers. comm.). No detailed soil mapping, however, had been done within Site 1 nor had there been a chemical, physical or mineralogical characterisation of soils within the site boundaries. Because these data were considered necessary for assessment of the soils for the waste water disposal program, the field studies reported here were directed towards providing:

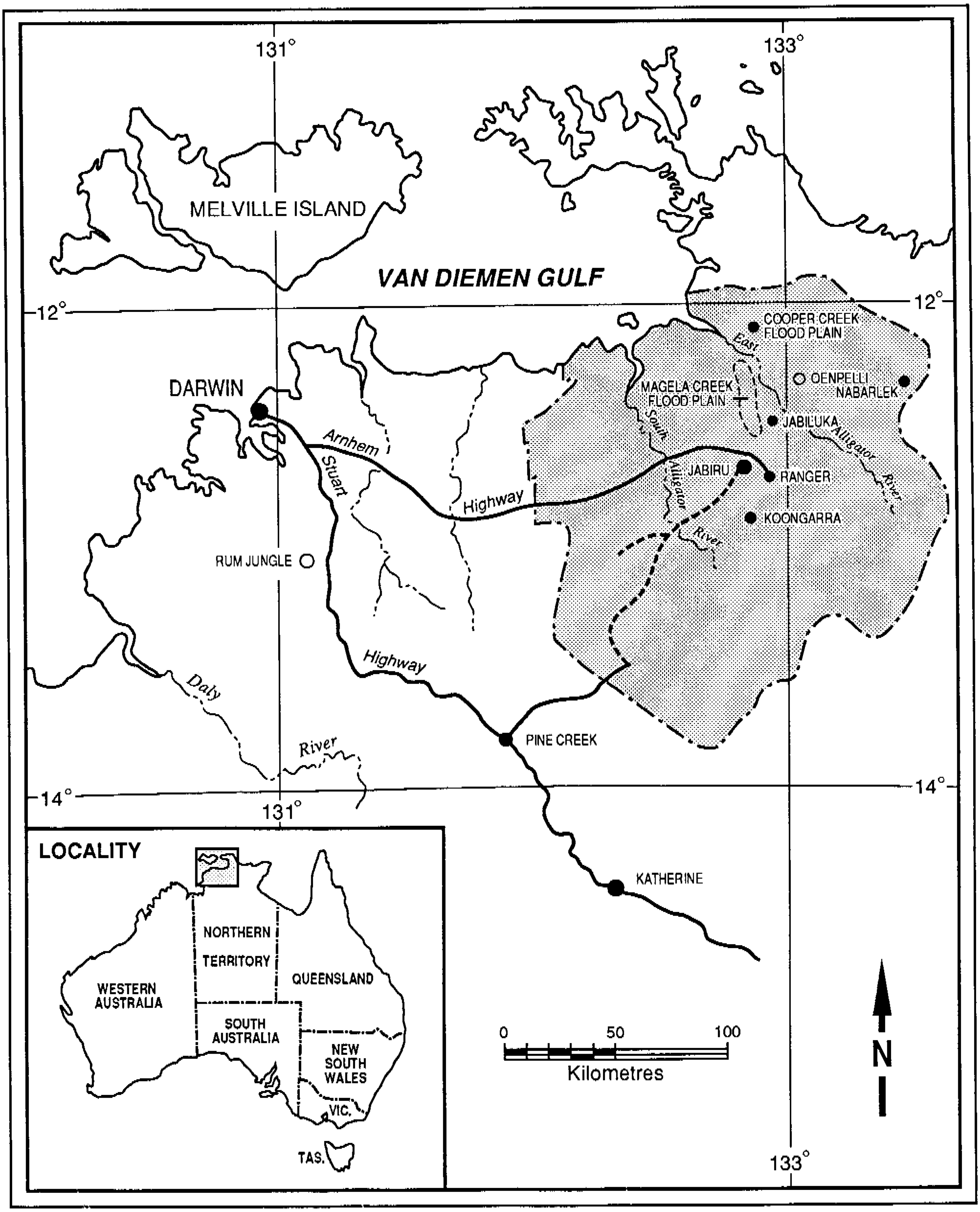


Figure 1. Alligator Rivers Region

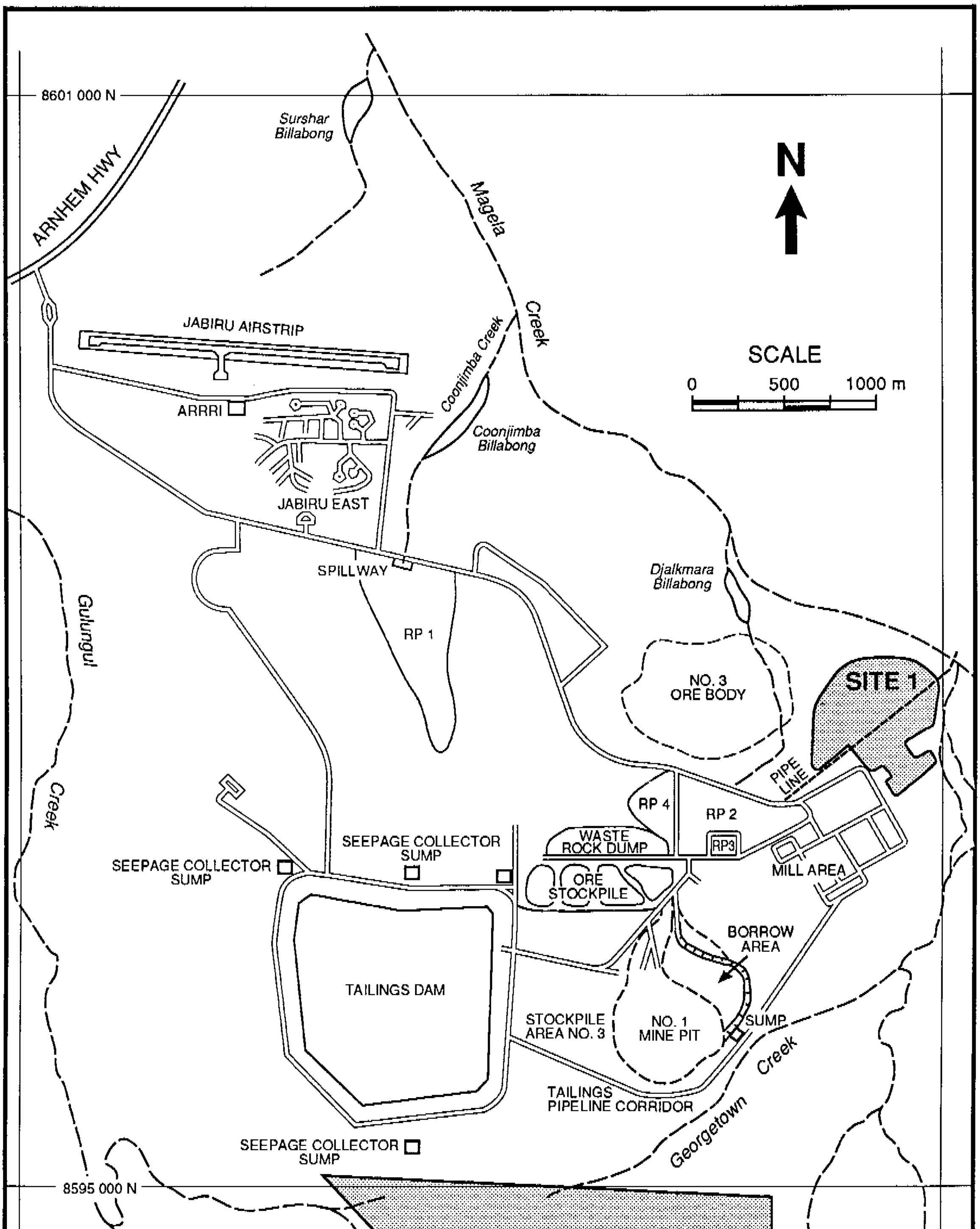


Figure 2. Current land application area (Site 1) and potential application area (Site 2), Ranger Uranium Mine

(i) field descriptions of the soils,
(ii) a detailed map showing soil distribution and,
(iii) information on groundwater levels, water infiltration rates and soil hydraulic conductivities.

In addition to the field studies, the physical, chemical and mineralogical properties of the soils of each recognised mapping unit were characterised by laboratory analyses. The results formed the basis upon which experimental procedures relating to sorption/desorption reactions and fixation of potential pollutants could be planned. Particular attention was also focussed on the potential effects of waterlogging (which occurs in the field during the Wet season) on the reductive dissolution of iron and manganese in the soils.

Some preliminary field and laboratory data are also presented for soils of Site 2, a nearby area of 160 ha to the south of the Ranger tailings dam (Fig. 2). This area may be considered for waste water disposal only at a later date. It has been studied in less detail than Site 1.

2 BACKGROUND

2.1 Climate

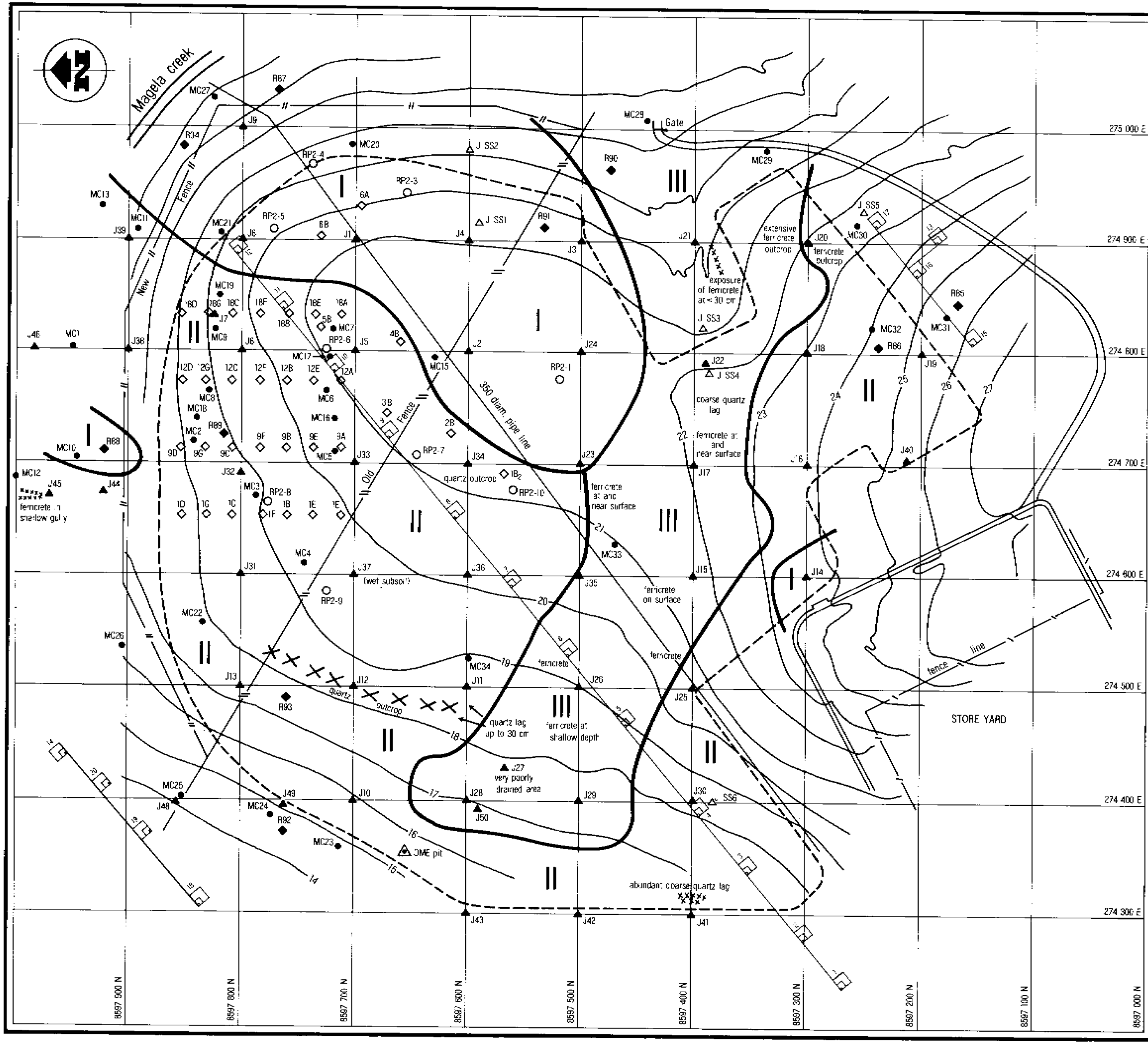
Climatic data for Jabiru East airstrip, 4 km from the two surveyed sites, are summarised in Table 1. Mean annual rainfall is 1543 mm, ninety per cent of which falls during the period November to March. Mean annual pan evaporation is 2524 mm with approximately seventy-five per cent occurring between May and December (inclusively). Highest mean monthly maximum temperature is 37.2°C in October and the lowest mean monthly minimum temperature is 17.7°C for July. These data suggest that dry soil conditions would occur from May or June until October each year.

Table 1. Summary of selected meteorological data for Jabiru airport (September 1971 to August 1986)
Source: Ranger Uranium Mines, Northern Territory, Australia

		J	F	M	A	M	J	J	A	S	O	N	D	Annual
Rainfall[a]		362	347	317	74	8.0	0.9	0.8	4.9	11.3	28.3	116	223	1543
(mm)		(104)	(199)	(114)	(80)	(7.4)	(2.7)	(1.9)	(16.7)	(23.0)	(21.8)	(81)	(104)	
Pan evaporation[b]		164	150	159	197	216	196	213	243	266	285	228	207	2524
(mm)		(27)	(29)	(17)	(22)	(15)	(31)	(20)	(21)	(17)	(26)	(43)	(25)	
Temperature	max.	33.3	32.8	32.8	34.2	33.2	31.2	31.2	33.7	35.5	37.2	36.4	35.0	33.9
(°C)	min.	24.3	24.2	24.1	23.2	21.5	18.8	17.7	19.2	21.4	23.4	24.7	24.6	22.3

[a] Mean and (standard deviation)
[b] Evaporation data are derived from a Class A pan; the monthly record ranges from 13 to 15 years during the period 1971-86.

Figure 3. *(Opposite)* Soils of the current land application area at Ranger uranium mine



SOILS OF THE RANGER LAND APPLICATION AREA, JABIRU, NORTHERN TERRITORY.

COMPILED BY C.J. CHARTRES, P.H. WALKER, J. EAST. and R. CULL.

SEPTEMBER, 1986

SCALE 0 — 100 metres

Map plotted on Ranger Uranium Mines drawing No. 05-A-8018 (15 July, 1986)

LEGEND

MAPPING UNIT	MAJOR SOILS[1]	DESCRIPTION
UNIT I	Red earths (Gn 4.11, Gn 4.14, Gn 2.11, Gn 2.14)	Brownish, gravelly, massive loamy sand to sandy loam A horizons. Gravelly, massive to weakly pedal reddish sandy clay loam to light clay B horizons. Merging with weathered ferruginised schists below 75 cm. Well drained.
UNIT II	Yellow earths, lithosols, podzolics (Gn 2.21, Gn 2.11, Gn 2.81, Uc 2.12, Dr 3.41)	Brownish, gravelly, massive loamy sand A_1 horizons. Yellowish brown, massive, cobbly, sandy loam A_2/A_3 horizons. Gravelly, massive to weakly pedal, mottled yellowish red to red B horizons by 20 to 70 cm or weathered schistose substrates by 50 cm. Moderately well to imperfectly drained.
UNIT III	Siliceous sands (Uc 2.12)	Brownish to yellowish brown, single grain sands to loamy sand A_1 horizons. Gravelly to cobbly, often bleached, massive, sandy loam A_2 horizons. Ferricrete at shallow depth (30-50 cm). Imperfectly to poorly drained.

(1) Great soil groups as defined by Stace et al. 1968 ("Handbook of Australian Soils", Rellim, Adelaide). First named soil is dominant within mapping unit. Letters and numbers in brackets refer to Principal Profile Forms of the Factual Key (K.H. Northcote, 1979. "A Factual Key for the Recognition of Australian Soils", 4th edition, Rellim, Adelaide).

- Approximate boundary of Irrigation area
- 20 Vegetation quadrats
- ● MC 15 Magela Creek monitoring bore
- ◇ 2B Ranger soil sampling site
- ◆ R 93 Land Conservation Unit soil sampling site
- O RP2-1 Office of the Supervising Scientist auger sites
- ▲ J 43 CSIRO soil auger site
- △ J SS6 CSIRO soil sampling pit

Drawn R.M.S. CSIRO Soils Division 1987

2.2 Vegetation

Wells (1979) has listed the vegetation occurring in Land Unit 4a which includes both the areas mapped in the present study. It consists of open eucalypt forest dominated by *E. tetradonta, E. miniata, E. bleeseri* and *E. porrecta.* The understorey is characterised by *Acacia* spp., *Livistona humilis* and *Gardenia megasperma* with a variable grass cover of *Sorghum* spp., *Themeda triandra* and *Eriachne triseta.*

2.3 Geology and geomorphology

Sites 1 and 2 are located within an area mapped by the Bureau of Mineral Resources (Sheet SD53-1 Alligator River (1983) and an unnumbered sheet 'Geology of the Pine Creek Syncline' (1979)). The Ranger Mine area is shown as having a superficial cover of Cainozoic soil, unconsolidated sands, ferruginous material and laterite over Lower Proterozoic schists of the Cahill Formation. Mt Brockman, a highland feature located 2 km to the south of Site 2, consists of quartzose sandstones and conglomerates of the Middle Proterozoic Kombolgie Formation. Quaternary clayey sand alluvium has infilled the Pleistocene valley of Magela Creek and now comprises the flood plain of that stream. Mobile Holocene sands fill the contemporary channels of the Magela and its tributaries.

Soils at Sites 1 and 2 have developed on erosional slopes of the Koolpinyah Surface. This landsurface is an extensive plain formed by the erosion, weathering and duricrusting of the Lower Proterozoic metasediments and more recent sediments during Late Tertiary and early Pleistocene times (Williams 1969). Later planation and dissection yielded a lowland surface of broad valleys, long low-angle slopes and isolated hills, while the duricrust layer has been reduced to remnant ferricrete (hardened zones cemented mainly by iron oxides) pavements and benches. The Koolpinyah Surface has a thick weathered (ferruginised) zone which may extend up to 60 m into the bedrock below the present soil cover.

Surface-wash processes predominate on the slopes of the Koolpinyah Surface with selective removal of the finer soil particles resulting in the formation of a lag of subangular quartz gravels and well rounded ironstone gravels.

At Site 1, the landscape consists of a low hillcrest at 21 m (A.H.D.) with adjacent convex slopes (Figure 3). A shallow, concave drainage line separates this northerly portion from a gentle slope rising to 27 m (A.H.D.) in the south. The elevation range at the site is 15 to 27 m (A.H.D.) and maximum slope gradients are 3 per cent.

