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Catchment Salinity: Report on a Study of the East Perenjori Catchment

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1. Summary

Dryland secondary salinisation has debilitated large areas of land in Western Australia due to clearing of native vegetation for agricultural development. The initial aim of the project (which is the subject of Part I of this report) was to establish a landscape framework for hydrogeological examination of the salinity problem. A catchment of 139 km^2, located 30 km east of Perenjori townsite was selected for detailed study. It was mapped for soils, vegetation, topography, landform and salinity using both old and recent aerial photography. A field survey of soil hydraulic conductivity was undertaken to help define recharge areas.

Soil-vegetation associations were related to geomorphology to develop five land units. The constant head permeameter gave some indication of relative rates of recharge between the land units and deep acid sandplain soils were seen to have a relatively high groundwater recharge potential. Soil salinity has shown significant spread in recent years and 2.4 per cent of the area of the catchment was severely affected in 1986.

2. Introduction

The Western Australian Department of Agriculture has established a number of catchment studies in recent years aimed at quantifying hydrological processes associated with salinity problems. The catchments have been selected to cover a range of climatic and geographic zones in the south western agricultural area.

The widespread secondary salinization of soils in the agricultural areas in Western Australia has resulted from the clearing of native perennial vegetation and its replacement with shallow rooted annual crops and pastures (Wood, 1924; Burvill, 1947). The causes, mechanisms and processes involved in salinization were documented by Peck (1978). Although these mechanisms have been qualitatively described, the quantification of the individual hydrological components has been generally lacking.

Simple hydrological models of a catchment require defined areas for groundwater recharge, flow paths and likely discharge areas. Attempts to define recharge areas so that appropriate management strategies may be developed to increase water useage, have not always been successful. Smith (1962) considered that the main intake areas for groundwater were higher level soils with sandy or lateritic surfaces, while Bettenay (1964) suggested that coarse skeletal soils below granite rock outcrops were significant recharge areas. The method for defining recharge areas by measurement of saturated soil hydraulic conductivity (K_5) on a grid basis was described by Nulsen and Baxter (1983). They found high values of K_5 within coarse textured soils which accounted for 25 per cent of a catchment studied at East Wongan.

A strong need exists in identifying the proportion of catchments that act as recharge areas and hence the proportion of the catchment that needs to be managed to reduce recharge. Hence catchment studies should define the relationships that exist between landforms, weathering materials and secondary salinization. Land units should be defined so as to ensure essentially uniform hydrological properties. Such units have been called domains by Aston and Dunin (1979) or provinces by Bettenay et al. (1980).

The objectives of this study were to describe in detail the soils and hydrology of the East Perenjori catchment and to assess management strategies to control saline encroachment. Part I of the report involves a detailed catchment description which includes preliminary identification of recharge and discharge areas as well as defining problem areas in the catchment which will require special management.

3. Site Characterization

3.1 Location

A catchment was chosen, which is representative of a low rainfall environment. It typified the relatively large, low relief drainage basins characteristic of the ‘north eastern wheatbelt” of Western Australia. The catchment at East Perenjori is located 30 km east of Perenjori townsite and 280 km north of Perth, Western Australia (see Fig. 1).

3.2 Geomorphology and Geology

The catchment has an area of 139 km^2 and takes the form of a narrow elongate basin (23 km long and 5 to 8 km wide). Elevations range from just under 270 m to 366 m above mean sea level. Surface water drains to the north-east into Mongers Lake which is part of a palaeodrainage system.

The catchment is over 90 per cent mantled by superficial sediments and weathering materials including laterite and residual deposits of sand, clay and duricrust. There are small pockets of aeolian reworked sandplain on the slopes and alluvial/colluvial deposits in the broad valley. The underlying bedrock consists of granite, quartz-biotite phyric, adamellite—granodiorite and adamellite (Baxter and Lipple, 1985). The rocks are generally deeply weathered to form pallid zones of kaolinitic clays and residual quartz.

3.3 Climate

The climate is dry warm Mediterranean. Daily rainfall records have been maintained by a landholder within the catchment for the period, 1965-1986 inclusive. These data show that the average annual rainfall is 310 mm, of which 204 mm falls during the growing season (May-September). Summer rainfall is local and erratic being derived mainly from thunderstorms.

3.4 Land Use

Clearing of native vegetation for agriculture development commenced in this catchment in 1962 and the catchment was 67 per cent cleared by 1967. Another 10 per cent of the catchment was cleared in the following decade. An uncleared pastoral lease occurs at the downstream end of the catchment.