The landscape at Site 2 is more complex, containing drainage depressions associated with Georgetown Creek and parts of the drainage divide between Georgetown and Coonjimba creeks. Elevations range from 20 to 40 m (A.H.D.) and maximum slope gradients are also 3 per cent (Fig. 4).

2.4 Previous soil studies

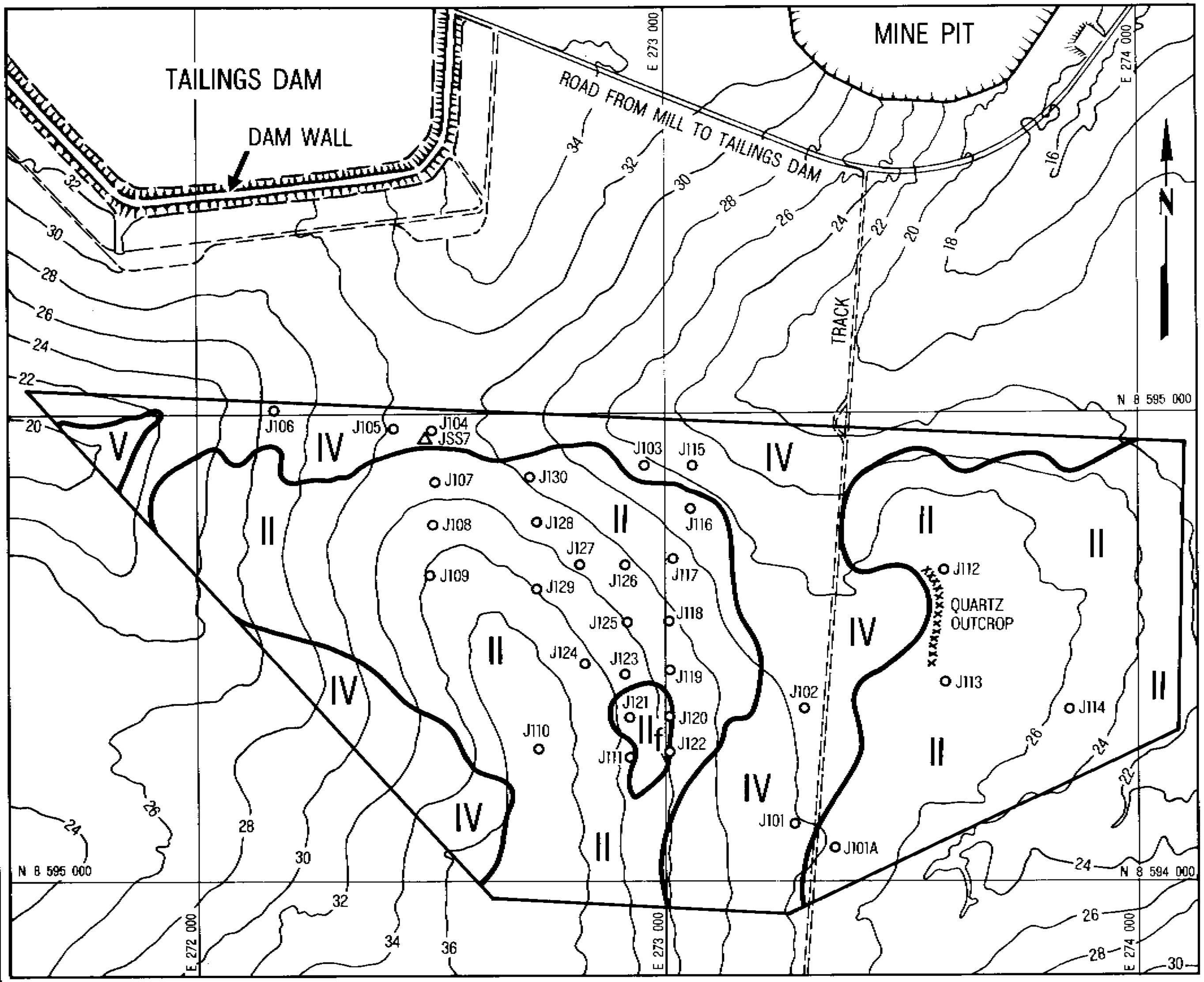
Sites 1 and 2 occur within a unit mapped at a small scale by Hooper (1969) with soils described as those of the 'Koolpinyah Surface'. The unit includes gradational (Gn2) and uniform (Uc5) red and yellow-red soils on lateritic remnants with minor skeletal and gradational (Gn2) yellow earths on slopes (soil classification terminology follows Northcote

Figure 4. (*Opposite*) **Soils of a potential land application area at Ranger uranium mine**

SOILS OF A POTENTIAL LAND APPLICATION AREA, RANGER, JABIRU, NORTHERN TERRITORY.

SCALE 0 100 200 300 400 500 metres

COMPILED BY C.J. CHARTRES, P.H. WALKER, J. EAST, and R. CULL.
SEPTEMBER, 1986



MAPPING UNIT	MAJOR SOILS[1]	DESCRIPTION
UNIT II	Yellow earths, lithosols, podzolics (Gn 2.21, Gn 2.11, Gn 2.81, Uc 2.12, Dr 3.41)	Brownish, gravelly, massive loamy sand A_1 horizons. Yellowish brown, massive, cobbly, sandy loam A_2/A_3 horizons. Gravelly, massive to weakly pedal, mottled yellowish red to red B horizons by 20 to 70 cm or weathered schistose substrates by 50 cm. Moderately well to imperfectly drained.
UNIT II_f	Yellow earths, lithosols, podzolics (Gn 2.21, Gn 2.11, Gn 2.81, Uc 2.12, Dr 3.41)	As for Unit II except that A horizons are marked by an accumulation of rounded ferricrete concretions.
UNIT IV	Yellow earths, siliceous sands (Gn 2.21, Gn 2.11, Gn 2.81, Uc 2.12)	Generally less gravelly and deeper profiles than in Units II, II_f. Brownish sandy A_1 and bleached sandy to loamy sand A_2 horizons. Yellowish brown, massive, sandy to sandy clay loam B horizons by 50 cm with increasing ferricrete nodules to depth. B horizons often extend to >2 m. Well to imperfectly drained.
UNIT V	Grey clays (Ug 5,6)	Grey, alluvial heavy clays with some intercalated sand deposits. Poorly drained. (Not described in detail).

(1) Great soil groups as defined by Stace et al. 1968 ("Handbook of Australian Soils", Rellim, Adelaide). First named soil is dominant within mapping unit. Letters and numbers in brackets refer to Principal Profile Forms of the Factual Key (K.H. Northcote, 1979. "A Factual Key for the Recognition of Australian Soils", 4th edition, Rellim, Adelaide).

O J130 CSIRO Inspection site △JSS7 CSIRO Soil sampling pit.

Map base :- Sheet E.83/18 Magela Creek, N.T.
Mudginberri BE. 50/20.12, Australian Survey Office, (April, 1985)

Soil map compiled on the basis of air photo interpretation and field reconnaissance. Soil inspection sites indicated by numbers.

——34—— CONTOURS (2 metre interval)

Drawn R.M.S., CSIRO Soils Division 1987

(1979) and Stace et al. (1968)). Site 1 lies within Unit A of the 1:10,000 soil map of Wells (1979). The dominant soils were considered to be shallow, yellow, uniform sands with gravels throughout and an A_2 horizon (Uc4.24) with associated sandy soils (Uc5.23) without A_2 horizons. The Land Conservation Unit of the Conservation Commission of the N.T. also mapped soils in the Ranger area at a scale of 1:10,000 (White & McLeod 1985). Site 1 lies within their Unit B5, predominantly shallow earthy sands with gravel throughout. Site 2 lies within Units B5 and H, the latter being predominantly duplex soils associated with the old valley fill of Georgetown Creek. Profile descriptions, representing the range of soils, were given at specific reference points. None of these, however, is located within Sites 1 and 2.

In addition to the above information, descriptions of ten profiles at monitoring points within Site 1 were made available from the Conservation Commission of the Northern Territory (K. Greenwood, unpub. data). These profiles included red earths (Gn2.1), brown earths (G2.41, 2.44), earthy sands (Uc5.2, 5.23) and siliceous sands (Uc1.23, 2.23). Soil descriptions and notes on lithology for ten other profiles within Site 1 were made available by the Alligator Rivers Region Research Institute. These soils usually had gradational texture profiles with subsoil colours ranging from red to yellow. All profiles had 25 per cent or more gravel in their subsoils.

To our knowledge, no profile data have been obtained previously for Site 2.

3 SOILS OF SITE 1

3.1 Soil mapping units

At Site 1, a base map at an original scale of 1:1,500 was available which had contours at 1-metre intervals and a grid at 100 m spacing (Fig. 3). The soil profile at each of 43 of these grid points was examined from shallow pits, which were deepened to approximately 0.5-1.0 m by hand augering. The soil profiles were described using the terminology of McDonald et al. (1984); the descriptions (J1-J43) have been included as Appendix 2.

On the basis of these observations, three soil mapping units were defined and their boundaries identified. Another seven sites (J44-50) were described and surface features such as ferricrete outcrops noted in the course of determining the final composition of the mapping units and the position of their boundaries on Fig. 3.

In general the soils are shallow and gravelly and overlie weathered, ferruginised schist. The three mapping units, I, II and III correlate closely with upper, mid and lower slope positions respectively. Profile characteristics of the dominant soil in each mapping unit are shown in Fig. 5.

Mapping unit I, occupying c. 6 ha of Site 1, consists predominantly of well drained red earths (Gn4.11, 4.14, 2.11, 2.14) with brownish, gravelly, massive, loamy sand to sandy loam A horizons. The latter overlie gravelly, massive to weakly and occasionally moderately structured reddish sandy clay loam to light clay B horizons which grade into weathered ferruginised schist.

Mapping unit II (c. 20 ha) consists of a more variable group of soils than the other units. It is dominated by moderately well drained to imperfectly drained yellow earths, lithosols and podzolic soils (Gn2.21, 2.11, 2.81, Uc2.12, Dr3.41) with brownish, massive, gravelly loamy sand A_1 horizons and yellowish brown, massive, gravelly sandy loam A_2 horizons, some of which are bleached. These overlie mottled yellowish red to red, massive to weakly structured B horizons or weathered schist substrates.

Mapping unit III (c. 7.5 ha) consists of predominantly shallow, sandy and gravelly siliceous sands (Uc2.12) which overlie more or less continuous, hard ferricrete at variable depths. These soils occupy the lower slope positions and drainage lines within the mapped area.

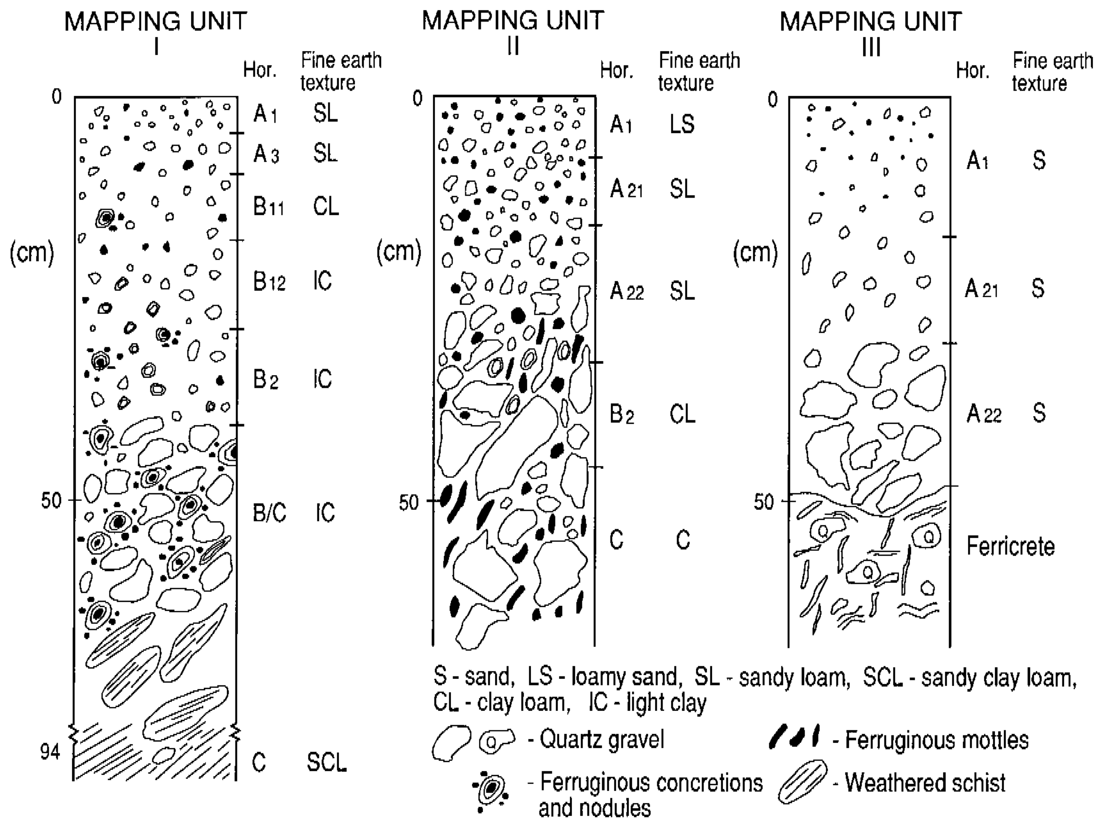


Figure 5. Representative soil profiles for soil mapping units I, II and III at current and potential land application sites, Ranger Uranium Mine

3.2 Soil properties

Methods

The laboratory data obtained include particle-size analyses, pH, electrical conductivity, chloride content, organic carbon, exchangeable cations, cation exchange capacity and dithionite and oxalate extractable iron, aluminium and manganese contents. Details of specific methods used are listed below.

Bulk samples of several kilograms were collected in the field and dried at 40°C. Gravels (> 2 mm diameter) were separated from the fine earth (< 2 mm diameter) and reported as a percentage of the total sample. Results of all other analyses are reported on a fine-earth fraction (< 2 mm) basis. Particle-size analyses were made on samples treated with 20 min high speed stirring followed by overnight end-over-end shaking in the presence of sodium tripolyphosphate and sodium hydroxide. A plummet balance was used to determine silt and clay and the sand fractions determined by dry sieving of the residues. Surface samples with > 1.0% organic carbon were also pretreated with H_2O_2.

Organic carbon was extracted by a modified Walkley-Black digestion and measured colorometrically on an auto-analyser. pH, electric conductivity and chloride content were determined in 1:5 soil to water suspensions.

Exchangeable cations and cation exchange capacity were determined at soil solution pH and ionic strength using the compulsive exchange method of Gillman & Sumpter (1986). Dithionite extractable Fe, Al and Mn were measured by atomic absorption spectroscopy (AAS) after extraction following the method of Mehra & Jackson (1960). Oxalate extractable Fe, Al and Mn were extracted in acid ammonium oxalate (pH 3.0) after 2 h shaking in darkness and measured by AAS. Reductive dissolution of free iron and manganese during waterlogging was estimated following the method of Willett & Malafant (1986).

Clay fractions ($< 2.0\ \mu m$) were separated following particle-size analyses and suspensions pipetted onto glass slides for x-ray diffraction using a Siemens D501 diffractometer. Samples were pretreated in the following manner:

(a) Air-dry oriented aggregates (Na^+ saturated)
(b) as (a) and treated with ethylene glycol
(c) Heated to 300°C
(d) Treated with citrate solution (Tamura 1958)
(e) as (d), Ca^{2+} saturated and treated with ethylene glycol
(f) as (d), K^+ saturated and air-dried
(g) as (f), heated to 300°C
(h) as (f), heated to 500°C

Particle-size analyses are necessary to determine the proportions of gravel (> 2 mm), sand (2-0.02 mm), silt (0.02-0.002 mm) and clay (< 0.002 mm) in the soils. Of these fractions the gravels consist predominantly of ferricrete and quartz. The sand and silt consist predominantly of quartz, which is essentially chemically inert, whereas the clay fraction consists predominantly of layer silicate minerals with varying capacities to retain metals and take part in low affinity cation exchange reactions. Soil pH data were required to determine the degree to which the soils have been leached and is a particularly important measurement in soils which are likely to contain variable charge minerals, such as kaolinite and iron oxides. In such soils, surface charge characteristics and consequently the ability of the soil to exchange and retain some cations and anions, are pH-dependent. Electrical conductivity and chloride determinations are used as measures of soluble salt content. Organic carbon content is an indicator of the total amount of organic matter present. Information regarding exchangeable cations and cation exchange capacity was required to provide 'base-line' data for future investigations. Finally, dithionite-extractable iron, manganese and aluminium were determined to measure the amount of these elements present in the soil as free oxides. Oxalate extracts remove poorly ordered forms of iron, aluminium and manganese oxides, whereas dithionite extracts the more stable crystalline oxides as well. Consequently, oxalate to dithionite ratios give an approximation of the proportions of poorly ordered to total free oxides present. In the case of iron and manganese, oxalate to dithionite ratios also give an indication of the proportions of readily reducible to less readily reducible phases present.

Two profiles representing each mapping unit were sampled at Site 1; one of each pair was from within the spray-irrigated zone and the other outside it. The field descriptions of these profiles with their chemistry and clay mineralogy are tabulated in Appendix 1.

Results

A notable feature of all six profiles is their high gravel contents. As the bulk properties of the whole soil are of significance in this project this gravel content needs to be taken into account when considering the properties of the fine earth fraction (< 2 mm). For example, in sample JSS4 (5-12 cm), clay content of the whole soil is 3.5 per cent and the CEC is

0.6 (cmol (p^+)/kg) as compared with values of 7.0 and 1.2 respectively for the fine earth. Table 2 presents mean values of CEC on a whole soil basis and for the fine earth fraction in the upper 50 cm of each sampling site.

In general, soil pH values are slightly to moderately acidic with the soils of mapping unit III (JSS3, JSS4) tending to strongly acidic. Soluble salt contents as indicated by electrical conductivity and chloride contents are very low. Organic carbon data (organic carbon × 1.7 = organic matter) indicate that the level of organic matter of all the soils is also low, usually being less than one per cent of the fine earth below 10 cm.

Oxalate-extractable iron (Fe_{ox}) and aluminium (Al_{ox}) are higher in soils of mapping units I and II than in those of unit III. Extractable manganese is highest in soils of unit I, variable in soils of unit II and overall least in soils of unit III. Cation exchange capacities of the fine earth fraction are generally very low. The increases of CEC noted in the 0-10 cm samples (Appendix 1 and Fig. 6) are the result of the higher organic matter contents in these horizons. Below approximately 10 cm depth, CEC values of < 10 cmol (p^+)/kg of clay are consistent with a clay mineralogy dominated by low activity clays, such as kaolinite. Among the individual exchangeable cations, Ca^{2+} is dominant in most surface horizons (0-2 cm) but Mg^{2+} becomes dominant in samples from below 2-5 cm depth. The proportion of the total soil exchange complex occupied by alkali and alkaline-earth cations (referred to hereafter as base saturation) is generally greater than 60 per cent in all the irrigated profiles examined (JSS1, 4, and 6). The profiles examined outside the irrigated area (JSS2, 3 and 5) have lower base saturation per centages particularly below 5 cm depth.