Up to 90 per cent of the catchment was continuously cropped with wheat in the period 1976—1983. More recently there has been increased cropping of lupins and triticale and increased sheep grazing on annual pastures. Current economics indicates that reduced cropping intensity and increased sheep production is more profitable.

4. Methods

4.1 Soil Distribution and Classification

Soil mapping was carried out using both pre-clearing and post-clearing aerial photography at a scale of 1:50,000. Photo interpreted boundaries were verified in the field from ground traverses. Mapping units used by the Western Australian Department of Lands and Surveys (1971) were chosen for the survey.

Soils were described from about 100 site observations. Classification was according to Northcote (1979) and Northcote (1975). Dominant species of vegetation growing on each of the major soil units were sampled and classified. A description of landform elements using terminology outlined in McDonald et al. (1984) was carried out.

Soil and vegetation associations were related to landform and topography and five land units were proposed. Land units were numbered in sequence from one to five progressively downward from the catchment divide.

4.2 Soil Salinity Mapping

Areas of land suspected of being affected by salinity were mapped onto stereo photographs taken in 1969, 1980 and 1983 to 1986 inclusive. Ground truthing was carried out in the latter four years. Two classes of soil salinity were mapped: (1) Actual salinity was defined as areas of land where an increase in soil salinity had reduced the productive capacity of the soil. This included land which was already severely salt affected i.e. cereal crop growth was either very poor or non-existent. (2) A salinity hazard class (incipient salinity) was recognized as being areas of land where under current land use practices it was expected that soil salinity would increase to a level that would reduce the productive capacity of the soil. This land was already showing early signs of salinity development and crop growth was becoming patchy or stunted in places. A number of traverses using an electromagnetic induction meter (EM38) were carried out to help define boundaries of the salt affected land.

4.3 Soil Measurements

Pits at twelve sites provided soil samples and cores for the measurement of various soil properties. Electrical conductivity (EC) and pH were obtained on 1:5 soil—water extracts while chloride ion concentration (Cl-) was determined by titration. The pipette method was used for particle size analysis (McIntyre and Loveday, 1974).

Measurement of field saturated hydraulic conductivity (K_5) was determined using a constant head permearneter (Talsma and Hallam, 1980). Five sites were selected on each of the major soil mapping units with duplicate measurements being conducted over the 10—30 cm, 30-60 cm and 60—80 cm depth ranges. Laboratory measurement of K was carried out on 83 mm diameter cores of soil for the A and B horizons of the major soil types.

5. Results And Discussion

5.1 Description of Land Units

Distribution of the land units in the East Perenjori catchment is shown in Fig. 2

(1) Lateritic uplands
Land unit 1 referred to as the lateritic uplands, comprised 22 per cent of the catchment and consisted of shallow gravelly soils occupying crests and upper slopes. Surface gradients were very gently inclined at about 2 per cent. The dominant soils were shallow and gravelly earthy sands (Uc5.22). Laterite duricrust was at a shallow depth on the crests. Soil profiles consisted of brown sandy loam grading to a light sandy clay loam at about 20 cm. Ironstone gravel dominated the soil profile at depths from 15 to 45 cm. An average of 30 to 40 per cent gravel occurred in the A horizon while the B horizon had 60 per cent or more gravel. The A horizon had a pH (1:5 H_20) of about 5.0 at the surface, decreasing to as much as 4.2 in the B horizon. Soil profiles were underlain by laterite duricrust at depths of from 20 to 50 cm on the crests and upper slopes and this depth increased to 2 m further downslope. A profile description of a soil in this land unit is provided in the Appendix.

Remnant vegetation existing on this land unit consisted of low thickets of wodgil about 1.5 m high. Wodgil is a general name for a species of Acacia which have the characteristics of being rigid and erectly branched. Two common species were *Acacia signata* and *A. neurophylla*. *Allocasuarina spp*. also occurred on the shallow gravelly soils. Further downslope where gravel was at 45 cm depth, a mixed community of Acacia-Casuarina-Melaleuca thicket occurred.

This land unit is a modified remnant of the upland portion of the Tertiary landscape Bettenay and Hingston (1964) and Bettenay (1964). This is an erosional surface, caused by truncation of the lateritic profile down to the mottled zone, which was subsequently indurated to form duricrust.

Although not a lot of surface runoff was observed in this land unit, saturation overland flow occurred on shallow soils after heavy rainfall, when the soil above the shallow duricrust was saturated. Bligh (1979) noted that temporary waterlogging of parts of the Ulva association (a similar soil type in the Merredin area) could result before water had drained through the shallow indurated layer along old root channels. Bettenay ~ ~i. (1980) considered that the blocky condition of the duricrust could enhance water transmission into the underlying pallid zone.

(2) Sandplain slopes
Land unit 2, called sandplain slopes, occupied 28 per cent of the catchment and occurred on surface grading to yellowish the mid and lower slopes. Gradients generally did not exceed 2 per cent. Soil profiles (see Appendix) consisted of yellow brown loamy sands at the brown light sandy clay loains at depth. Ironstone gravel occurred at depths of greater than 45 cm. Pockets of much deeper coarse textured soils occupied 20 km^2 (50 per cent of land unit 2 / 15 per cent of the catchment). These sandy pockets ranged from 0.1 to 5 km^2 in area. Pedological discontinuities indicated the presence of buried soils. At the base of the deep profiles there was a thin band of angular to subrounded quartz gravel conglomerate occurring within ironstone gravels. Water was seeping into the pits at this level. This colluvial material would have undergone secondary cementation within the zone of a fluctuating watertable.

Although sandplain profiles in this region were classified by Northcote et al (1967) as yellow earths (Gn2.21), examination of the B horizon fabric indicated that it was more sandy than earthy. Hence the gradational soils of the sandplain were classified as Gnl.2l. Uniform coarse textured profiles also occurred and although the fabrics were earthy to sandy, they have been classifed as earthy sands (Uc5.22). Bleach spots and patches within these sandplain profiles suggest leaching. The fabric may be changing over time and while it was presumably earthy in the past, it is becoming increasingly sandy with a remnant earthy fabric. This may be due to increased leaching following clearing of the native vegetation.

Brewer and Bettenay, (1973) considered that these sandplain soils have been formed by colluvial sedimentary deposits derived from erosion of older lateritic profiles. Alternatively, the soils may have been derived from aeolian sedimentation. Deep sandy deposits flanking the lateritic surfaces have been termed spiliways by Mulcahy and Hingston (1961).

Natural vegetation consisted of tall thickets (over 3 m) of wodgil (*Acacia resinomarginea* and *A. nigripilosa*). Some mallee forms of eucalyptus such as Tamrnin mallee (*Ecualyptus leptopoda*) also occurred in this land unit. Other plants included *Grevillea eriobotrya, Hakea coriacea* and *Phebalium spp*. When these soils have been cleared or subject to fire, the native poplar (*Codonocarpus continifolius*) and fireweed (*Gyrostemon spp.*) tend to become dominant.

The deep coarse textured soils of land unit 2 are prone to minor wind erosion and water erosion. These soils have a relatively low productivity with wheat yields averaging 0.5 t ha-1. Other problems include subsoil acidity and low nutrient and trace element status. The impact of rain drops during intense summer and autumn storms on the generally unprotected soil surface caused a surface crust resulting in the generation of overland flow and severe water erosion.

3. Pediment Slopes

The pediment slopes (land unit 3) extended from the upper slopes to the lower slopes and occupied 28 per cent of the catchment. The term pediment refers to a land surface (in this case the lateritic sandplain) which has been stripped by errosion to form a new base level of low relief. Surface gradients ranged from 1 per cent on the lower slopes to as much as 3 per cent on the upper slopes.

The upper pediments were often rimmed by crescent shaped breakaways (low escarpments) resulting in an alcove landform as described by McDonald et al. (1984). The breakaways were composed of indurated weathered kaolinized granite and the resulting skeletal soils of the upper pediment consisted of brown gritty sandy barns to sandy clay barns over sandy clay. Small areas of salt scalds were observed on this landform. These were caused by the inherently high salt content of the exposed pallid zone material immediately downslope of the breakaways.

Soils of the mid and lower pediments (see Appendix) comprised red brown sandy barns to sandy clay barns grading to red sandy clays at depth. Calcareous nodules and soft lime patches were common in the B horizon with occasional calcareous nodular pisolites. The soils were classified as Gn2.12, Gn2.13, Dr2.12 and Dr2.13.

An indurated layer (red brown hardpan) or decomposed granite was usually encountered at depths below 1 m. This red brown hardpan was previously described by Bettenay and Churchward (1974) and known as the Wiluna hardpan. It occurs extensively over much of arid inland Western Australia and the Perenjori area represents the south—western limit of this hardpan.

Outcrops of fresh granite bedrock were rare on the pediment slopes, although a relatively large monolith occurred in the north-east part of the catchment near to the salt lake system. Skeletal soils surrounding granite outcrops consisted of brown to yellow brown to red brown loamy sand to sandy clay loam which was underlain by either coarse sandy clay, arkosic gravel (derived from decomposing granite) or shallow bedrock. Granite bedrock was often encountered within 30 to 90 cm of the ground surface. Granite outcrop with associated skeletal soils occurred over 3 km^2 (2 per cent) of the catchment area.