Clay (< 2 μm) contents of all soils are low, especially when account is taken of the per cent gravel in the whole soil samples (Appendix 1). Only two whole soil samples (JSS1) have more than 20 per cent clay. Silt contents are also low in all profiles and, apart from the prominence of gravel, the soils are dominated by fine and coarse sand fractions.

The increases in iron that can be extracted in acetate buffer during laboratory waterlogging are shown in Fig. 7a. Extractable iron increased during waterlogging in the surface (0-2 cm) samples of each of the soils representing units I, II and III. There were little or no increases in extractable iron in samples from lower down the profiles. Levels of extractable iron appeared to stabilise between 4 and 8 weeks of waterlogging in profile JSS4 (0-2 cm), and decreased slightly during this time interval in profile JSS6 (0-2 cm). Hence, for these soils, the maximum amount of iron reduction occurs after 4-8 weeks of waterlogging. The reduction of iron during waterlogging was initially slower in profile JSS1 (0-2 cm) than in the other soils but continued to increase up to 8 weeks. Differences in the rate of iron reduction in waterlogged soils (at constant temperature) depends on initial soil pH, the level of readily oxidisable organic carbon (Willett 1986) and the crystallinity of the

Table 2. Average cation exchange capacities for the upper 50 cm of soil profile

Soil	Mapping unit	Fine earth (excludes gravel) CEC (cmol (p^+)/kg)	Whole soil (includes gravel) CEC (cmol (p^+)/kg)
JSS1	I	1.6	0.87
JSS2	I	1.3	0.65
JSS3[a]	III	0.7	0.55
JSS4	III	1.3	0.49
JSS5	II	1.8	0.65
JSS6	II	1.7	0.56

[a] Soil profile only 48 cm deep over ferricrete. N.B. No corrections made for changes in bulk density with depth. (x cmol (p^+)/kg = x meq/100 g)

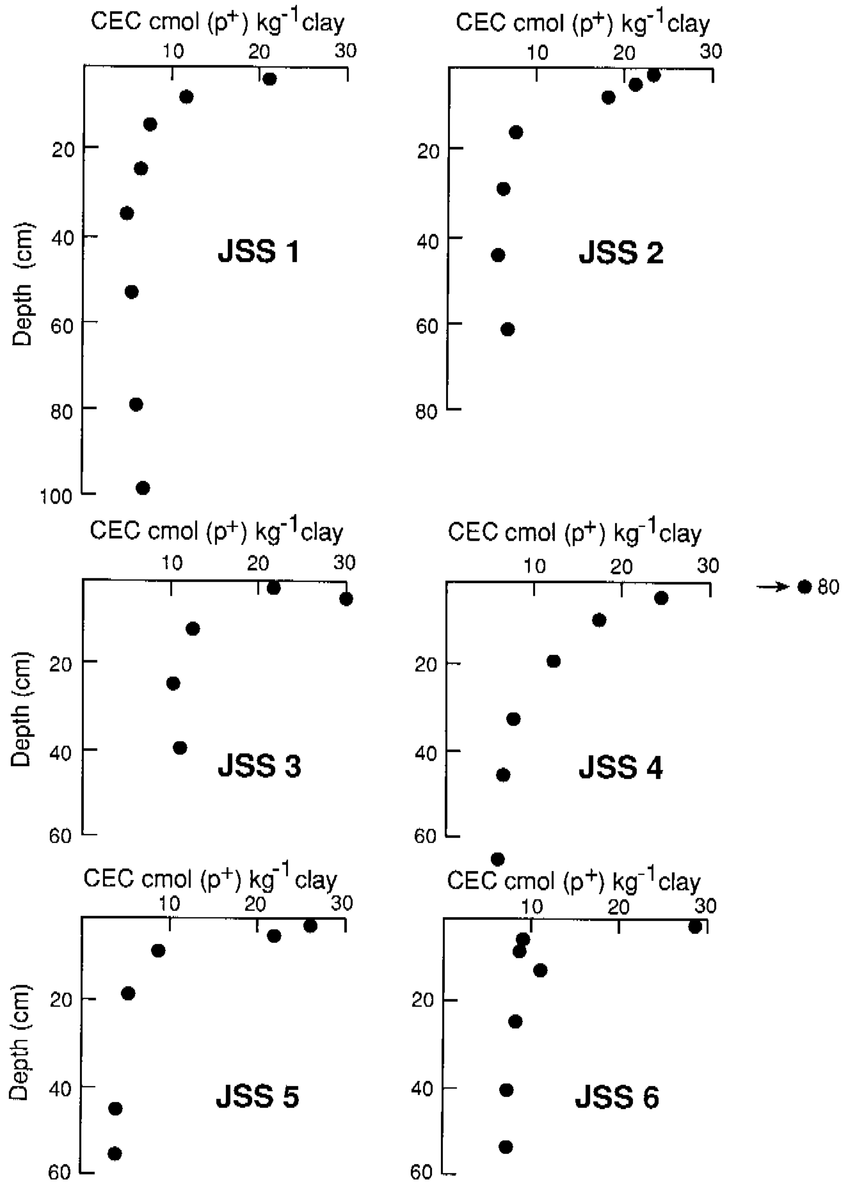


Figure 6. Cation exchange capacity (CEC) for soils in current land application area, Ranger Uranium Mine

iron oxide phases (Willett & Malafant 1986). Soil pH values were similar in each of the surface (0-2 cm) layers (Appendix 1). JSS6 (0-2 cm) had lower levels of organic carbon than the other soils, but not the slowest rate of reduction. It appears that the higher degree of crystallinity of the iron oxides in JSS1 (0-2 cm), as indicated by its ratio of Fe_{ox}/Fe_d of 0.04, was the cause of the slower rate of reduction in this sample.

The extent to which the total free iron (reducible in dithionite-citrate-bicarbonate) was reduced to Fe (II) is shown in Table 3. Only a small fraction (up to 7%) of the total free iron was reduced by waterlogging in the surface (0-2 cm) samples. The relatively limited extent of Fe(III) reduction in these soils is presumed to have been caused predominantly by the limited supply of oxidisable carbon. The absence of iron reduction in the subsoils of Oxisols, despite extended periods of saturation, has been observed in field studies in Brazil (Couto et al. 1985). The relatively low values (< 0.2) of Fe_{ox}/Fe_d observed in all the present profiles further indicates that the oxides are not susceptible to reduction in the field, and that they will be resistant to reduction during extended waterlogging associated with spray irrigation.

Extractable Mn levels during waterlogging are shown in Table 4 and Fig. 7b. The data indicate that larger proportions of Mn were reduced during waterlogging in the surface than the lower horizons. The proportions of the total free Mn reduced in the surface soils of the different mapping units were similar (Table 4) indicating that the levels of extractable Mn reached during waterlogging were related to the amount of Mn oxides available for reduction. The more limited extent of Mn reduction in the subsoils is again likely to be the result of very low levels of readily oxidisable carbon, as was the case for iron. The greater extent of Mn reduction, than Fe reduction, is consistent with the expected thermodynamic stability of the respective oxides under reducing conditions (Willett 1983).

Clay mineralogical analyses were required to achieve several of the project's objectives. Primarily, data were necessary to establish the types of clays present and the proportions of each. Such information enables assessments of the origin of the soil's permanent and variable charge characteristics to be made. Information regarding the long term effects of weathering processes and the effects of waterlogging on the clay fraction can also be obtained from clay mineral analyses. Finally, an estimation of the types of clays present was required to help plan laboratory experiments of interactions between potential pollutants and clay minerals.

Table 3. Proportion of total free iron reduced during waterlogging

		Weeks of waterlogging			
		1	2	4	8
Soil	Depth (cm)	% total reduced			
JSS1	0-2	0.03	0.31	1.7	2.5
JSS1	5-10	0.01	0.02	0.02	0.05
JSS1	29-42	0	0	0	0
JSS4	0-2	1.5	2.6	6.7	7.0
JSS4	12-26	0	0	0	0
JSS4	37-53	0	0	0	0
JSS6	0-2	1.1	3.7	5.5	4.5
JSS6	16-33	0	0	0	0
JSS6	33-46	0	0	0	0

Table 4. Proportion of total free manganese reduced during waterlogging

		Weeks of waterlogging			
		1	2	4	8
Soil	Depth (cm)	% total reduced			
JSS1	0-2	34.9	45.9	56.9	62.4
JSS1	5-10	12.0	15.9	15.9	8.85
JSS1	29-42	2.2	1.1	0	0
JSS4	0-2	42.5	47.0	51.5	56.0
JSS4	12-26	17.1	14.3	4.30	0
JSS4	37-53	0	0	0	0
JSS6	0-2	39.0	43.4	47.9	56.9
JSS6	16-33	0	0	0	0
JSS6	33-46	0	0	0	0

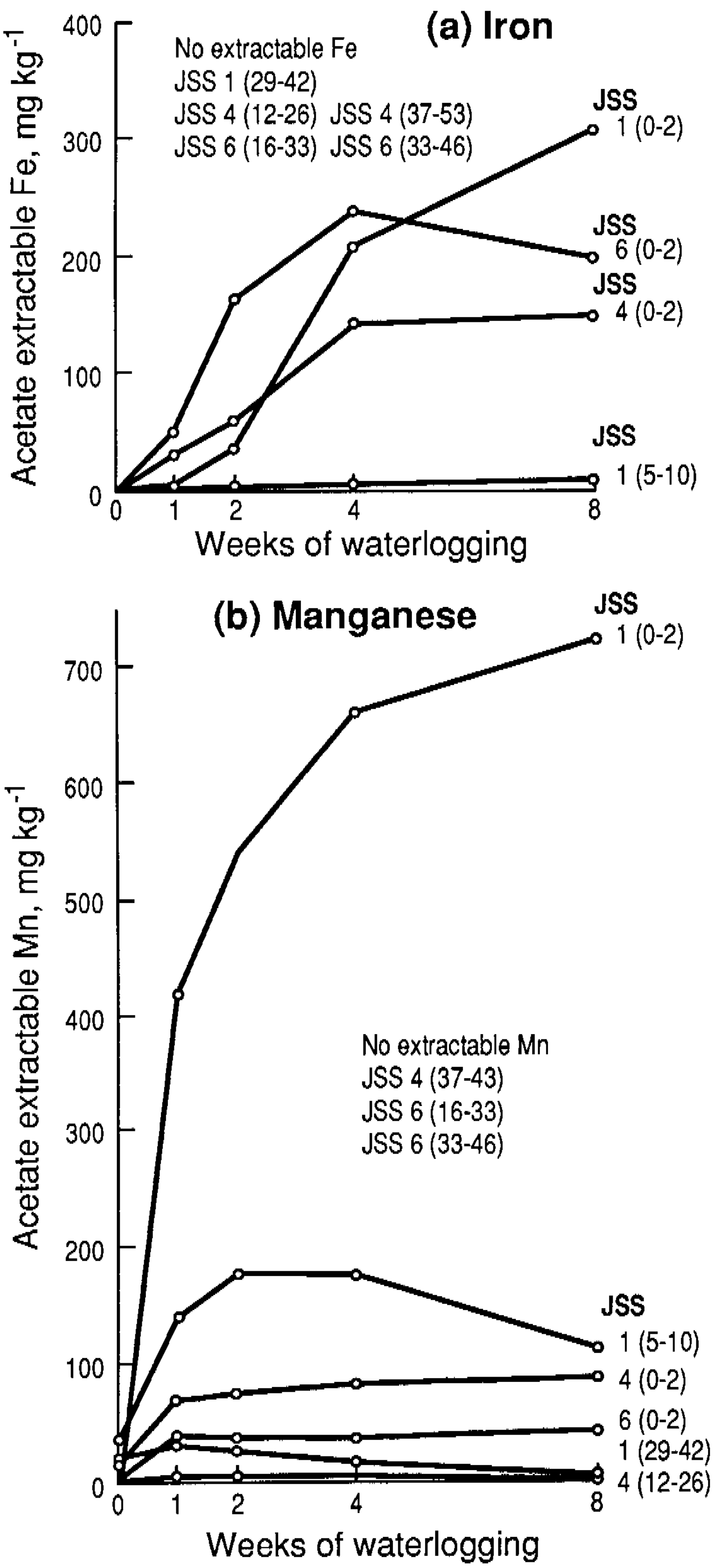


Figure 7. Reduction of iron and manganese in soils of the land application area during saturation with water

Weathered rock samples from the base of profiles JSS2 (mapping unit I), JSS4 (unit II) and JSS6 (unit III) were powdered and examined by X-ray diffraction. The sample from JSS2 (55-65 cm) was predominantly quartz with subsidiary kaolinite, some mica and traces of goethite and possibly gibbsite also present. The sample from JSS4 (80 cm+) was also quartz-rich, with traces of mica, kaolinite, goethite and hematite also detected. The diffraction pattern also indicated that the goethite was an aluminous variety. A similar composition was also observed in the sample from JSS6 (46-62 cm) except that more kaolinite than mica was probably present. Very small and poorly defined peaks around 1.4 nm in profiles JSS2 and JSS6 suggested the occurrence of traces of either chloritic minerals or vermiculite in the weathered rocks.

In profile JSS1 (mapping unit I) the finer than 2 μm fraction for near surface (2-5 cm) samples contained predominantly kaolinite (0.71 nm) with some illite (1.0 nm) and traces of interstratified (c. 1.2 1.4 nm) clays which collapsed on heating to 300°C (Fig. 8). Samples from 5-10 cm had a similar clay mineral composition, but treatment with sodium citrate solution (Tamura 1958) followed by glycollation (Ca^{2+} saturated) indicated some swelling of the interstratified material to c. 1.7 nm, although a 1.4 nm peak was also still present. Heating to 300°C of the original (non-citrate treated) samples caused the collapse to 1.0 nm of the 1.4 nm peaks and the remaining interstratified materials. The 1.7 nm material also collapsed upon heating of citrate treated samples to 300°C. This sequence of behaviour suggests that some small amounts of vermiculite and smectite are present. At 10-18 cm depth kaolinite is predominant, with some illite and traces of 1.2-1.4 nm material also being noted (no citrate treatments made). At 29-42 cm the pattern was similar. No swelling of the interstratified material upon glycollation was noted either prior to or after citrate treatment at the latter depth. In the samples from 29-42 cm (B horizon) kaolinite was predominant with minor illite and traces of interstratified material (1.2-1.4 nm). Diffraction peaks close to 0.483 nm, which disappeared upon heating the samples to 300°C possibly indicate the presence of gibbsite.

The finer than 2 μm fraction for samples examined from JSS2 (2-5 cm, 5-9 cm, 9-24 cm and 35-54 cm; not illustrated) was dominantly kaolinitic with some illite and traces of 1.2-1.4 nm interstratified, non-swelling minerals, which collapsed upon heating to 300°C. This behaviour suggests that they most probably have an illite-vermiculite interstratification.

In soils from mapping unit II (JSS5, JSS6), illite peaks in the surface layers were larger than those for kaolinite in JSS5 (2-5 cm and 10-25 cm) and approximately equal to kaolinite peak heights in JSS6 (2-5 cm). At greater depths in both profiles, kaolinite peaks were substantially larger than illite peaks, suggesting a greater proportion of the former. In JSS5 (10-25 cm, 25-40 cm and 40-50 cm) and in JSS6 (8-16 cm, 16-33 cm and 33-46 cm) 1.4 nm peaks persisted after heating to 300°C. Treatment with citrate solution intensified and sharpened these peaks, whereas citrate followed by K^+ saturation and heating to 300 and 500°C caused them to collapse (Fig. 9). Glycollation of a Ca^{2+} saturated sample from JSS6 (8-16 cm) caused some expansion to 1.6-1.7 nm. This sequence of behaviour suggests the presence of some chloritised-vermiculite in these samples along with some smectite in the sample from 8-16 cm.

In mapping unit III (JSS3 and JSS4) kaolinite was the major clay mineral present (Fig. 10) with some vermiculite and illite also being identified. In the surface samples (2-5 cm), kaolinite, illite and traces of interstratified minerals occur with a similar pattern occurring throughout profile JSS4. In the samples from JSS3 (5-18 cm, 18-31 cm and 31-48 cm) small, but increasing proportions of non-swelling 1.4 nm minerals, which did not collapse on heating to 300°C were observed. Treatment with citrate solution followed by K^+ saturation and heating to 300 and 500°C caused their progressive collapse; this suggests that the mineral may be chloritized vermiculite.

Quartz occurred in the clay fraction of all the samples from map units I, II and III.

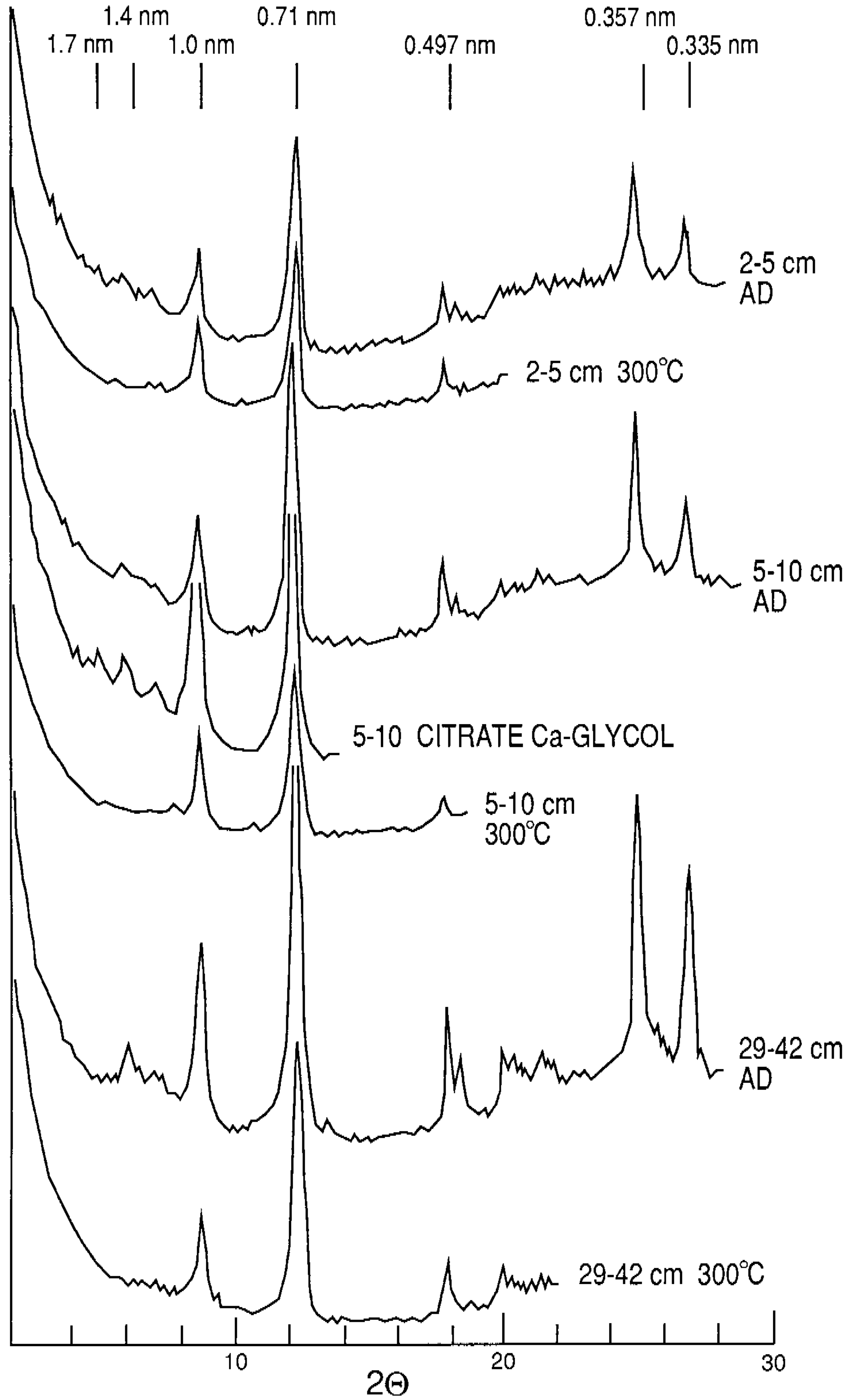


Figure 8. X-ray diffractograms for < 2 μm fraction from profile JSS1 (mapping unit 1)

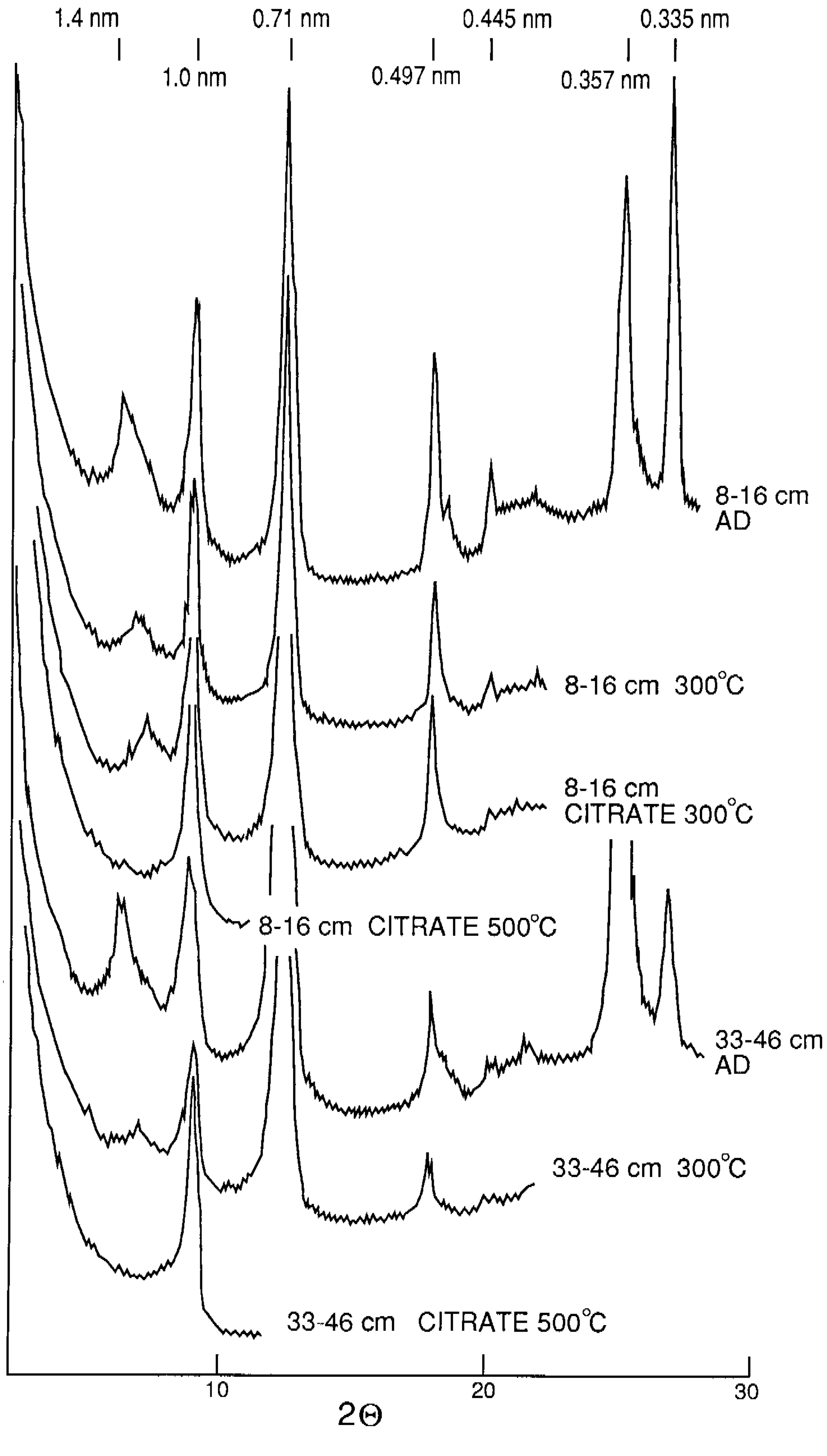


Figure 9. X-ray diffractograms for < 2 μm fraction from profile JSS6 (mapping unit II)

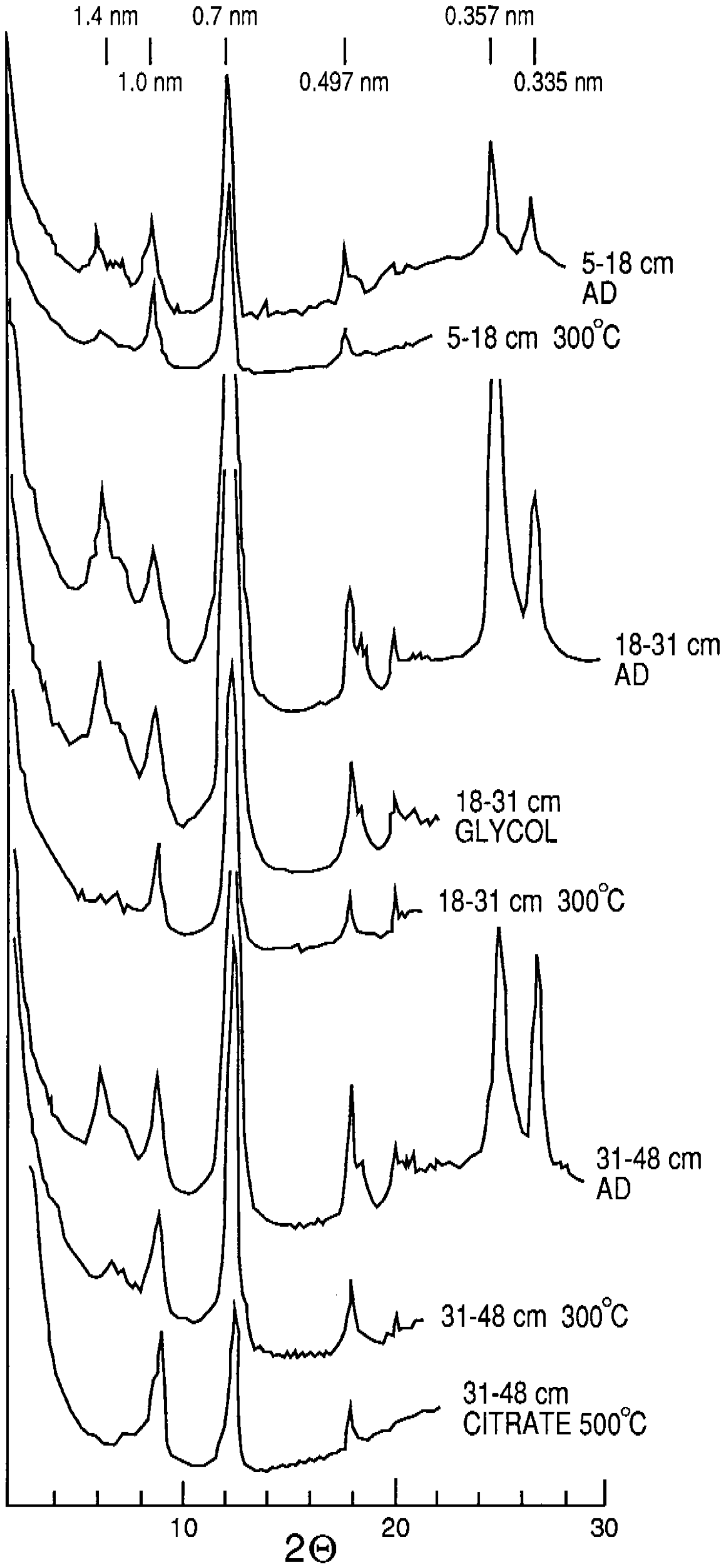


Figure 10. X-ray diffractograms for < 2 μm fraction from profile JSS3 (mapping unit III)

4 SOILS OF SITE 2

4.1 Soil mapping units

An airphoto base map at a scale of 1:5,000 with 2-metre contours was available for Site 2 (Fig. 4). Field observations were obtained by hand augering and from a network of pits to 1.5 m which had been dug several years previously during geotechnical studies of the area. Detailed soil descriptions were not made, except for pit JSS7.

On the basis of these observations, four units were defined and mapped. A brief field check was made of the mapped boundaries but their reliability was not tested to the same extent as the soil boundaries at Site 1.

Soil mapping unit II at Site 2 (Fig. 4) is similar to that unit at Site 1. Unit IIf is similar to unit II except that the soil surface is characterised by a dense accumulation of ferruginous nodules. Unit IV is also similar to unit II except that the individual horizons and overall profiles are thicker and have much lower gravel contents. Mapping unit IV occurs along drainage depressions and consists of grey, cracking clays (Ug4.6) with some intercalated sandy strata.

4.2 Soil properties

Methods

The laboratory methods used were identical to those described in the previous section.

Results

Strong similarities exist between the one profile sampled in Site 2 (JSS7, mapping unit IV) and those of the closely related mapping unit II of Site 1 (JSS5, JSS6). Soil pH is slightly acid and soluble salt and organic carbon values are very low; oxalate extractable iron, aluminium and manganese are comparable with values for profiles JSS5 and JSS6. Cation exchange capacities are very low and the small amounts of exchangeable cations are dominated by Ca^{2+} in surface horizons and by Mg^{2+} at depth. Maximum clay and silt contents of the bulk soil are less than 22 per cent and 6 per cent respectively. In contrast to the high gravel contents of the two profiles sampled from mapping unit II at Site 1, gravel contents of profile JSS7 are low (less than 6 per cent in the top 70 cm).

5 HYDROLOGY OF SITE 1

An assessment of the capacity of the soil to accept and transmit water was made by measuring soil hydraulic conductivity of both surface soil and underlying strata. At Site 1, some 33 watertable monitoring bores (MC1-33, shown in Fig. 3) had been installed to between 3-5 m depth below the soil surface. Twenty nine of these bores contained sufficient depth of water for drawdown tests to be undertaken during the field study in September, 1986. These holes were partially emptied and rates of return flow, measured immediately afterwards, were converted to hydraulic conductivity, K, using the nomographic solution of Maasland & Haskew (1957). The results, presented in Table 5, indicate a log-normal distribution of K values ranging over two orders of magnitude, with a geometric mean value of around 0.38 m/day. For a log-normal distribution, the antilog of the standard deviation of the transformed data (antilog S_1) may be used as an index of variability (Rogawski 1972). The value of the antilog S_1 for the data in Table 5 is 4.4, well above the limit of 2 suggested by Rogawski to indicate a uniform soil, but similar to the variability found for many other field sites (Talsma & Hallam 1980).

The hydraulic conductivity of B and C horizons was assessed, at the 19 locations shown in Fig. 3, using the well permeameter method described by Talsma & Hallam (1980) and Talsma (1987). Measurements were made over the soil depth intervals 20-50 cm and 50-80 cm. The hydraulic conductivity was calculated using the equation:

$$K = 3.3\ Q/\pi H^2$$

where Q is the steady rate of flow of water into the soil from a borehole in which the depth of water is maintained at H. Results are listed in Table 6; values again vary by over two orders of magnitude, with overall geometric mean values of about 1 m/day. The value of antilog S_1 is 3.6 for the 20-50 cm depth interval data and 4.4 for the 50-80 cm depth interval, again indicating a high degree of variability. Soils of map unit III tend to have highest values of hydraulic conductivity.

Hydraulic conductivity of the soil A horizons was not measured. It is usually found that A horizons under natural vegetation are much more permeable than B horizons (Talsma & Hallam 1980). With mean values of hydraulic conductivity of B and C horizons around 1 m/day and deeper strata around 0.5 m/day, all soils at Site 1 are classified as 'well drained to excessively drained soils' (Schwab et al. 1981).

The hydrology of Site 2 was not studied.

Table 5. Hydraulic conductivity (K) for current land application area. Calculated from drawdown tests in existing test wells (September 1986)

Mapping unit	Test well no. (Map 3)	Well depth (m)	Static water level (m below ground surface)	K (m/day)
I	MC 10	5.0	1.9	1.00
I	MC 21	4.0	0.8	0.69
I	MC 20	4.5	2.0	0.81
I	MC 15	3.0	1.2	0.38
II	MC 13	2.1	1.2	0.19
II	MC 1	4.0	1.6	0.09
II	MC 12	2.7	0.7	0.39
II	MC 26	3.6	2.1	0.19
II	MC 11	3.2	1.2	0.04
II	MC 19	4.1	0.7	0.10
II	MC 9	4.2	0.7	0.11
II	MC 8	4.3	1.3	0.41
II	MC 18	4.0	1.2	0.22
II	MC 2	3.5	1.1	0.50
II	MC 22	6.1	1.6	0.12
II	MC 25	5.3	1.2	7.00
II	MC 7	3.9	0.9	0.41
II	MC 17	3.6	0.9	0.07
II	MC 6	3.8	0.9	0.28
II	MC 16	4.8	0.9	0.06
II	MC 5	4.0	1.2	0.15
II	MC 3	4.0	0.9	5.00
II	MC 4	3.0	0.9	0.07
II	MC 24	5.3	1.2	0.47
II	MC 23	3.9	1.0	1.75
II	MC 34	2.5	0.7	2.80
II	MC 32	3.6	2.3	0.30
III	MC 33	3.1	0.5	4.00
III	MC 28	4.1	1.7	1.02

Table 6. Hydraulic conductivity (K) for current land application area determined by the well permeameter method (September 1986)

Location[a]	Mapping unit	Hydraulic conductivity (m/day) Soil depth 20-50 cm	50-80 cm
J4	I	0.74	0.11
JSS2	I	4.76	2.38
JSS2	I	2.04	0.62
J5	II	1.94	1.54
J6	II	0.18	0.15
JSS5	II	0.58	7.92
JSS6	II	0.26	0.30
J25	II	0.54	NM
J25	II	1.18	NM
J32	II	0.44	0.94
DME PIT	II	NM	0.70
J36	II	1.84	0.78
J15	III	0.41	NM
J15	III	2.06	NM
J22	III	0.62	2.36
J26	III	2.34	1.76
J35	III	5.30	6.16
JSS3	III	3.70	0.74
JSS3	III	19.60	NM
Overall mean		1.29	0.99
Map unit I mean		1.93	0.55
Map unit II mean		0.64	0.83
Map unit III mean		2.40	2.09

[a] Refers to symbols on Fig. 3.
NM - not measured.

6 DISCUSSION

6.1 Soil chemistry and mineralogy

Soil pH, electrical conductivity, cation exchange capacity and exchangeable cation analyses indicate that the soils of all three mapping units are moderately leached and have very low cation exchange capacities under natural conditions (Table 2). These findings are to be expected with the Sites 1 and 2 on an old, highly weathered surface under present climatic conditions. Clay mineral analyses indicate that the underlying weathered schistose rocks contain predominantly kaolinite and illite, with some chlorite, vermiculite and iron oxides. Strong weathering processes acting on these materials appear to have chemically destroyed much of this clay leading to the development of residual sandy A horizons, but the extent to which termite activity may have redistributed materials laterally is unknown. Some of the sand in the A horizons, however, may also have been derived from fluvial, colluvial and aeolian activity in the area during the late Quaternary period.

The occurrence of chloritised vermiculite in the soil A and B horizons is assumed to be the result of weathering of the vermiculite, derived from the underlying substrates, in an acidic, seasonally wet environment. Brinkman (1979) suggests that chloritised vermiculites can form as a result of ferrolysis, which can occur in acid seasonally wet soil. For ferrolysis to occur, however, some reduction of ferric oxides is required. As discussed below reduction of iron and manganese oxides, except in the upper 0-2 cm of the soils, is minimal. This suggests that the formation of the chloritised vermiculite is either a relict process, or that it takes place at extremely slow rates. The chloritisation of the vermiculite is, however, of some significance to metal-clay interactions: the capacity of clay for cation-exchange and specific adsorption reactions can be respectively suppressed and enhanced by formation of Al-hydroxy interlayers within 2:1 layer silicates (Harsh & Doner 1984). Thus, in spite of the presence of vermiculite type minerals in the soils, CEC levels of the clay fraction (< 2 μm) are characteristic of soils dominated by low activity clays.

Assessment of the ability of soil constituents to adsorb and retain both cationic and anionic species applied in irrigation water is the major aim of further work. However, at this stage it is possible to make some comments on certain aspects of the problem, particularly with respect to the capacity of the soils to adsorb (but not necessarily retain) cations such as magnesium, calcium, potassium and sodium through exchange reactions. When the high gravel contents of most of the soils of the irrigation area are taken into account, CEC values for the upper 50 cm of the whole soil are calculated to be extremely low, indicating a very limited potential for the assimilation of major cations (Table 2). Using a range of CEC values between 1.0 to 3.0 cmol (p^+)/kg (equivalent to 1 to 3 meq/100 g), which is close to the measured range (Table 2), assimilative capacities for major cations for the soils of the irrigation area can be estimated (Table 7).

Table 7. Capacity of the upper 50 cm of soil at the current land application area to bind metals in Retention Pond 2 water by cation-exchange reactions

Calculations based on a range of best and worst possible values for CEC and ionic-strength, and assuming only divalent cations in the irrigation water.