The upper pediment is an erosional surface (Bettenay and Hingston, 1964). The process of pedimentation proceeds by scarp retreat following headward erosion of the duricrust, with sheetwash removing debris across the pediment. The resultant landforms consist of a low escarpment and debris slope (the breakaway) and a gently sloping pediment.

Where stripping of the land surface has been more pronounced, fresh granite bedrock is exposed. The erosional surface of this association corresponds to the exposed country rock and the depositional surface corresponds to detritus resulting from weathering of the exposed rock. The lower pediment is a depositional surface and has extensive alluvial and colluvial deposits.

Three soil-vegetation associations were defined on the pediment slopes. The first consisted of a woodland of salmon gum (*Eucalyptus salmonophboia*) and gimlet (*E. salubris*). This was associated with soils having a shallow A horizon (10 cm) and deep fine textured clay subsoils. The second association was comprised of york gum (*E. loxophleba*) with the principal understory species being jam tree (*E. acacinata*). The soils consisted of a thicker A horizon than the first association, with an indurated horizon (red brown hardpan) at depths of around 60 cm. The third association consisted of a mixed woodland of *loxophleba*, mallee, (*oleosa*) on the coarser textured soils and *E. redunca* on the finer textured soils. Some scattered native pine (*Callitris columellaris*) were also present. Soils were deep red brown sandy loams with gradually increasing clay content with depth.

The dominant vegetation on the skeletal soils surrounding breakaways and granite outcrops included *Acacia* spp. and ti-tree (*Melaleuca* spp.) Small shrubs of *Thryptomene* spp., *Banksia* spp. and pincushion plant (*Borya nitida*) occurred on arkosic soils adjacent to granite. Some samphire (*Habosarcia* spp.) occurred on saline soils on the upper pediments.

Significant amounts of surface runoff may be generated from granite outcrops and breakaways. Bligh (1979) observed that runoff from outcropping granite bosses usually infiltrated fairly rapidly into the surrounding gritty soils in the Merredin district. In the East Perejori catchment, local wet areas occurred in the relatively flat regions immediately downsbope of outcrops and breakaways. From field observations, infiltration appeared to be very slow probably because of the presence of shallow rock or red brown hardpan. Excess water then flowed across the pediment slopes resulting in flooding and waterbogging of flat land downslope.

(4) Valley Flanks

The valley flanks (land unit 4) in effect comprised a junction between the valley floor of unit 5 and the sandplain slopes of unit 2. This unit accounted for 9 per cent of the catchment and surface gradients were less than 1 per cent. Soils were predominantly Gn2.21 and consisted of reddish brown loamy sands changing gradually to reddish yellow sandy clay loam with depth. The mottled B horizon became indurated at depth and was underlain by a silicified hardpan at depths of around 1 m. This hardpan had macropores which were transmitting groundwater.

The soils of this land unit produce a depositional landform consisting of sandy colluvium over indurated mottled clay. A distinct feature of this land unit is the presence of a silcrete hardpan. Two possible mechanisms (Bettenay, pers. comm.) in the formation of the silicified hardpan are: (1) Waterbogging above the clay B horizon releases silicates which leach downward and precipitate as a pan, or (2) groundwater injects silica in solution towards the groundsurface and precipitates out at the watertable. The presence if this pan suggests valley flanks may have been groundwater discharge zones during previous wet cycles.

Groundwater seepage was observed in this unit resulting in waterlogging and salinity. Saturation overland flow was also occurring resulting in ribbing of the sandy surfaced soils.

(5) Valley floor
Land unit 5 is the valley floor which covered 13 per cent of the catchment. The surface gradients were less than 0.2 per cent. The soils (see Appendix) were brown to red-brown hardsetting loamy sand to sandy loam with a gradual or sharp change to yellowish brown medium clay. The soils were classified as Dy4.12, Dy3.43, Dy3.72, Db2.43 and Gn2.13.

The B horizon tended to be weakly cemented and was underlain by an indurated horizon (the red brown hardpan) at depths of 25 to 40 cm, with hardpan thicknesses ranging from 20 to 100 cm. The red brown hardpan was underlain by green clay with bands of white orange and red gritty sand, suggesting an alluvial origin. At depths of three to five metres indurated sands and grits consisting of subrounded quartz and kaolin skins occurred. Subsequent deep drilling showed that this “lower hardpan” had an average thickness of 2.5 m, but could attain thicknesses of 8 m. Butt (1981) suggested that such “sandstones” result from dissolution of kaolinite from the profile resulting in the formation of residual sand deposits, which are subsequently indurated by the addition of quartz-anatase cement. Alternatively, this hardpan could be of sedimentary origin due to the somewhat rounded nature of the quartz grains and the relatively even grain size. This material had macropores which were transmitting groundwater.

The main vegetation growing in this land unit was the ti-tree (*Melaleuca laterifbora* and *M. uncinata*). On the deeper soils *loxophleba* became dominant. The natural vegetation indicates that portions of land unit 5 were prone to flooding, waterlogging and salinity in the native state. Following clearing, these soils were often subject to in-situ waterlogging in winter, resulting from impeded infiltration caused by the shallow indurated layer. The flat nature of this land unit combined with ill-defined drainage, resulted in flood waters spreading out and inundating large areas of land.

Claypans occurred in this band unit and along the boundary of band units 4 and 5. They were shallow level-floored closed depressions with diameters of 50 to 250 m. The larger claypans were surrounded by low lunettes of red sand which were most conspicuous on the south—eastern margins of the claypans. Surface runoff entered the pans after heavy rainfall and the largest pan in the catchment ponded water for 10 months after it had filled to capacity. Claypans were a pre-clearing feature on the landscape indicating that they could represent groundwater discharge remnants of a former wet period (R.J. George pers. comm.). *Melaleuca* spp. were the dominant vegetation surrounding claypans, with *loxophleba* in places.

At the lower end of unit 5, the valley floor became braided and tributary channels were affected by primary salinization. Vegetation within the channels consisted of samphire (*Halosarcia* spp.) with dense thickets of *Melaleuca* spp. on adjacent sandy ridges.

5.2 Salinity Distribution and Spread

The distribution and spread of salinity with time in the catchment is illustrated in Fig. 3. The data (see Table 1) shows that soil salinity began spreading during the 1980 decade, about 20 years after commencement of clearing. By September 1986, 2.4 per cent of the catchment was severely salinized and another 9.6 per cent was showing early signs of salinity development.

Table 1. Spread of salinity with time in the East Perenjori catchment

Survey date	Actual salinity (km^2)	Incipient salinity (km^2)
No 1969	0	0.3
Oc 1980	0.3	2.1
No 1983	1.3	3.5
No 1984	1.1	7.1
Au 1985	2.5	10.4
Se 1986	2.5	10.3

Changing seasonal conditions (particularly the amount of autumn rainfall) were found to have an effect on the area of saltland. Some decreases occurred in the wetter years of 1984 and 1986 due to the leaching effect of heavy autumn rains on cultivated land. Increased areas of salinity were evident in the following drier seasons. Further increases in the area of saline land would be expected over the next 20 years due to the clearing of an additional 13.6 km^2 of "wodgil soils" carried out in 1970 and 1979.

5.3 Soil Measurements

Some indication of relative rates of recharge in each of the band units was obtained from both field and laboratory measurements of saturated hydraulic conductivity (K_5). The data in Table 2 show that the highest K~ rates occurred in land units 1, 2 and 4, while the lowest rates occurred in land units 3 and 5.

Table 2. Field and laboratory hydraulic conductivity of soils within land units (m day^{1})

Land Unit	Depth Interval (cm)		
	10-30	30-60	60-80
1. Lateritic uplands	0.28	0.23	0.06
2. Sandplain slopes	1.03 (3.77)[A]	0.72	0.57 (2.33)
3. Pediment slopes	0.07 (3.47)	-	0.03 (1.47)
4. Valey flanks	0.26	0.16	0.18
5. Valley floor	0.09	0.02	-

[A] Laboratory values are shown in brackets

In land unit 3, some measurements were taken on skeletal soils surrounding breakaways and granite outcrops to assess the recharge potential of these soils. Breakaway soils showed a high variability of K_s depending upon the nature of the soil profile. Values ranged from 0.01m day^{-1} to 1.0 m day$^{-1.}$ Similarly, skeletal soils surrounding granite outcrops showed high variability, ranging from less than 0.1 m day^{-1} to 1.0 m day$^{-1.}$

The laboratory K_s was one to two orders of magnitude higher than the field K_5. Treatment of the cores with rhodamine dye showed that flow tended to occur through natural fractures and fine root channels in pediment soils. In sandplain soils piston/matrix flow was the dominant mechanism of percolation. Cores taken from the upper pallid zone had a K_s of almost 5 m day-^{1}.