Fine earth CEC	=	1.0 to 3.0 cmol (p^+)/kg
Fine earth proportion	=	30 to 90% wt/wt
Therefore whole soil CEC	=	(3 to 27) x 10^{-3} mol (p^+)/kg
Soil depth	=	0.5 m
Soil area	=	3.3 x 10^5 m^2
Therefore total volume	=	1.6 x 10^5 m^3
Soil bulk density	=	(1.4 to 1.7) x 10^3 kg/m^3
Therefore soil mass	=	(2.2 to 2.7) x 10^8 kg
Therefore total CEC	=	(6.6 to 72.9) x 10^5 mol (p^+)
Average irrigation rate	=	12 mm/day over 33 ha
Average irrigation period	=	180 days (June-Dec.)
Volume of RP2 water used	=	$1.2 \times 10^{-2} \times 10^4 \times 33 \times 180 = 7.1 \times 10^5$ m^3
Ionic strength of RP2 water	=	5 to 10 mol/m^3
Therefore maximum divalent cation concentration	=	1.25 to 2.5 mol/m^3 (see Note 1)
Therefore maximum annual divalent cation load in the applied irrigation water	=	($2 \times 1.25 \times 7.1 \times 10^5$) to ($2 \times 2.5 \times 7.1 \times 10^5$)
	=	(1.3 to 3.6) $\times 10^6$ mol(p^+)

Note 1: $I = 0.5\ \Sigma C_i Z_i^2$
where I = ionic strength (mol/dm^3), C_i = concentration of ion i (mol/dm^3) and Z_i = valence of i.

Based on the assumptions given in Table 7, the time until the exchange complex comes into equilibrium with the irrigation water will range from:

$[(6.6 \times 10^5)/(3.6 \times 10^6)]$ to $[(7.29 \times 10^6)/(1.3 \times 10^6)]$ years,

i.e 0.18 to 5.6 years.

While the irrigation water is dominated by divalent cations, exchange with monovalent cations will shorten the above time estimates. Any additional load of major cations applied to the soil would therefore be expected to pass through the upper 50 cm layer. It is emphasised that these predictions take no account of biological sinks or pathways; these may lead to temporary or permanent storage of the applied cations within the site or to removal and dissemination of cations from the site. Thus biological factors may prolong the equilibrium periods calculated above.

The foregoing conclusions regarding the capacity of the soil to assimilate major cations do not necessarily apply to other cations present in RP2 water in minor or trace concentrations; these latter cations include manganese, uranium and radium. In these cases (high affinity), specific-adsorption reactions are likely to contribute to metal uptake, the reversibility of which will depend on solution variables such as metal levels, pH and ionic strength. At this stage, there is insufficient information available to enable quantitative assessment of the likely significance of these mechanisms. However, it is possible to draw some important qualitative conclusions.

Virtually all the profiles examined contain a high proportion of gravels, consisting of relatively inert quartzose material. A smaller, as yet undefined, proportion is made up of ironstone nodules and concretions and ferruginised fragments of schistose rock. These ferruginous gravels are expected to play an important part in the retention of specifically-adsorbing ionic species.

The redox chemistry of iron and manganese in soils can cause immobilisation of metals because of their adsorption onto and incorporation into the relatively insoluble compounds of Mn(III), Mn(IV) and Fe(III), following oxidation of the dissolved Mn(II) and Fe(II). Conversely, the reductive dissolution of such oxidised compounds during waterlogging can cause remobilisation of formerly bound heavy metals. The soils of the irrigation area are generally low in total reducible iron and manganese in comparison with many soils (Stace et al. 1968). The low levels of oxidisable organic carbon, in all except the surface 0-2 cm, were sufficient to enable the reduction of less than 17% of the total reducible manganese available, during waterlogging periods of up to 8 weeks. The corresponding reduction of iron was less than 1% of the total available. The low Fe_{ox}:Fe_d ratio (< 0.2) indicates that the oxides are relatively resistant to reductive dissolution; this suggests that the soils have not undergone recent cycles of oxidation and reduction. The 0-2 cm layer, in which there is sufficient readily oxidisable carbon to enable reduction of iron and manganese oxides to occur is, however, unlikely to be waterlogged for long periods. It is therefore unlikely that cyclic reduction and oxidation will significantly affect the mobilisation, or immobilisation, of heavy metals and radionuclides in the soils of the irrigation area.

6.2 Hydrology

Data from the drawdown tests and measurements of the hydraulic conductivities of B and C soil horizons indicate that flow rates through the profile are relatively rapid. In September 1986 the average water table depth measured over Site 1 was 1.2 m. Given the average water application rate of 12 mm/day and an average evapotranspiration rate of 4.6 mm/day (0.6 times the average pan evaporation for the dry season (Table 1)) the net infiltration rate is calculated to be 7.4 mm/day. Assuming an average steady state volumetric moisture content θ_v of 0.25 (25%) the average residence time for water above the watertable is found to be 41 days (see following equations):

$$\text{Travel rate} = \frac{\text{flux}}{\theta_v} = \frac{7.4 \text{ mm of water/day}}{0.25} = 29.6 \text{ mm/day}$$

$$\text{Residence time} = \frac{\text{Depth of watertable}}{\text{Travel rate}} = \frac{1200 \text{ mm}}{29.6 \text{ mm/day}} = 41 \text{ days}$$

The largest uncertainty in this calculation stems from the assumption of average water content, which will vary considerably from profile to profile and will depend predominantly upon gravel content. If the average water content is lower than 0.25, water applied to the surface will take less time to reach the watertable.

The analysis of Jury (1975) may be used to estimate the time that water will take to move from the top of the watertable in the irrigation area to Magela Creek, a distance of between 100 and 800 m. The analysis of Jury applies to the flow geometry shown in Fig. 11 and assumes that the watertable is at equilibrium with the application rate. It also assumes that the water moves by 'piston' flow, i.e. without any preferential pathways. Talsma (1981)

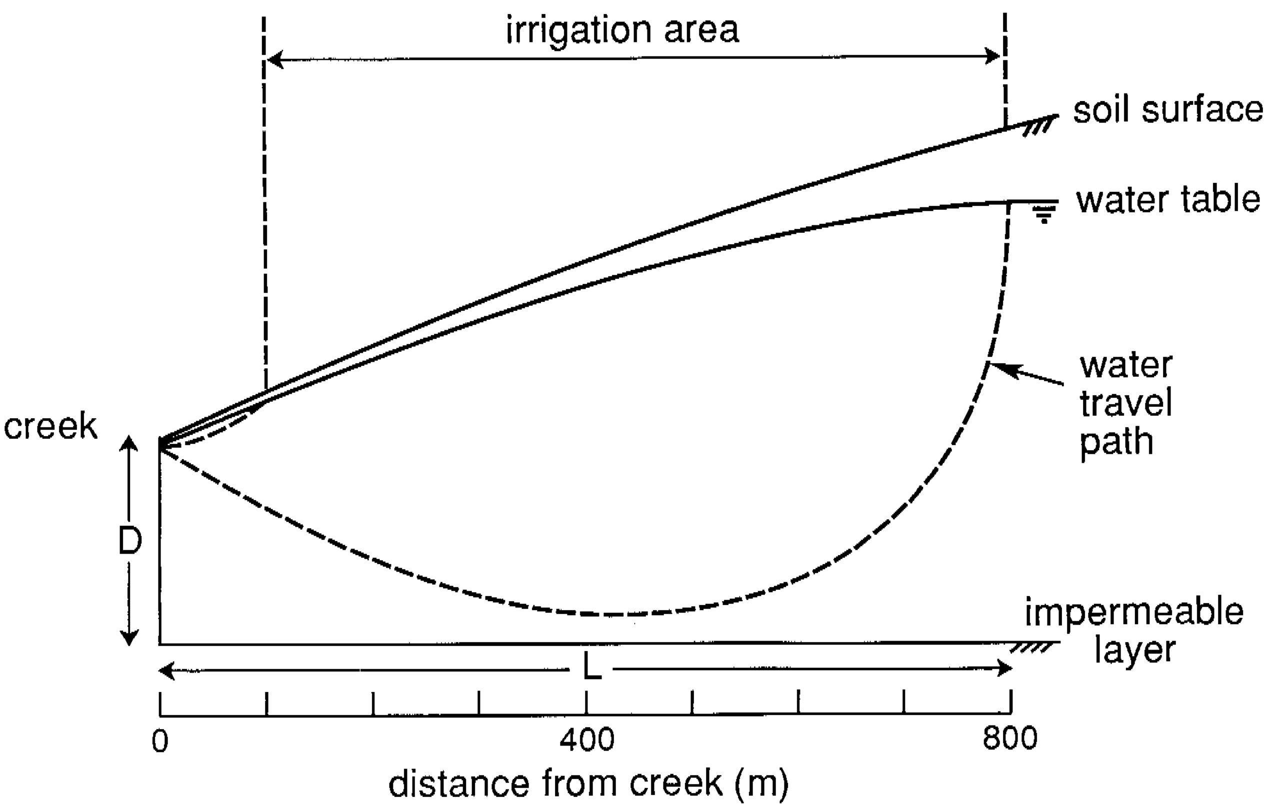


Figure 11. Schema of groundwater travel path to Magela Creek, current Ranger land application area

describes the application of Jury's analysis to a situation similar to that at RUM. For the calculations here, it is assumed that the depth of the permeable aquifer (D) is 80 m, the saturated volumetric water content is 0.25 and the rate of arrival of water at the watertable of 7.4 mm/day (as calculated above). When these values are used in Jury's analysis it is found that the travel times for water moving from the top of the watertable to the creek will range from 9 months (for water arriving at the watertable at a distance of 100 m from Magela Creek) to 30 years (for water arriving at the watertable at a distance of 800 m from the creek). The principal potential source of error in this analysis is the estimate of the depth of the permeable aquifer, which may well be much less than 80 m. Jury's analysis does not permit calculation of travel times for values of D/L less than 0.1, but the effect of a shallow aquifer would be to decrease the travel times from 800 m, while having little effect on those from points close to the creek.

Field observations of soil morphological properties and topography indicate that the soils of mapping unit I are well drained and unlikely to become waterlogged. In mapping unit II the soils are characterised by the presence of mottled subsoils, suggesting that for some period of the year drainage may be impeded and the profile saturated. Analyses of iron released as a result of waterlogging indicate, however, that reduction of subsoils in the short term (8 weeks) does not occur in the deeper soil layers (Fig. 7a, Table 3). Consequently, the mottling observed in the B horizons of the soils of unit II has either developed extremely slowly during prolonged periods of saturation, which are uncommon now, or is the result of other non-reductive processes of iron mottling and precipitation. Although the soils of mapping unit III are not mottled, they are conspicuously bleached in their upper layers, suggesting that processes of iron oxide removal have been active. Free iron oxide contents are also extremely low in the A horizons of this unit.

Field observations during February 1987, indicated that the soils of mapping unit III were in fact waterlogged to the surface, whereas in mapping units I and II, although being relatively moist, the soils were not waterlogged. When soil morphological properties are considered along with topography, and hydraulic conductivity measurements, it appears that although the soils of unit III have rapid permeabilities, both internal and external drainage of the unit are poor. This poor drainage may result from the intersection of the watertable with the surface of unit III because of its low elevation, or due to the occurrence of relatively impermeable ferricrete layers within the unit. Unit III may also receive some throughflow from neighbouring more elevated areas of unit II.

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APPENDIX 1

Field descriptions and laboratory analyses of sampled soil profiles (Munsell colours are for moist soil).

(CP numbers are CSIRO laboratory sample nos)

JSS1 (CP249) Mapping unit I Lat. 8597 590N, Long. 274 915E

(irrigated) Red earth; Gn4.11; Torrox

Depth cm	Horizon	Description
0-2	A_{11}	Dark brown (7.5YR 3/1) gravelly sandy loam; massive; very weak in the moist state ferruginous nodules and quartz gravel to 5 mm; arbitrary boundary
2-5	A_{12}	Dark reddish brown (5YR 3/2) gravelly sandy loam; massive; very weak in the moist state; few ferruginous nodules and quartz gravel to 5 mm; gradual boundary to
5-10	A_3	Dark reddish brown (5YR 3/3) gravelly sandy loam; massive; very weak in the moist state; common ferruginous nodules and quartz gravel to 2 cm; gradual boundary to
10-18	B_{11}	Dark red (2.5YR 3/6) gravelly clay loam; weak, subangular blocky structure (5 cm); moderately weak in the wet state; many ferruginous nodules and quartz gravels to 2 cm; gradual boundary to
18-29	B_{12}	Dark red (2.5YR 3/6) gravelly light clay; weak subangular blocky (5 cm) structure; moderately weak in the wet state; many ferruginous nodules and quartz gravels to 2 cm; gradual boundary to

					Exchangeable cations					
Depth cm	$pH_{1:5}$	$EC_{1:5}$ mS/cm	$Cl_{1:5}$ mg/kg	O.C. %	Ca	Mg	K mmol(p^+)/kg	Na	CEC	Base Sat. %
0-2	6.2	0.10	< 20	1.80	15.0	26.0	1.0	0.5	36.0	100
2-5	5.6	0.08	< 20	1.27	6.1	13.0	0.8	0.4	23.0	88
5-10	5.4	0.09	< 20	0.82	3.1	9.3	0.9	0.5	16.0	86
10-18	5.4	0.10	< 20	0.61	3.0	9.2	0.8	0.3	14.0	95
18-29	5.5	0.10	< 20	0.41	3.0	11.0	1.0	0.4	14.0	100
29-42	5.6	0.09	< 20	0.24	3.0	11.0	1.1	0.4	13.0	100
42-64	5.9	0.08	< 20	0.18	2.3	13.0	1.2	0.6	16.0	100
64-94	6.1	0.07	< 20	0.09	0.1	19.0	1.1	0.7	19.0	100
94+	5.9	0.04	< 20	0.07	0.0	17.0	0.9	1.2	19.0	100

[a] % of field sample

Depth cm	Horizon	Description
29-42	B_2	Red (2.5YR 4/6) gravelly light clay; weak, subangular blocky (2 cm) structure; moderately weak in the wet state; many ferruginous nodules and quartz gravels to 2 cm; gradual boundary to
42-64	BC	Red (2.5YR 4/6) clayey gravel; massive; moderately weak in the wet state; abundant ferruginous nodules and quartz gravel to 6 cm; gradual boundary to
64-94	BC	Red (2.5YR 4/6) clayey gravel; massive; moderately firm in the wet state; abundant weathered schist fragments to 20 cm; clear boundary to
94-100	C	Red (2.5YR 5/8) gravelly sandy clay loam with many, medium, distinct strong brown (7.5YR 5/8) mottles; moderate platy (1 x 2 cm) structure; moderately firm in the wet state; red (2.5YR 5/8) argillans on ped faces; many weathered schist fragments to 2 cm; continues with depth

Dithionite Extr.			Oxalate Extr.			$Fe_{ox}:Fe_d$	Particle-size distribution (%)				
Fe	Al mg/kg	Mn	Fe	Al mg/kg	Mn		Gravel[a] > 2000 μm	Coarse sand 2000-200 μm	Fine sand 200-20 μm	Silt 20-2 μm	Clay < 2 μm
12211	2414	1092	485	132	63	0.04	36	38	47	10	9
12207	2472	948	462	1253	945	0.04	38	30	49	11	11
14308	2553	923	424	1076	817	0.03	39	28	49	11	14
16733	2712	765	466	971	717	0.03	39	27	46	9	19
16100	2724	710	531	848	680	0.03	35	27	43	8	23
18402	2734	554	500	711	475	0.03	47	24	43	7	28
18381	2703	356	398	560	223	0.02	69	27	38	6	30
25639	3083	334	355	522	94	0.01	64	23	34	12	33
22147	2923	154	245	397	56	0.01	21	17	37	16	30

JSS2 (CP250) Mapping unit I Lat. 8597 600N, Long. 274 975E

(unirrigated) Red Earth; Gn2.11; Torrox

Depth cm	Horizon	Description
0-2	A_{12}	Dark brown (7.5YR 3/2) gravelly loamy sand; massive; moderately weak in the dry state; common ferruginous nodules and quartz gravel to 2 cm; arbitrary boundary
2-5	A_{12}	Dark brown (7.5YR 3/2) gravelly loamy sand; as above; gradual boundary to
5-9	AB	Dark reddish brown (5YR 3/3; 5YR 6/4 dry) gravelly sand; massive; moderately weak in the dry state; moderate amount of ferruginous nodules and quartz gravel to 2 cm; gradual boundary to
9-24	B_{11}	Dark reddish brown (5YR 3/4) gravelly sandy loam; massive; moderately weak in the dry state; moderate amounts of ferruginous nodules and quartz gravel to 6 cm; gradual boundary to

					Exchangeable cations					
Depth cm	$pH_{1:5}$	$EC_{1:5}$ mS/cm	$Cl_{1:5}$ mg/kg	O.C. %	Ca	Mg	K mmol(p^+)/kg	Na	CEC	Base Sat. %
0-2	6.0	0.02	< 20	1.54	8.3	6.2	1.2	0.3	21.0	76
2-5	5.8	0.02	< 20	1.26	5.0	5.7	0.9	0.2	19.0	62
5-9	5.8	0.01	< 20	1.02	1.7	3.0	0.7	0.2	18.0	31
9-24	5.9	0.01	< 20	0.64	1.3	3.1	0.4	0.2	12.0	42
24-35	5.9	0.01	< 20	0.45	1.0	3.8	0.3	0.1	11.0	47
35-54	5.8	<0.01	< 20	0.24	1.0	4.0	4.0	0.1	11.0	50
54-70	5.8	<0.01	< 20	0.12	1.0	9.6	0.6	0.1	18.0	63

[a] % of field sample

Depth cm	Horizon	Description
24-35	B_{12}	Reddish brown (5YR 4/4) gravelly loam; massive; moderately weak in the dry state; moderate amounts of ferruginous nodules and quartz gravel to 6 cm; clear boundary to
35-54	B_2	Red (2.5YR 4/6) clayey gravel; massive; very weak in the dry state abundant ferruginous nodules and quartz gravel to 15 cm; abrupt, irregular boundary to
54-70	C	Red (10R 4/8) clayey gravel with many, medium distinct brownish yellow (10YR 6/6) mottles; very strong in the dry state; reddish brown (5YR 4/4) cutans on faces of weathered rock fragments; more or less continuous ferruginous schist; continues with depth

Dithionite Extr.			Oxalate Extr.			Fe_{ox}:Fe_d	Particle-size distribution (%)				
Fe	Al mg/kg	Mn	Fe	Al mg/kg	Mn		Gravel[a] > 2000 μm	Coarse sand 2000-200 μm	Fine sand 200-20 μm	Silt 20-2 μm	Clay < 2 μm
8036	2246	612	634	1190	627	0.08	39	37	46	9	9
8460	2374	696	640	1416	768	0.08	46	37	46	9	9
9587	2568	700	634	1463	706	0.07	42	33	49	10	10
10490	2370	606	602	1266	615	0.06	41	32	47	7	15
12291	2221	500	507	1036	475	0.04	45	29	47	6	18
14252	2408	294	383	630	242	0.03	63	29	44	6	21
21309	2994	321	230	509	237	0.01	70	30	31	14	28

JSS6 (CP254) Mapping unit II Lat. 8597 380N, Long. 274 400E

(irrigated) Yellow Earth; Gn2.84; Torrox

Depth cm	Horizon	Description
0-2	A_{11}	Very dark greyish brown (10YR 3/2) gravelly loamy sand; weak, subangular blocky structure (2 mm); very weak in the moist state; abundant ferruginous nodules and quartz gravels to 2 cm; arbitrary boundary
2-5	A_{12}	Dark greyish brown (10YR 4/2) gravelly loam and; as above; arbitrary boundary
5-8	A_{13}	Dark greyish brown (10YR 4/2) gravelly loamy sand; massive; very weak in the moist state; moderate amounts of ferruginous nodules and quartz gravels to 2 cm; gradual boundary to
8-16	A_{21}	Yellowish brown (10YR 6/4; 10YR 6/2 dry) gravelly sandy loam; massive; moderate amounts of ferruginous nodules and quartz gravels to 2 cm; gradual boundary to

					Exchangeable cations					
Depth cm	$pH_{1:5}$	$EC_{1:5}$ mS/cm	$Cl_{1:5}$ mg/kg	O.C. %	Ca	Mg	K mmol(p^+)/kg	Na	CEC	Base Sat. %
0-2	6.2	0.06	< 20	1.06	7.0	16.0	0.6	0.4	23.0	100
2-5	5.5	0.05	< 20	0.61	2.0	3.9	0.4	0.4	7.7	87
5-8	5.2	0.07	< 20	0.45	3.0	4.9	0.4	0.6	8.4	100
8-16	5.3	0.08	< 20	0.35	2.0	8.0	0.4	0.5	12.0	91
16-33	5.3	0.09	< 20	0.26	2.0	10.0	0.5	0.6	12.0	100
33-46	5.8	0.06	< 20	0.14	1.4	23.0	0.5	1.6	25.0	100
46-62+	5.9	0.02	< 20	0.09	0.4	20.0	0.4	1.5	26.0	86

[a] % of field sample

Depth cm	Horizon	Description
16-33	A_{22}	Light yellowish brown (10YR 6/4; 10YR 7/2 dry) gravelly sandy loam; massive; very weak in the moist state; moderate amounts of ferruginous nodules and quartz gravels to 10 cm; gradual boundary to
33-46	B_2	Light yellowish brown (10YR 6/4) gravelly clay loam with many, coarse distinct red (2.5YR 5/8) mottles; massive; moderately strong in the moist state; few soft ferruginous nodules to 1 cm; abrupt boundary to
46-62	C	Red (2.5YR 4/8) clayey gravel with common light yellowish brown (10YR 6/4) mottles; massive; moderately strong in the moist state; abundant soft ferruginous nodules to 1 cm; continues with depth

Dithionite Extr.			Oxalate Extr.			$Fe_{ox}:Fe_d$	Particle-size distribution (%)				
Fe	Al mg/kg	Mn	Fe	Al mg/kg	Mn		Gravel[a] > 2000 μm	Coarse sand 2000-200 μm	Fine sand 200-20 μm	Silt 20-2 μm	Clay < 2 μm
4352	1608	67	709	742	68	0.16	54	35	52	5	8
3956	1707	23	510	729	20	0.13	52	33	56	4	8
4654	1835	6	534	722	1	0.11	50	35	53	4	10
5959	2131	2	613	703	0	0.10	51	35	49	7	10
6613	2673	1	451	561	0	0.07	75	34	47	6	15
17275	3827	3	392	627	0	0.02	71	28	25	12	35
19412	3363	4	329	555	0	0.02	58	31	28	9	37

JSS5 (CP253) Mapping unit II Lat. 8597 250N, Long. 274925E

(unirrigated) Yellow Earth; Gn2.24; Torrox.

Depth cm	Horizon	Description
0-5	A_{11}	Black (10YR 2/1) gravelly loamy sand; weak subangular blocky (5 cm) structure; very weak in the dry state; moderate amounts of ferruginous nodules and quartz gravels to 2 cm; arbitrary boundary
2-5	A_{12}	Very dark grey (10YR 3/1) gravelly loamy sand; very weak in the dry state; moderate amounts of ferruginous nodules and quartz gravels to 2 cm; arbitrary boundary
5-10	A_{13}	Very dark greyish brown (10YR 3/2) gravelly loamy sand; very weak in the dry state; moderate amounts of ferruginous nodules and quartz gravels to 5 cm; gradual boundary
10-25	A_2	Brown (7.5YR 4/4; 7.5YR 6/4 dry) gravelly sandy loam; massive; moderately weak in the dry state; abundant ferruginous nodules and quartz gravels to 5 cm; gradual boundary to

					Exchangeable cations					
Depth cm	$pH_{1:5}$	$EC_{1:5}$ mS/cm	$Cl_{1:5}$ mg/kg	O.C. %	Ca	Mg	K mmol(p^+)/kg	Na	CEC	Base Sat. %
0-2	6.0	0.04	< 20	3.89	58.0	24.0	2.1	0.3	52.0	100
2-5	6.0	0.02	< 20	1.98	20.0	12.0	1.0	0.2	39.0	85
5-10	5.9	0.01	< 20	1.19	0.0	5.8	0.7	0.2	16.0	42
10-25	5.8	0.01	< 20	0.75	1.0	4.3	0.7	0.3	13.0	48
25-40	5.8	0.01	< 20	0.34	0.0	5.3	0.6	0.2	14.0	44
40-50	5.7	0.01	< 20	0.26	0.0	9.1	0.7	0.3	18.0	56
50-60	5.9	0.01	< 20	0.19	1.0	16.0	0.7	0.3	22.0	82

[a] % of field sample

Depth cm	Horizon	Description
25-40	B_1	Strong brown (7.5YR 5/8) gravelly silt loam; massive; moderately weak in the dry state; moderate amount of ferruginous nodules and quartz gravels to 5 cm; clear boundary to
40-50	B_2	Strong brown (7.5YR 5/8) gravelly silty clay loam; moderately weak in the dry state; moderate amount of ferruginous nodules to 5 cm; abrupt boundary to
50-60	C	Yellowish red (5YR 5/8) clayey gravel with many dark red (2.5YR 3/6) mottles; is essentially ferruginous schist; continues with depth

Dithionite Extr.			Oxalate Extr.			$Fe_{ox}:Fe_d$	Particle-size distribution (%)				
Fe	Al mg/kg	Mn	Fe	Al mg/kg	Mn		Gravel[a] > 2000 μm	Coarse sand 2000-200 μm	Fine sand 200-20 μm	Silt 20-2 μm	Clay < 2 μm
6104	2626	556	647	1874	591	0.11	65	42	33	10	10
5862	2472	498	549	1604	544	0.09	62	43	37	10	9
6082	2407	403	493	1341	433	0.08	61	42	39	9	10
8465	2543	270	453	1078	305	0.05	65	36	43	9	12
11400	2940	98	310	646	98	0.03	59	35	40	8	18
15543	3903	34	267	598	21	0.02	67	33	33	8	27
23875	4891	24	283	645	7	0.01	68	29	25	12	35

JSS4 (CP 252) Mapping unit III Lat. 8597 390N Long. 274780E

(irrigated) Yellow Earth; Gn2.34; Torrox

Depth cm	Horizon	Description
0-2	A_{11}	Very dark grey (10YR 3/1) gravelly sand; single grained; very weak in the moist state; few ferruginous nodules and quartz gravel to 2 cm; arbitrary boundary
2-5	A_{12}	Very dark greyish brown (10YR 3/2) gravelly sand; single grained; very weak in the moist state; common ferruginous nodules and quartz gravel to 2 cm; arbitrary boundary
5-12	A_{21}	Brown (10YR 4/3; 10YR 7/2 dry) gravelly loamy sand; massive; very weak in the moist state; common ferruginous nodules and quartz gravel to 2 cm; gradual boundary to
12-26	A_{22}	Yellowish brown (10YR 5/4; 10YR 7/2 dry) gravelly loamy sand; massive; very weak in the moist state; moderate amounts of ferruginous nodules and quartz gravel to 2 cm; gradual boundary to

					Exchangeable cations					
Depth cm	$pH_{1:5}$	$EC_{1:5}$ mS/cm	$Cl_{1:5}$ mg/kg	O.C. %	Ca	Mg	K mmol(p^+)/kg	Na	CEC	Base Sat. %
0-2	6.2	0.06	< 20	1.73	15.0	26.0	0.5	0.7	40.0	100
2-5	5.8	0.04	< 20	1.00	3.0	7.7	0.4	0.4	17.0	68
5-12	5.6	0.05	< 20	0.78	1.0	5.8	0.4	0.4	12.0	63
12-26	5.3	0.07	< 20	0.61	1.0	6.3	0.4	0.0	12.0	68
26-37	5.2	0.08	< 20	0.38	1.5	5.7	0.5	0.5	9.4	87
37-53	5.4	0.08	< 20	0.20	0.0	9.1	0.5	0.5	12.0	84
53-80	5.5	0.08	< 20	0.13	0.0	12.0	0.7	0.7	15.0	89

[a] % of field sample

Depth cm	Horizon	Description
26-37	B_1	Brown (7.5YR 5/5) gravelly loam; massive; very weak in the moist state; abundant dominantly quartz gravel to 10 cm; clear boundary to
37-53	B_{21}	Strong brown (7.5YR 5/6) clayey gravel with common, medium, distinct red (2.5YR 4/8) mottles; massive; very weak in the wet state; abundant dominantly quartz gravel to 10 cm; gradual boundary to
53-80	B_{22}	Yellowish brown (10YR 5/6) clayey gravel with common, medium, distinct yellowish red (5YR 4/8) mottles; massive; very weak in the wet state; abundant ferruginous nodules with minor quartz gravel to 10 cm; abrupt boundary to
88-100	D	Dark red (2.5YR 3/6) very strong, more or less continuous ferricrete which contains small cells of loose brownish yellow (10YR 6/5) sand; continues with depth

Dithionite Extr.			Oxalate Extr.			$Fe_{ox}:Fe_d$	Particle-size distribution (%)				
Fe	Al mg/kg	Mn	Fe	Al mg/kg	Mn		Gravel[a] > 2000 μm	Coarse sand 2000-200 μm	Fine sand 200-20 μm	Silt 20-2 μm	Clay < 2 μm
2115	1007	134	356	617	138	0.17	54	38	51	4	5
2793	1255	91	474	777	92	0.17	52	39	51	5	7
2910	1440	57	495	951	60	0.17	50	36	52	5	7
3732	1714	21	548	1057	21	0.15	54	36	49	4	10
4303	1866	11	463	831	11	0.11	67	34	50	3	13
5964	2028	5	319	564	2	0.05	80	35	42	4	19
7548	2271	3	265	520	1	0.04	80	33	38	3	26

JSS3 (CP 251) Mapping unit III Lat. 8597 390N Long. 274825E

(not irrigated) Siliceous sand; Uc2.12; Torrox

Depth cm	Horizon	Description
0-2	A_{11}	Very dark grey (10YR 3/1) sand with gravel; single grained; very weak in the dry state; very few ferruginous nodules and quartz gravel to 6 mm; arbitrary boundary
2-5	A_{11}	As above; arbitrary boundary
5-18	A_{12}	Dark grey (10YR 4/1) sand with gravel; single grained; loose in the dry state; few ferruginous nodule and quartz gravel to 6 mm; gradual boundary to
18-31	A_{21}	Light brownish grey (10YR 6/2; 10YR 7/2 dry) sand with gravel; single grained; loose in the dry state; few ferruginous nodules and quatrz gravel to 6 mm; gradual boundary to

					Exchangeable cations					
Depth cm	$pH_{1:5}$	$EC_{1:5}$ mS/cm	$Cl_{1:5}$ mg/kg	O.C. %	Ca	Mg	K mmol(p^+)/kg	Na	CEC	Base Sat. %
0-2	4.8	0.20	< 20	2.38	5.5	4.5	0.8	1.3	16.0	76
2-5	5.0	0.02	< 20	1.67	2.0	2.4	0.3	0.3	18.0	28
5-18	5.3	0.01	< 20	0.35	0.2	0.8	0.2	0.1	7.0	19
18-31	5.4	0.01	< 20	0.11	1.0	1.4	0.1	0.1	6.2	42
31-48	5.3	0.01	< 20	0.05	1.0	3.6	0.1	0.2	8.0	61

[a] % of field sample

Depth cm	Horizon	Description
31-48	A_{22}	Very pale brown (10YR 7/3; 10YR 8/2 dry) gravelly sand; single grained; loose in the dry state; moderate amounts of predominantly quartz gravel to 10 cm abrupt boundary
48-68	D	Dark red (10YR 3/8) massive, rigid, continuous ferricrete with common brownish yellow (10YR 6/8) mottles; pockets of loose, light grey (10YR 7/2) sand; quartz gravel up to 5 cm cemented in the ferricrete; continues with depth

Dithionite Extr.			Oxalate Extr.			$Fe_{ox}:Fe_d$	Particle-size distribution (%)				
Fe	Al mg/kg	Mn	Fe	Al mg/kg	Mn		Gravel[a] > 2000 μm	Coarse sand 2000-200 μm	Fine sand 200-20 μm	Silt 20-2 μm	Clay < 2 μm
2095	1208	38	1094	782	41	0.52	12	25	62	5	7
1266	1206	9	699	1002	11	0.55	16	28	61	3	6
391	842	1	108	492	1	0.28	16	32	59	3	5
381	511	1	72	321	1	0.19	22	35	56	3	6
551	340	1	43	149	0	0.08	45	40	50	2	7

JSS7 (CP255) Mapping Unit IV Lat. 8594950N Long. 272500E

Field description and laboratory data for profile JSS7 at Site 2.
Yellow earth; Gn2.24; Torrox

Depth cm	Horizon	Description
0-2	A_{11}	Very dark greyish brown (10YR 3/2) loamy sand; massive;moderately firm in the dry state; arbitrary boundary
2-5	A_{12}	As above; arbitrary boundary
5-10	A_{13}	As above; gradual boundary to
10-24	A_2	Dark yellowish brown (10YR 4/4; 10YR 6/4 dry) coarse sandy loam; massive; moderately weak in the dry state; diffuse boundary to
24-37	B_{21}	Yellowish brown (10YR 5/6) clay loam with coarse sand; massive; moderately weak in the dry state; arbitrary boundary

					Exchangeable cations					
Depth cm	$pH_{1:5}$	$EC_{1:5}$ mS/cm	$Cl_{1:5}$ mg/kg	O.C. %	Ca	Mg	K	Na	CEC	Base Sat. %
					mmol(p^+)/kg					
0-2	6.2	0.03	< 20	0.84	7.3	3.4	2.5	0.4	17.0	80
2-5	5.6	0.01	< 20	0.54	3.2	1.9	1.1	0.3	12.0	54
5-10	5.5	0.01	< 20	0.33	2.2	1.8	0.8	0.3	12.0	43
10-24	5.7	0.01	< 20	0.28	1.2	1.6	0.6	0.3	13.0	29
24-37	5.6	0.01	< 20	0.23	1.0	7.7	0.7	0.3	17.0	57
37-50	5.9	< 0.01	< 20	0.16	1.2	11.0	0.6	0.3	19.0	69
50-70	6.0	0.01	< 20	0.11	0.7	13.0	0.6	0.3	18.0	81
70-82	6.0	0.01	< 20	0.10	0.4	18.0	0.7	0.3	23.0	84
82-97+	6.2	0.01	< 20	0.08	0.3	21.0	0.8	0.4	26.0	87

[a] % of field sample

Depth cm	Horizon	Description
37-50	B_{22}	As above; arbitrary boundary
50-70	B_{23}	As above; common ferruginous nodules to 2 cm; clear boundary
70-82	B_{31}	Yellowish brown (10YR 5/5) gravelly coarse sandy loam with many coarse, distinct red (2.5YR 5/8) mottles; massive; moderately firm in the dry state; abundant ferruginous nodules to 2 cm; gradual boundary
82-97	B_{32}	As above; continues with depth

Dithionite Extr.			Oxalate Extr.			$Fe_{ox}:Fe_d$	Particle-size distribution (%)				
Fe	Al mg/kg	Mn	Fe	Al mg/kg	Mn		Gravel[a] > 2000 μm	Coarse sand 2000-200 μm	Fine sand 200-20 μm	Silt 20-2 μm	Clay < 2 μm
5909	2030	67	789	669	62	0.13	2	49	39	5	8
6078	2016	52	882	698	50	0.15	3	55	34	4	9
6563	2161	26	780	681	26	0.12	3	51	35	5	10
7285	2452	13	507	624	14	0.07	2	53	31	5	11
10584	3572	3	353	575	1	0.03	3	57	23	4	17
10666	3380	1	228	601	0	0.02	4	55	22	5	20
11377	3549	0	163	353	0	0.01	5	63	16	4	17
8762	2530	1	99	306	0	0.01	32	63	14	3	20
11330	3085	0	137	263	0	0.01	15	63	13	4	21

APPENDIX 2

Soil Profile Descriptions for augered boreholes for Site 1

In most cases a shallow pit was dug to determine horizon boundaries and structural properties of A and B horizons.

Depth (cm)	Horizon	Description
J1 (8597 6700N 274 900E)		
0-8	A_1	Black (10YR 2/1) gravelly loam; massive; moist, very weak; 10 to 20% ferruginous nodules and quartz gravel to 5 mm; gradual boundary to
8-23	A_2	Brown (7.5YR 4/4, 7.5YR 7/2 dry) gravelly loam; massive; moist, very weak; 10 to 20% ferruginous nodules and quartz gravel to 5 m; clear boundary to
23-30	B_1	Reddish brown (5YR 4/3) gravelly clay loam; massive; 20 to 50% ferruginous nodules to 2 cm; clear boundary to
30-55	B_2	Yellowish red (5YR 5/6) ferruginous schist nodules in a clay matrix; large quartz and ferricrete boulders prevented further drilling.
J2 (8597 600N 274 800E)		
0-3	A_1	Very dark greyish brown (10YR 3/2) gravelly loamy coarse sand; massive; moist, very weak; 10-20% ferruginous nodules and quartz gravel to 5 mm; clear boundary to
3-43	A_2	Yellowish brown (10YR 5/4, 10YR 7/3 dry) gravelly coarse sandy loam; massive; moist,very weak; 10 to 20% ferruginous nodules and quartz gravel to 5 mm becoming 20 to 50% and up to 5 cm at depth; clear boundary to
43-75	B(?)	Reddish yellow (5YR 6/6) ferruginous nodules in a clayey matrix
75-105	R	Dark red (2.5YR 3/6) with common fine distinct reddish yellow (5YR 6/6) mottles; essentially ferruginous schist; water table at 1 m; augering hard

J3 (8597 400N 274 800E)

0-4	A_1	Very dark grey (10YR 3/1) gravelly coarse sandy loam; massive; moist, very weak; 10 to 20% ferruginous nodules and quartz to 5 mm; clear boundary to
4-20	A_2	Strong brown (7.5YR 5/6,7.5YR 7/2 dry) gravelly coarse sandy loam; massive; moist,very weak; 10 to 20% ferruginous nodules and quartz to 5 mm; gradual boundary to
20-60	B	Reddish yellow (7.5YR 6/6) gravelly coarse sandy clay loam; massive; 20 to 50% ferruginous gravel and quartz to 5 cm
60-90	R	Red (10R 4/6) with strong brown (7.5YR 6/6) mottles; ferruginous schist; augering hard

J4 (8597 600N 274 900E)

0-6	A_1	Very dark grey (7.5YR 3/1) gravelly sandy loam; massive; moist, very weak; 2 to 10% ferruginous nodules and quartz to 5 mm; gradual boundary to
6-30	B	Reddish brown (5YR 4/4) with few coarse dark brown (7.5YR 4/2) mottles; gravelly sandy clay loam massive; moist, very weak; 10 to 20% ferruginous nodules and quartz to 2 cm
30-85	B	Red (2.5YR 4/6) gravelly sandy light clay; 20 to 50% ferruginous nodules and quartz to 2 cm
85-110	C	Red (2.5YR 5/8) gravelly sandy medium clay with common medium strong brown (7.5YR 5/8) mottles; 20 to 50% ferruginous nodules and quartz to 2 cm.