Hence it would appear that the field technique greatly underestimates Ks, especially where preferred flow occurs. Table 2 indicates a significant difference in field K_5, but nearly identical laboratory K_5 between soils of land units 2 and 3.

In land unit 1 a low field K_5 occurred at 60-80 cm in the gravels. This is due to a clay matrix and varying degrees of induration within the ironstone gravels. However, R.J. George (pers. comm.) has provided evidence for movement of rainfall through ironstone gravel and duricrust from abandoned quarries in the Merredin area. Preferential flow of water was indicated by secondary cementation of iron-silicates along old tree root channels.

Particle size analysis was carried out for some soil horizons in land units 2 and 3. Sandplain slope soils (profile 2 in the appendix) had a relatively high coarse sand content in the A horizon and coarse sand also dominated the B horizon. However, the clay content gradually increased down the profile. Pediment slope soils showed significantly greater clay contents and much lower sand contents than sandpbain soils.

Table 3. Particle size analysis (as percentages) for some soil horizons in land units 2 and 3

Land unit	PPF	Horizon	Depth (cm)	Coarse sand	Fine sand	Silt	Clay
2	Gnl.21	All	0—	58	25	4	12
		B2b	10	44	31	6	20
		B22	50—170	43	31	2	24
			170—200				
3	Dr2.12	B2	50—100	26	19	17	38

Laboratory measurement of soil EC and Cl- showed that soil profiles in land units 1 and 2 had very low salt concentrations and the pH showed distinctly acid trends (Table 4).

Table 4. Average chloride and pH for topsoil and subsoil in each land unit

Land Unit	No. of samples	Chloride (%)		pH	
		0-25 cm	50-100 cm	0-25cm	50-100cm
1. Lateritic uplands	5	0.008	0.016	5.0	4.3
2. Sandplain slopes	7	0.006	0.007	5.0	4.4
3. Pediment slopes	5	0.03	0.04	5.7	7.7
4. Valley Planks[A]	6	0.12	0.09	5.4	4.8
5. Valley floor	7	0.03	0.10	5.7	8.7

[A] Measurements only taken in seepage areas

Pediment slope soils had higher concentrations of C1 in their profile, particularly on the upper pediment where some salt was being derived from partly exposed pallid zone clays and their weathering products.

The development of local seepage areas along the break-in-slope of land unit 4 resulted in topsoil Cl^- showing a maximum concentration at the soil surface with a rapid decrease in the top 10—20 cm with low concentrations in the subsoil (Fig. 4). However, in land unit 5, Cl- tended to be relatively low in the A horizon but increased in the alluvial materials below the red brown hardpan as shown in Fig. 5. In both land units 3 and 5, pH levels were slightly acidic at the surface and showed a neutral to alkaline trend with depth.

6. Conclusions

This study has suggested that land units 1 and 2 could have the highest groundwater recharge potential of all the land systems in the East Perenjori catchment. This is due to the relatively high K~ rates and low salt concentrations in the soil profiles. Granite rock outcrops are not significant contributors to groundwater recharge due to their low frequency of occurrence and the generally low infiltration values of the soils surrounding the outcrops. Three major problem areas in the catchment which require land management strategies were identified according to field observations:

(1) Local pockets of deep acid sandy soil which have low productivity, are erosion prone and contribute to the groundwater recharge.

(2) Seepage areas occurring along the valley flanks and resulting in waterlogged and saline land below the seepage face.
Ill-defined drainage along the broad central valley floor. This results in flooding problems and waterlogged areas exacerbated by a shallow natural indurated soil horizon. Saline encroachment is continuing to increase along the valley floor, but is subject to some extent by seasonal conditions.

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References

Aston, A.R. and Dunin, F.X. (1979). Coupled infiltration and surface runoff on a 5 ha experimental catchxnent, Krawarree, N.S.W. ~Aust. J, Soil Res. 17, 53—64.

Baxter, J.L. and Lipple, S.L. (1985). Explanatory Notes on the Perenjori Geological Sheet. Geol. Surv. of W.A. Sheet SH/50—6 International Index.

Bettenay, E., Blackmore, A.V. and Hingston, F.J. (1964). Aspects of the hydrologic cycle and related salinity in the Belka Valley, Western Australia. Aust. J. Soil Res. 2, 187—210.

Bettenay, E., and Churchward, H.M. (1974). Morphology and stratigraphic relationships of the Wiluna Hardpan in Western Australia. J. Geol. Soc. Aust. 21, 73—80.

Bettenay, E., and Hingston, F.J. (1964). Development and distribution of soils in the Merredin area, Western Australia. Aust. J. Soil Res. 2, 173—86.