J5 (8597 700N 274 800E)

0-6	A_1	Very dark grey (10YR 3/1) gravelly loam sand; massive; moist, very weak; 10 to 20% ferruginous nodules and quartz to 2 cm; clear boundary to
6-14	A_2	Yellowish brown (10YR 5/4, 10YR 6/2 dry) gravelly loamy sand; massive; moist, very weak; 10 to 20% ferruginous nodules and quartz to 5 cm; clear boundary to
14-50	B	Brown (7.5YR 5/5) gravelly sandy clay loam; massive; wet, very weak; 20 to 50% ferruginous nodules and quartz to 5 cm; clear boundary to
50-100	C	Red (10R 4/6) clayey gravel with common medium brownish yellow (10YR 6/6) mottles; essentially ferruginised schist

100-130	R	Red (2.5YR 4/6) fractured ferruginised schist with yellowish brown (10YR 5/5) mottles

J6 (8597 900N 274 800E)

Common surface occurrence of quartz pebbles to 20 cm diameter.

0-9	A_1	Very dark greyish brown (10YR 3/2) gravelly loamy sand; massive; moist, very weak; 20 to 50% ferruginous nodules and quartz to 2 cm; pH 7; gradual boundary to
9-20	A_2	Yellowish brown (10YR 5/4, 10YR 6/2 dry) gravelly loamy sand; massive; moist very weak; 20 to 50% ferruginous nodules and quartz greater than 5 cm; gradual boundary to
20-40	B_1	Reddish yellow (7.5YR 6/6) gravelly sandy loam; massive; moist, moderately weak; 20 to 50% ferruginous nodules and quartz to 5 cm; pH 6; gradual boundary to
40-75	B_2	Red (2.5YR 4/6) gravelly sandy light clay with common medium reddish yellow (7.5YR 6/6) and yellowish brown (10YR 5/6) mottles; 10 to 20% ferruginous nodules and quartz to 2 cm; pH 5.5.
75-95	C	Red (10R 4/6) gravelly light clay with yellowish brown (10YR 5/6) and light brownish grey (2.5Y 6/2) mottles; 20 to 50% ferruginous schist fragments to 2 cm; pH 5.

J7 (8597 820N 274 925E)

Observation of a 1.5m pit exposure: water table at 55 cm.

0-10	A_1	Dark gravelly sandy loam
10-30	A_2	Pale yellowish gravelly sandy loam with a pronounced quartzose gravel layer between 15 and 30 cm, gravel to 10 cm diameter.
30-40	AC	Mixed horizon of A2 and red moderately weak clay nodules
40-150	C	Red very firm ferruginous horizon with yellow and grey mottles forming a layered pattern.

J8 (8597 800N 274 900E)

0-6	A1	Very dark greyish brown (10YR 3/2) gravelly sandy loam; massive; moist, very weak; 2 to 10% ferruginous nodules and quartz gravel to 2 cm; gradual boundary to
6-20	A_2	Strong brown (7.5YR 5/5) gravelly sandy loam; massive; moist, very weak; 10 to 20% ferruginous nodules and quartz gravel to 2 cm; gradual boundary to
20-40	B	Yellowish red (5YR 5/6) gravelly loam; massive; 10 to 20% ferruginous nodules and quartz gravel to 2 cm; clear boundary to
40-65	R	Red (10R 4/8) very gravelly clay loam with common fine yellowish brown (10YR 5/6) mottles; sample consists of fractured ferruginous schist.

J9 (8597 800N 275 000E)

0-9	A_1	Dark brown (7.5YR 3/2) gravelly loam; massive; dry, moderately firm; 20 to 50% ferruginous nodules and quartz to 2 cm; gradual boundary to
9-45	B_1	Yellowish red (5YR 4/6, 7.5YR 5/4 dry) gravelly clay loam; massive; dry; moderately weak; 20 to 50% ferruginous nodules and quartz to 2 cm
45-105	B_2	Dark red (2.5YR 6/6) gravel with clay; greater than 50% ferruginous schist fragments
105-110	R	Red (10R 4/6) gravel with clay with greyish brown (2.5Y 5/2) mottle; weathered schist fragments and quartz gravels.

J10 (8597 700N 274 400E)

0-7	A_1	Dark greyish brown (10YR 4/2) gravelly coarse sandy loam; massive; moist, very weak; 2 to 10% ferruginous nodules and quartz to 5 mm; gradual boundary to
7-55	A_2	Dark yellowish brown (10YR 4/4) gravelly coarse sandy loam; massive; moist, very weak; 10 to 20% ferruginous nodules and quartz to 2 cm; gradual boundary to
55-70	R	Red (10R 4/6) gravel with clay with strong brown (7.5YR 5/6) and light brownish grey (2.5Y 6/2) mottles; 10 to 20% weathered schist fragments and ferruginous nodules to 2 cm.

J11 (8597 600N 274 500E)

0-9	A_1	Very dark grey (10YR 3/l) gravelly sandy loam; massive; moist, very weak; 10 to 20% ferruginous modules and quartz gravel to 5 mm; gradual boundary to
9-45	A2	Brown (10YR 5/3, 10YR 7/3 dry) gravelly strong sandy loam; massive; moist, very weak; 20 to 50% ferruginous nodules and quartz gravel to 2 cm; clear boundary to
45-80	B	Red (2.5YR 4/6) gravelly light clay with common medium distinct light brownish grey (2.5Y 6/3) mottles; 10 to 20% ferruginous nodules and quartz gravel to 5 mm; clear boundary to
80-90	BD	Red (10R 4/6) clayey gravel with common medium distinct yellowish brown (10YR 5/6) mottles; 20 to 50% ferruginous nodules and fragments of weathered schist; impenetrable to hand drilling.

J12 (8597 700N 274 500E)

0-9	A_1	Very dark greyish brown (10YR 3/2) gravelly sandy loam; massive; moist, very weak; 20 to 50% ferruginous nodules and quartz gravel to 2 cm; clear boundary to
9-30	A_{21}	Brown (7.5YR 5/4) gravelly sandy loam; massive; moist, very weak; 20 to 50% ferruginous nodules and quartz gravel to 2 cm; gradual boundary to
30-50	A_{22}	Reddish yellow (7.5YR 6/6) gravelly sandy clay loam; 20 to 50% ferruginous nodules and quartz gravel to 2 cm; clear boundary to
50-90	B	Red (10R 4/6) gravelly sandy clay; 20 to 20% ferruginous nodules with minor quartz gravel to 5 mm; gradual boundary to
90-120	R	Red (2.5YR 4/6) gravelly sandy clay with common distinct brown (10YR 5/5) mottles; predominantly fragments of ferruginous schist; impenetrable to hand augering; water seeped in at this level.

J13 (8597 800N 274 500E)

0-4	A_1	Very dark grey (10YR 3/1) gravelly sandy loam; massive; dry, very weak; 20 to 50% predominantly quartz gravel and ferruginous nodules to 2 cm; clear boundary to

4-20	A_2	Yellowish brown (10YR 5/4, 10YR 7/2 dry) gravelly sand; massive; dry, very weak; greater than 50% predominantly quartz gravel with ferruginous nodules to 5 cm; clear boundary to
20-50	B	Dark red (2.5YR 3/6) gravelly clay loam; greater than 50% predominantly ferruginous nodules
50-60	D	Dusky red (10R 3/4) gravelly sandy light clay with light grey (10YR 7/1) and yellowish brown (10YR 5/6) mottles; greater than 50% ferruginous schist fragments;impenetrable by hand auger.

J14 (8597 300N 274 600E)

0-11	A_1	Dark brown (7.5YR 3/2) gravelly loamy sand; massive; wet, very weak; 20 to 50% ferruginous nodules and quartz gravel to 6 mm; clear boundary to
11-20	B_1	Yellowish red (5YR 4/6) gravelly light clay; massive; wet, very weak; 20 to 50% ferruginous nodules and quartz gravel to 2 cm; clear boundary to
20-70	B_{21}	Red (10R 4/8) gravelly medium to heavy clay; 20 to 50% ferruginous nodules and quartz gravel to 2 cm; clear boundary to
70-85+	B_{22}	Red (10R 4/8) medium to heavy clay with common coarse distinct pale olive (5Y 6/3) mottles; continues

J15 (8597 400N 274 600E)

0-10	A_1	Dark brown (7.5YR 3/2) gravelly fine sandy loam; massive; moist, very weak; ferruginous nodules and quartz gravel to 6 mm.
10-30	A_2	Yellowish brown (10YR 5/4) gravelly loamy sand; massive; moist, very weak; abundant ferruginous nodules and quartz gravel to 6 mm.
30-70	A_3	Brownish yellow (10YR 6/6) gravelly fine sandy loam; massive; wet, very weak; abundant ferruginous nodules quartz gravel to 2 cm
70-80	B_1	Reddish yellow (7.5YR 6/6) gravelly fine sandy loam with red (2.5YR 4/6) mottles; massive; wet, very weak; abundant ferruginous nodules and quartz gravel to 2 cm.
80+	D	Ferricrete horizon; impenetrable with soil auger.

J16 (8597 300N 274 700E)

0-8	A_1	Dark brown (10YR 3/3) gravelly sandy loam; massive; moist, very weak; 10 to 20% ferruginous nodules and quartz gravel to 6 mm; gradual boundary to
8-30	A_{21}	Yellowish brown (10YR 5/4, 10YR 7/3 dry) gravelly sandy loam; massive; moist, very weak; 10 to 20% ferruginous nodules and quartz gravel to 6 mm; abrupt boundary to
30-40	A_{22}	Yellowish brown (10YR 5/4) coarse gravel with a clayey sand matrix; massive; more than 50% quartz gravel to 10 cm; abrupt boundary to
40-60	B	Light brown (7.5YR 6/4) gravelly sandy clay loam with red (10R 4/6) ferruginised schist fragments making up 10 to 20% of the horizon
60-80	R	Red (10R 4/6) gravelly sandy clay with common fine brownish yellow (10YR 6/6) mottles; greater than 50% ferruginous schist fragments; continues.

J17 (8597 400N 274 700E)

0-3	A_1	Very dark brown (10YR 2/2) gravelly sand; massive; moist, very weak; abundant ferruginous and quartz gravels to 10 cm; gradual boundary
3-32	A2	Light yellowish brown (2.5Y 6/4) gravelly sand; massive; moist, very weak; abundant ferruginous nodules to 1 cm; abrupt boundary to
32+	D	Very hard ferricrete horizon.

J18 (8597 300N 274 800E)

0-9	A_1	Black (10YR 2/1) gravelly loamy sand; massive; wet, very weak; 2 to 10% ferruginous nodules and quartz gravel to 6 mm; gradual boundary to
9-24	A_2	Yellowish brown (10YR 5/4) gravelly loamy sand; massive; wet, very weak; 10 to 20% ferruginous nodules and quartz to 6 mm; gradual boundary to
24-60	B	Light brown (7.5YR 6/5) gravelly clay loam; massive; wet, very weak; 20 to 50% ferruginous gravel and quartz to 2 cm; clear boundary to

60-80	R	Red (10R 4/6) clayey gravel with pale brown (10YR 6/3) mottle; more than 50% ferruginous nodules and weathered substrate; impenetrable with soil auger.

J19 (8597 200N 274 800E)

0-3	A_1	Very dark grey (10YR 3/1) gravelly sand; massive; moist, very weak; common ferruginous nodules to 6 mm.
3-25	A_2	Yellowish brown (10YR 5/4) gravelly loamy sand; massive; moist, very weak; more than 50% ferruginous nodules and quartz gravel.
25-50	B	Brownish yellow (10YR 6/6) gravelly sandy loam; more than 50% ferruginous nodules and quartz gravel
50-75	R	Strong brown (7.5YR 5/6) gravelly light clay with fine red (2.5YR 4/8) mottles; more than 50% ferruginous nodules and weathered substrate.

J20 (8597 300N 274 900E)

0-7	A_1	Very dark greyish brown (10YR 3/2) gravelly loamy sand; massive; moist, very weak; 10 to 20% ferruginous gravel and quartz gravel up to 6 mm; gradual boundary to
7-25	A_2	Yellowish brown (10YR 5/4, 10YR 7/3 dry) gravelly loamy sand; massive; moist, very weak; 10 to 20% ferruginous gravel and quartz gravel up to 6 mm; clear boundary to
25-53	A_2	Light brown (7.5YR 6/5) gravelly coarse sand; massive; wet, very weak; 20 to 50% ferruginous nodules and quartz gravel to 2 cm; clear boundary to
53-80	B	Dark red (2.5YR 3/6) gravelly medium clay with common, medium strong brown (7.5YR 5/8) mottles; 20 to 50% ferruginous nodules and quartz gravel to 6 mm.
80-85	C	Dark red (2.5YR 3/6) gravelly medium clay with 20 to 50% ferruginous nodules and weathered substrate fragments; impenetrable by soil auger.

J21 (8597 400N 274 900E)

0-3	A_{11}	Very dark grey (10YR 3/1) gravelly sand; massive; dry, moderately firm; pH 5.5

3-12	A_{12}	Dark grey (10YR 4/l) gravelly loamy sand; massive; dry, moderately weak
12-23	A_2	Brown (10YR 4/3, 10YR 6/3 dry) gravelly loamy sand; massive; dry moderately weak; pH 5.
23-30	A_2	Yellowish brown (10YR 5/4, 10YR 6/4 dry) gravelly loamy sand; pH 4.5; abrupt boundary to
30+	D	Ferricrete horizon impenetrable to hand augering.

J22 (8597 390N 274 790E)

0-9	A_1	Very dark greyish brown (10YR 3/2) gravelly coarse sand; massive; moist, very weak; 10 to 20% ferruginous nodules and quartz gravel to 2 cm; gradual boundary to
9-25	A_2	Yellowish brown (10YR 5/4), 10YR 7/3 dry) gravelly sandy loam; massive; moist, very weak; 20 to 50% ferruginous nodules and quartz gravel to > 6 cm
25-45	A_2	Pale brown (10YR 6/3) gravelly sandy loam; massive; wet; more than 50% ferruginous nodules and quartz gravel to > 6 cm
45+	D	Impenetrable ferruginous horizon.

J23 (8597 500N 274 700E)

0-5	A_1	Very dark grey (10YR 3/1) gravelly loamy sand; massive; moist, very weak; 10 to 20% ferruginous nodules and quartz gravel to 2 cm; clear boundary to
5-30	A_2	Yellowish brown (10YR 5/4, 10YR 6/4 dry) gravelly sandy loam; massive; moist very weak; 20 to 50% ferruginous nodules and quartz gravel to 6 cm; gradual boundary to
30-45	B_1	Light yellowish brown (10YR 6/4) gravelly sandy clay loam; massive; wet; 20 to 50% ferruginous nodules and quartz gravel to 20 cm; clear boundary to
45-60	C	Light yellowish brown (10YR 6/4) gravelly clay loam with few, medium, distinct light red (2.5YR 6/8) mottles; massive; wet; 20 to 50% mainly ferruginous nodules and fragments to 2 cm; impenetrable to soil auger.

J24 (8597 500N 274 800E)

0-7	A_1	Very dark grey (10YR 3/1) gravelly sandy loam; massive; moist, very weak; 10 to 20% ferruginous nodules and quartz gravel to 2 cm; gradual boundary to
7-26	A_2	Brown (10YR 5/3, 10YR 7/3 dry) gravelly sandy loam; massive; moist, very weak; 20 to 50% ferruginous nodules and quartz gravel to 6 cm; gradual boundary to
26-45	AB	Light yellowish brown (10YR 6/5) gravelly sandy clay loam; massive; wet; more than 50% ferruginous nodules and quartz gravel to > 6 cm; gradual boundary to
45-80	B	Light red (2.5YR 6/6) gravelly sandy loam with red (10R 4/6) mottles; wet; more than 50% ferruginous nodules and fragments to 6 cm; gradual boundary to
80-90+	R	Red (10R 4/6) gravelly sandy medium clay with light yellowish brown (10YR 6/5) mottles; ferruginous schist.

J25 (8597 400N 274 500E)

0-10	A_{11}	Very dark greyish brown (10YR 3/2) gravelly sand; massive; moist, very weak; ferruginous nodules common
10-50	A_2	Yellowish brown (10YR 5/4) gravelly loamy sand; massive; moist, very weak; abundant quartz gravel.
50-100	B	Red (2.5YR 4/6) gravelly light clay with many reddish yellow (7.5YR 6/6) mottles; moist, moderately firm.

J26 (8597 500N 274 500E)

0-9	A_1	Brown (10YR 5/3) loamy sand; massive; moist, very weak; less than 2% ferruginous nodules and quartz gravel to 2 cm; gradual boundary to
9-30	A_2	Brown (7.5YR 5/5, 10YR 7/4 dry) loamy sand; massive; moist, very weak; less than 2% ferruginous nodules and quartz gravel to 2 cm; gradual boundary to
30-60	D	Dark red (10R 3/6) gravelly sand with pale brown (10YR 6/3) mottles; moist, becoming strong with depth and impenetrable by auger at 60 cm; continuous ferruginous horizon.

J27 (8597 560N 274 430E)

0-9	A_1	Black (10YR 2/1) gravelly loamy coarse sand; massive; moist, very weak; 20 to 50% ferruginous nodules and quartz to 2 cm; gradual boundary to
9-25	A_2	Dark grey (10YR 4/1, 10YR 6/2 dry) gravelly loamy coarse sand; massive; moist, very weak; more than 50% ferruginous nodules and quartz to 6 cm; abrupt boundary to
25+	D	Impenetrable ferricrete horizon.

J28 (8597 600N 274 400E)

0-8	A_1	Very dark grey (10YR 3/1) gravelly coarse sand; massive; moist, very weak; 2 to 10% ferruginous nodules and quartz gravel to 2 cm
8-45	A_2	Brownish yellow (10YR 6/6, 10YR 7/3 dry) gravelly loamy coarse sand; massive; moist, very weak; 10 to 20% quartz rich gravel becoming more than 50% with depth and up to 6 cm
45+	D	Impenetrable ferricrete horizon.

J29 (8597 500N 274 400E)

0-18	A_1	Very dark grey (10YR 3/1) loamy sand with a few fine dark yellowish brown (7.5YR 4/4) mottles along root lines; massive; moist, very weak; gradual boundary to
18-45	A_2	Light brownish grey (10YR 6/2, 10YR 8/1 dry) gravelly loamy sand; massive; moist, very weak; 10 to 20% ferruginous nodules and quartz to 2 cm; clear boundary to
45-90	B	Red (2.5YR 4/6) gravelly sandy clay loam; massive; wet, very firm; 20 to 50% ferruginous nodules and fragments
90-95+	D	Red (10R 4/6) gravel horizon with common, medium yellowish brown (10YR 5/6) mottle; ferruginous zone just penetrable with soil auger.

J30 (8597 400 274 400E)

0-11	A_1	Very dark greyish brown (10YR 3/2) gravelly coarse sandy loam; massive; moist, very weak; 2 to 10% ferruginous nodules and quartz gravel to 2 cm; gradual boundary to
11-22	A_{21}	Brown (10YR 4/3, 10YR 7/3 dry) gravelly coarse sandy loam; massive; moist, very weak; 10 to 20% ferruginous nodules and quartz gravel to 2 cm; gradual boundary to
22-45	A_3	Yellowish brown (10YR 5/4) gravelly sandy clay loam; massive; wet; 20 to 50% ferruginous nodules and quartz gravel to 6 cm
45-55	B	Reddish yellow (7.5YR 6/6) gravelly medium clay with common red (2.5YR 5/8) mottles; moist; 20 to 50% dominantly quartz gravel to 20 cm
55-65+	C	Red (2.5YR 4/8) gravelly light clay; moist; more than 50% quartz gravel to 6 cm; difficult to auger

J31 (8597 800N 274 600E)

0-6	A_1	Very dark greyish brown (10YR 3/2) gravelly coarse sandy loam; massive; moist, very weak; 2 to 10% ferruginous nodules and quartz gravel to 2 cm; gradual boundary to
6-20	A_2	Yellowish brown (10YR 5/4, 10YR 7/2 dry) gravelly coarse sandy loam; massive; moist, very weak; 2 to 10% ferruginous nodules and quartz gravel to 2 cm; gradual boundary to
20-38	AB	Light yellowish brown (10YR 6/4) gravelly sandy clay loam; wet; 20 to 50% dominantly quartz gravel > 6 cm
38-50	B	Light brown (7.5YR 6/4) gravelly sandy medium clay with common, medium dark red (2.5YR 3/6) mottles; wet; more than 50% ferruginous nodules up to 2 cm
50-95+	R	Dark red (2.5YR 3/6) gravelly sandy medium clay; wet; is essentially ferruginous schist.

J32 (8597 700N 274 690E)

0-7	A_1	Very dark greyish brown (10YR 3/2) gravelly sand; massive; moist, very weak; 20 to 50% ferruginous nodules and quartz gravel to 2 cm; gradual boundary to

7-30	A_{21}	Yellowish brown (10YR 5/4) gravelly loamy sand; massive; moist, very weak; 20 to 50% ferruginous nodules and quartz gravel to 2 cm; gradual boundary to
30-48	A_{22}	Light yellowish brown (10YR 6/4) gravelly loamy sand; 20 to 50% ferruginous noduales and quartz gravel to 2 cm
48-80	B	Red (2.5YR 4/6) gravelly sandy clay with light grey (10YR 7/2) mottles; moist; more than 50% ferruginous nodules and quartz to 2 cm
80-95+	D	Red (2.5YR 4/6) gravel; wet; more than 50% ferruginous nodules; almost impenetrable with soil auger.

J33 (8597 700N 274 700E)

0-10	A_1	Very dark grey (10YR 3/1) gravelly loamy sand; massive; moist; many ferruginous nodules and quartz gravel to 2 cm.
10-20	A_2	Dark yellowish brown (10YR 4/4, 7.5YR 6/2 dry) gravelly sand; moist; many ferruginous nodules and quartz gravel to 2 cm
20-40	AB	Brownish yellow (10YR 6/6) gravelly sand; moist; abundant quartz gravel to 10 cm.
40-60	B	Yellowish brown (10YR 5/8) gravelly loam; moist; abundant ferruginous nodules to 2 cm.
60-95	C	Dark red (2.5YR 3/6) gravelly loam with yellow (10YR 7/6) mottle; moist; abundant ferruginous nodules to 2 cm which break up with field texturing.

J34 (8597 600N 274 700E)

0-8	A_1	Dark greyish brown (10YR 4/2) gravelly loamy sand; massive; moist, very weak; 20 to 50% ferruginous nodules and quartz gravel to 2 cm; gradual boundary to
8-20	A_2	Brown (10YR 5/3, 10YR 7/2 dry) gravelly coarse sandy loam; massive; moist, very weak; 20 to 50% ferruginous nodules and quartz gravel to 2 cm; gradual boundary to
20-45	B_1	Light yellowish brown (10YR 6/5) gravelly sandy clay loam; wet; more than 50% dominantly quartz gravel to 10 cm

45-70	B_2	Reddish yellow (7.5YR 6/6) gravelly coarse sandy clay with many medium dark red (10R 3/6) mottles; wet; more than 50% dominantly ferruginous nodules to 2 cm.
70-80	R	Dark red (10R 3/6) clayey gravel with few medium reddish yellow (7.5YR 6/6) mottles; wet; more than 50% ferruginous schist fragments to 2 cm; very hard to auger.

J35 (8597 500N 274 600E)

0-7	A_1	Very dark grey (10YR 3/1) gravelly loamy sand; massive; moist, very weak 2 to 10% ferruginous nodules and quartz gravel to 2 cm; gradual boundary to
7-23	A_2	Yellowish brown (10YR 5/5, 10YR 7/4 dry) gravelly sandy loam; massive; moist, very weak; 20 to 50% ferruginous nodules and quartz gravel to 6 cm; clear boundary to
23-45	A_3	Light yellowish brown (10YR 6/5) gravelly sandy loam; wet; more than 50% dominantly quartz gravel to 10 cm; clear boundary to
45-60	D	Red (10R 4/6) clayey gravel with many light yellowish brown (10YR 6/5) mottles; moist; more than 50% ferruginous schist fragments to 6 cm.
60-65	D	Red (10R 4/6) clayey gravel with few light yellowish brown (10YR 6/5) mottles; moist; impenetrable by soil auger.

J36 (8597 600N 274 600E)

0-8	A_1	Very dark greyish brown (10YR 3/2) gravelly loamy sand; massive; moist; moderate amount of ferruginous nodules and quartz gravel
8-25	A_{21}	Brown (7.5YR 4/4) gravelly loamy sand; massive; moist; moderate amount of ferruginous nodules and quartz gravel
25-40	A_{22}	Brown (7.5YR 4/4) gravel; abundant quartz gravel to 20 cm.
40-70	A_3	Strong brown (7.5YR 5/6) gravel; abundant ferruginous nodules to 1 cm.
70-120	B	Brownish yellow (10YR 6/6) gravelly clay loam; abundant ferruginous nodules to 1 cm.
120-130+	R	Red (2.5YR 4/6) ferruginous schist.

J37 (8597 700N 274 600E)

0-7	A_1	Very dark grey (10YR 3/1) gravelly sand; massive; moist, very weak; 20 to 50% ferruginous nodules and quartz gravel to 2 cm; gradual boundary to
7-30	A_2	Light brown (7.5YR 6/5, 7.5YR 7/4 dry) gravelly loamy sand; massive; moist, very weak; 20 to 50% ferruginous nodules and quartz gravel to 2 cm; gradual boundary to
30-55	B	Reddish yellow (5YR 6/6) clayey gravel with soft, red (10R 4/6) ferruginous segregations; wet; more than 50% dominantly quartz gravel to 6 cm; clear boundary to
55-95	R	Red (10R 4/6) gravelly light clay with reddish yellow (5YR 6/6) mottles; is ferruginous schist which is very difficult to auger.

J38 (8597 900N 274 800E)

0-7	A_1	Dark greyish brown (10YR 4/2) gravelly loamy fine sand; massive; dry, moderately weak; 2 to 10% ferruginous nodules and quartz gravel to 2 cm; gradual boundary to
7-25	A_2	Yellowish brown (10YR 5/4, 10YR 6/4 dry) gravelly loamy fine sand; moist; 10 to 20% ferruginous nodules and quartz gravel to 2 cm; gradual boundary to
25-50	A_3	Yellowish brown (10YR 5/4, 10YR 6/4 dry) clayey gravel; moist; more than 50% predominantly quartz gravel to 15 cm; clear boundary to
50-70	B	Red (10R 4/6) gravelly sandy clay loam with common medium light yellowish brown (10YR 6/4) mottles; moist; more than 50% ferruginous nodules to 2 cm.
70-75	R	Red (10R 4/6) gravelly sandy clay loam with few medium light yellowish brown (10YR 6/4) mottles; moist; more than 50% ferruginous schist fragments to 2 cm.

J39 (8597 900N 274 900E)

0-12	A_1	Very dark grey (10YR 3/1) gravelly loamy sand; dry; 20 to 50% ferruginous nodules and quartz gravel to 6 cm; gradual boundary to

12-30	A_2	Yellowish brown (10YR 5/4) gravelly loamy sand; dry; more than 50% ferruginous nodules and quartz gravel to 6 cm; gradual boundary to
30-45	A_3	Yellowish brown (10YR 5/6) clayey gravel; dry; 20 to 50% ferruginous nodules and quartz gravel to 6 cm; gradual boundary to
45-70	B	Dark red (10R 3/6) gravelly coarse sandy clay with many yellowish brown (10YR 5/5) mottles; 20 to 50% ferruginous nodules to 2 cm; gradual boundary to
70-100+	R	Dark red (10R 3/6) gravelly silty clay; is essentially ground up ferruginous schist.

J40 (8597 210N 274 705E)

0-5	A_1	Very dark greyish brown (10YR 3/2) gravelly loamy coarse sand; massive; moist, very weak; 10 to 20% ferruginous nodules and quartz gravel to 2 cm; gradual boundary to
5-30	A_2	Light yellowish brown (10YR 6/4, 10YR 7/3 dry) gravelly coarse sandy loam; massive; moist, very weak; 10 to 20% ferruginous nodules and quartz gravel to 2 cm; gradual boundary to
30-45	A_3	Light brown (7.5YR 6/4) gravelly coarse sandy loam; massive; wet; 20 to 50% ferruginous nodules and quartz gravel to 10 cm; clear boundary to
45-80	B	Light brown (7.5YR 6/4) gravelly sandy clay with many red (2.5YR 4/6) mottles representing moderately firm ferruginous segregations up to 2 cm; moist; gradual boundary to
80-105	R	Red (10R 4/6) gravelly sandy clay loam with a few light yellowish brown (10YR 6/4) mottles; moist; more than 50% ferruginous schist fragments up to 2 cm; very hard to auger

J41 (8597 400N 274 300E)

0-7	A_1	Dark greyish brown (10YR 4/2) gravelly loamy sand; dry; 20 to 50% ferruginous nodules and quartz gravel
7-35	A_2	Yellowish brown (10YR 5/4, 10YR 7/6 dry) gravelly loamy sand; dry; more than 50% ferruginous nodules and quartz gravel
35-50	B	Brownish yellow (10YR 6/6) gravelly loamy sand; dry; more than 50% quartzose gravel
50+	R	Dark red (2.5YR 3/6) ferruginous schist; very hard to auger.

J42 (8597 500N 274 300E)

0-9	A_1	Very dark greyish brown (10YR 3/2) gravelly loamy sand; dry moderately weak; 2 to 10% ferruginous nodules and quartz gravel to 2 cm; gradual bouandary to
9-25	A_2	Yellowish brown (10YR 5/5, 7.5YR 7/3 dry) gravelly loamy sand; dry, moderately weak; 2 to 10% ferruginous nodules and quartz gravel to 2 cm
25-50	B	Strong brown (7.5YR 5/6) gravelly sandy loam; dry, moderately weak; 10 to 20% ferruginous nodules and quartz gravel to 6 cm
50-60	R	Red (10R 4/6) gravelly coarse sandy loam with many light olive brown 2.5Y 5/4) mottles; moist; ferruginous schist; impenetrable with soil auger.

J43 (8597 600N 274 300E)

0-6	A_1	Very dark greyish brown (10YR 3/2) gravelly loamy sand; massive; dry; 20 to 50% ferruginous nodules and quartz gravel to 2 cm
6-20	A_2	Dark greyish brown (10YR 4/2) gravelly sandy loam; massive; dry; 20 to 50% ferruginous nodules and quartz gravel to 2 cm
20-45	A_3	Yellowish red (5YR 5/6) gravelly loamy sand; dry; more than 50% dominantly quartz gravel to 6 cm
45-55	R	Red (2.5YR 4/6) clayey gravel; essentially fragments of ferruginous schist.

J44 (8597 915N 274 680E)

Briefly described check sites*

0-25	A1 + A2, 7.5YR brown
25-55	A B to R; very gravelly
55-70+	R red; ferruginous substrate; very hard to auger

Replicated 1 m to east

0-20	as in 0-25 cm above
20-45	as above at 25-55cm
45-80+	R red; ferruginous substrate; very hard to auger

J45 (8597 970N 274 670E)

Casual observation in erosion gutter 0.75 m deep of a continuous horizon of ferricrete. At this time the profile was dry.

J46 (8597 980N 274 800E)

Briefly described check site

0-16	A_1 + A_2, 10 YR yellow
16-30	horizon of quartz cobbles
30-140	ferruginous rock; very hard to auger

Profile dry to depth.

J47 (8597 860N 274 400E)

Briefly described check site

0-15	Dark grey (moist)
15-40	Gravelly zone saturated with water
40-85+	Red ferruginous rock; very hard to drill; moist

J48 (8597 830N 274 430E)

Briefly described check site

0-30	A_1 + A_2; 10YR brown
30-45	Cobbly horizon
45-100+	Red ferruginous rock; very hard to drill

Profile dry to 70

J49 (8597 770N 274 395E)

0-30	A_1 + A_2; 10YR brown
30-60	Cobbly horizon
60-85+	Red ferruginous rock; very hard to drill

Profile moist throughout

J50 (8597 595N 274 395E)

Same profile as at J28.

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* Both profiles were dry to the depths augered.

SUPERVISING SCIENTIST FOR THE ALLIGATOR RIVERS REGION

RESEARCH PUBLICATIONS

Alligator Rivers Region Research Institute Research Report 1983-84
Alligator Rivers Region Research Institute Annual Research Summary 1984-85
Alligator Rivers Region Research Institute Annual Research Summary 1985-86
Alligator Rivers Region Research Institute Annual Research Summary 1986-87
Alligator Rivers Region Research Institute Annual Research Summary 1987-88
Alligator Rivers Region Research Institute Annual Research Summary 1988-89

Research Reports (RR) and Technical Memoranda (TM)

RR 1	The macroinvertebrates of Magela Creek, Northern Territory. April 1982 (pb, mf - 46 pp.)	R. Marchant
RR 2	Water quality characteristics of eight billabongs in the Magela Creek catchment. December 1982 (pb, mf - 60 pp.)	B.T. Hart & R.J. McGregor
RR 3	A limnological survey of the Alligator Rivers Region. I. Diatoms (Bacillariophyceae) of the Region. August 1983 (pb, mf - 160 pp.)	D.P. Thomas
	*A limnological survey of the Alligator Rivers Region. II. Freshwater algae, exclusive of diatoms. 1986 (pb, mf - 176 pp.)	H.U. Ling & P.A. Tyler
RR 4	*Ecological studies on the freshwater fishes of the Alligator Rivers Region, Northern Territory. Volume I. Outline of the study, summary, conclusions and recommendations. 1986 (pb, mf - 63 pp.)	K.A. Bishop, S.A. Allen, D.A. Pollard & M.G. Cook
	Ecological studies on the freshwater fishes of the Alligator Rivers Region, Northern Territory. Volume II. Synecology. 1990	K.A. Bishop, S.A. Allen, D.A. Pollard & M.G. Cook
	Ecological studies on the freshwater fishes of the Alligator Rivers Region, Northern Territory. Volume III. Autecology (in press)	K.A. Bishop, S.A. Allen, D.A. Pollard & M.G. Cook
RR 5	Macrophyte vegetation of the Magela Creek flood plain, Alligator Rivers Region, Northern Territory. March 1989 (pb - 41 pp.)	C.M. Finlayson, B.J. Bailey & I.D. Cowie
TM 1	Transport of trace metals in the Magela Creek system, Northern Territory. I. Concentrations and loads of iron, manganese, cadmium, copper, lead and zinc during flood periods in the 1978-1979 Wet season. December 1981 (pb, mf - 27 pp.)	B.T. Hart, S.H.R. Davies & P.A. Thomas
TM 2	Transport of trace metals in the Magela Creek system, Northern Territory. II. Trace metals in the Magela Creek billabongs at the end of the 1978 Dry season. December 1981 (pb, mf - 23 pp.)	S.H.R. Davies & B.T. Hart
TM 3	Transport of trace metals in the Magela Creek system, Northern Territory. III. Billabong sediments. December 1981 (pb, mf - 24 pp.)	P.A. Thomas, S.H.R. Davies & B.T. Hart
TM 4	The foraging behaviour of herons and egrets on the Magela Creek flood plain, Northern Territory. March 1982 (pb, mf - 20 pp.)	H.R. Recher & R.T. Holmes
TM 5	Flocculation of retention pond water. May 1982 (pb, mf - 8 pp.)	B.T. Hart & R.J. McGregor
TM 6	Dietary pathways through lizards of the Alligator Rivers Region Northern Territory. July 1984 (pb, mf - 15 pp.)	C.D. James, S.R. Morton, R.W. Braithwaite & J.C. Wombey
TM 7	Capacity of waters in the Magela Creek system, Northern Territory, to complex copper and cadmium. August 1984 (pb, mf - 42 pp.)	B.T. Hart & S.H.R. Davies

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TM 9	Textural characteristics and heavy metal concentrations in billabong sediments from the Magela Creek system, northern Australia. October 1984 (pb, mf - 39 pp.)	P.A. Thomas & B.T. Hart
TM 10	Oxidation of manganese(II) in Island Billabong water. October 1984 (pb, mf - 11 pp.)	B.T. Hart & M.J. Jones
TM 11	In situ experiments to determine the uptake of copper by the aquatic macrophyte Najas tenuifolia R.Br. December 1984 (pb, mf - 13 pp.)	B.T. Hart, M.J. Jones & P. Breen
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TM 13	Fate, of heavy metals in the Magela Creek system, northern Australia. I. Experiments with plastic enclosures placed in Island Billabong during the 1980 Dry Season: heavy metals. May 1985 (pb, mf - 46 pp.)	B.T. Hart, M.J. Jones & P. Bek
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