Bettenay, E., Russell, W.G.R., Hudson, D.R., Gilkes, R.J. and Edmiston, R.J. (1980). A description of experimental catchments in the Collie area, Western Australia. CSIRO Aust. Land Resour. Manage. Ser. No. 7.

Bligh, K.J. (1979). Runoff generation processes in a seasonally arid farmland catchrnent, a preliminary assessment. Hydrology Symposium, Inst. Eng. Aust., Perth, pp. 28-30.

Brewer. R., and Bettenay, E. (1973). Further evidence concerning the origin of the Western Australian sand plains. J. Geol. Soc. Aust. 19, 533-41.

Burvill, G.H. (1947). Soil salinity in the agricultural areas of Western Australia. J. Aust. Inst. Agric. Sci. 13, 9-19.

Butt, C.R.M. (1981). The nature and origin of the lateritic weathering mantle, with particular reference to Western Australia. In “Geophysical prospecting in deeply weathered terrain.~’ (Eds. Doyle, H.A., Clover, J.E. and Groves, D.I.) Univ. W. Aust. Geol. Dept. and Extension Serv., Pubb., 6, 11-29.

Mulcahy, M.J. and Hingston, F.J. (1961). The development and distribution of the soils of the York—Quairading area, Western Australia, in relation to landscape evolution. Soil Publ. CSIRO Aust., 17.

McDonald, R.C., Isbelb, R.F., Speight, J.G., Walker, J. and Hopkins, M.S. (Eds) (1984). Australian Soil and Land Survey Field Handbook. (Inkata Press: Melbourne).

McIntyre, D.S. and Loveday, J. (1974). Particle-size analysis. In “Methods for Analysis of Irrigated Soils.” (Ed. J. Loveday.) Tech. Comun. No. 54, pp. 88-99. (Commonw. Agric. Bur. Farnharn Royal, Bucks., U.K.).

Northcote, K.H. (1979). “A Factual Key for the Recognition of Australian Soils.” (Rellim Technical Publications: Glenside, S.A.).

Northcote, K.H., Bettenay, E., Churchward, H.M. and McArthur, W.M. (1967). Atlas of Australian Soils sheet 5. Explanatory data for sheet 5, Perth-Albany-Esperance area.

(CSIRO Aust. and Melb. Univ. Press:Melbourne).

Northcote, K.H., Hubble, G.D., Isbell, R.F., Thompson, C.H. and Bettenay, E. (1975). "A Description of Australian Soils." (Wilkie and Co. : Clayton, Vic.).

Nulsen, R.A. and Baxter, I.N. (1983). The potential of agronomic manipulation for controlling salinity in Western Australia. J. Aust. Inst. Agric. Sci. 48, 222—26.

Peck, A.J. (1978). Salinization of non—irrigated soils and associated streams: a review. Aust. J. Soil Res. 16, 157—68. S

Smith, S.T. (1962). Some aspects of soil salinity in Western Australia. M.Sc. (Agric.)

Thesis, Univ. of Western Australia, Perth.

Talsma, T. and Hallam, P.M. (1980). Hydraulic conductivity measurement of forest catchrnents. Mist. J. Soil Res. 30, 139-48.
Western Australian Department of Lands and Surveys (1971). Soil Classification between Rabbit Proof Fence and Warrdagga. Damperwah Sheet 1.

Wood, W.E. (1924). Increase of salt in soil and streams following the destruction of the native vegetation. J. R. Soc. West. Aust. 41, 57-83

9. Appendix

9.1 Soil Profile Descriptions of Land Units

For the following descriptions, the Munsell colour notations are for moist soil; the texture was determined by field manipulation and pH was determined in the laboratory on a 1:5 soil-water extract. The profiles are classified according to Northcote (1979) and descriptive terms are according to Northcote et al. (1975).

Profile 1: Land unit 1 (Lateritic uplands)
Location: Mongers 1:100,000 Sheet; Grid Reference: 455000 6734800
Topography: Upper slope
Elevation: 340 m Slope: 1°E
Classification: Uc5.22 (Earthy sand)

Horizon	Depth (cm)	Description
A	0-20	10 YR 4/3 (brown); sandy loam; gradual boundary pH 5.1
B21	20-50	10 YR 4/6 (dark yellowish brown); gravelly light sandy clay loam; pH 4.7; earthy fabric gradual boundary
B22	50—80	10 YR 5/4 (yellowish brown); gravelly sandy clay loam; pH 4.2; clear boundary
Cr	80	Sesquioxide pan

Profile 2: Land unit 2 (Sandplain slopes)
Location: Mongers 1:100,000 Sheet; Grid Reference: 458400 6729800
Topography: Mid-slope
Elevation: 328 m Slope: 1°N
Classification: Gnl.21

Horizon	Depth (cm)	Description
All	0—10	10 YR 4/4 (dark yellowish brown); loamy sand; structureless; pH 5.1; clear boundary
A12	10—17	10 YR 6/6 (brownish yellow); clayey sand; weak lenticular structure; pH 4.8; diffuse boundary
A13	17—50	10 YR 6/6 (brownish yellow); sandy loam; weak lenticular structure; pH 4.8; diffuse boundary
B21	50—170	10 YR 6/6 (brownish yellow); light sandy clay loam; weak polyhedral structure; sandy fabric; pH 4.6; diffuse boundary
B22	170—200	10 YR 6/6 (brownish yellow); gravelly sandy clay loam; rounded ironstone pebbles (5-30 mm); pH 4.4; gradual boundary
B23	200—290	10 YR 6/6 (brownish yellow); gravelly sandy clay loam; barge ironstone pebbles
	290—330	Conglomerate consisting of angular to subrounded quartz gravel (1-6 mm) and ferruginous concretions. Watertable present

Profile 3: Land unit 3 (Pediment slopes)
Location: Mongers 1:100,000 Sheet; Grid Reference: 459900 6730600
Topography: Upper-slope
Elevation: 335 m Slope: l°NW
Classification: Dr2.12

Horizon	Depth (cm)	Description
A	0-10	2.5 YR 3/4 (dark reddish brown); sandy clay loam; hardsetting surface; pH 6.8; abrupt boundary
B21	10—50	2.5 YR 3/6 (dark red); sandy clay; moderate polyhedral structure; smooth—ped fabric; pH 7.5; diffuse boundary
B22	50—100	10 R 4/8 (red); sandy clay; moderate polyhedral structure; pH 6.7; diffuse boundary
B23	100—125	10 R 4/8 (red); gritty sandy clay; moderate polyhedral structure; pH 7.9; diffuse boundary
Bm	125-175	Red-brown hardpan; moderately to strongly cemented; black stains; porous; calcareous nodules; pH 8.0

Profile 4: Land unit 4 (Valley flanks)
Location: Mongers 1:100,000 Sheet; Grid Reference: 457700 6734500
Topography: Lower slope
Elevation: 299 m Slope: 0°30'E
Classification: Gn2.21 (yellow earth)

Horizon	Depth (cm)	Description
Al	0—11	5 YR 4/3 (reddish brown); loamy sand; structureless; pH 5.6; clear boundary
El	11—45	7.5 YR 7/8 (reddish yellow); light sandy clay loam; massive structure; earthy fabric; pH 4.6; gradual boundary
B2b	45—77	7.5 YR 7/8 (reddish yellow); sandy clay loam; many coarse red mottles; massive to very weak structure; earthy fabric; pH 5.0; gradual boundary
B22	77-92	10 YR 8/8 (yellow); sesquioxide pan; weakly cemented; pH 6.2; gradual boundary
Emi	92—120	10 YR 7/2 (light grey); sesquioxide pan; strongly cemented; pH 8.1; diffuse boundary
Bm2	120+	10 YR 7/1 (light grey); pisolitic silicified pan; strongly cemented; pH 8.6

Profile 5: Land unit 5 (Valley floor)
Location: Mongers 1:100,000 Sheet; Grid Reference: 458000 6734600
Topography: Level
Elevation: 298 m Slope: O02O~
Classification: Dy4.l2

Horizon	Depth (cm)	Description
All	0-13	5 YR 3/4 (dark reddish brown); loamy sand; apedal massive structure; sandy fabric; pH 5.7; clear boundary
A12	13—24	5 YR 4/4 (reddish brown); loamy sand; apedal massive structure; sandy fabric; pH 6.8; sharp boundary
HEx	24—29	5 YR 7/3 (pink); sandy clay; few mottles: strong polyhedral structure; rough-ped fabric; weakly cemented; pH 7.2; abrupt boundary
B2x	29—40	5 YR 6/4 (light reddish brown); sandy clay; strong polyhedral structure: rough-ped fabric: weakly cemented: pH 7.4; clear boundary
Bml	40-60	Red brown hardpan; moderately cemented: massive structure; clay skins: black stains: pH 7.7; abrupt boundary
Bm2	60—110	2.5 YR 6/8 (light red) sandy clay; weakly cemented; pH 8.5

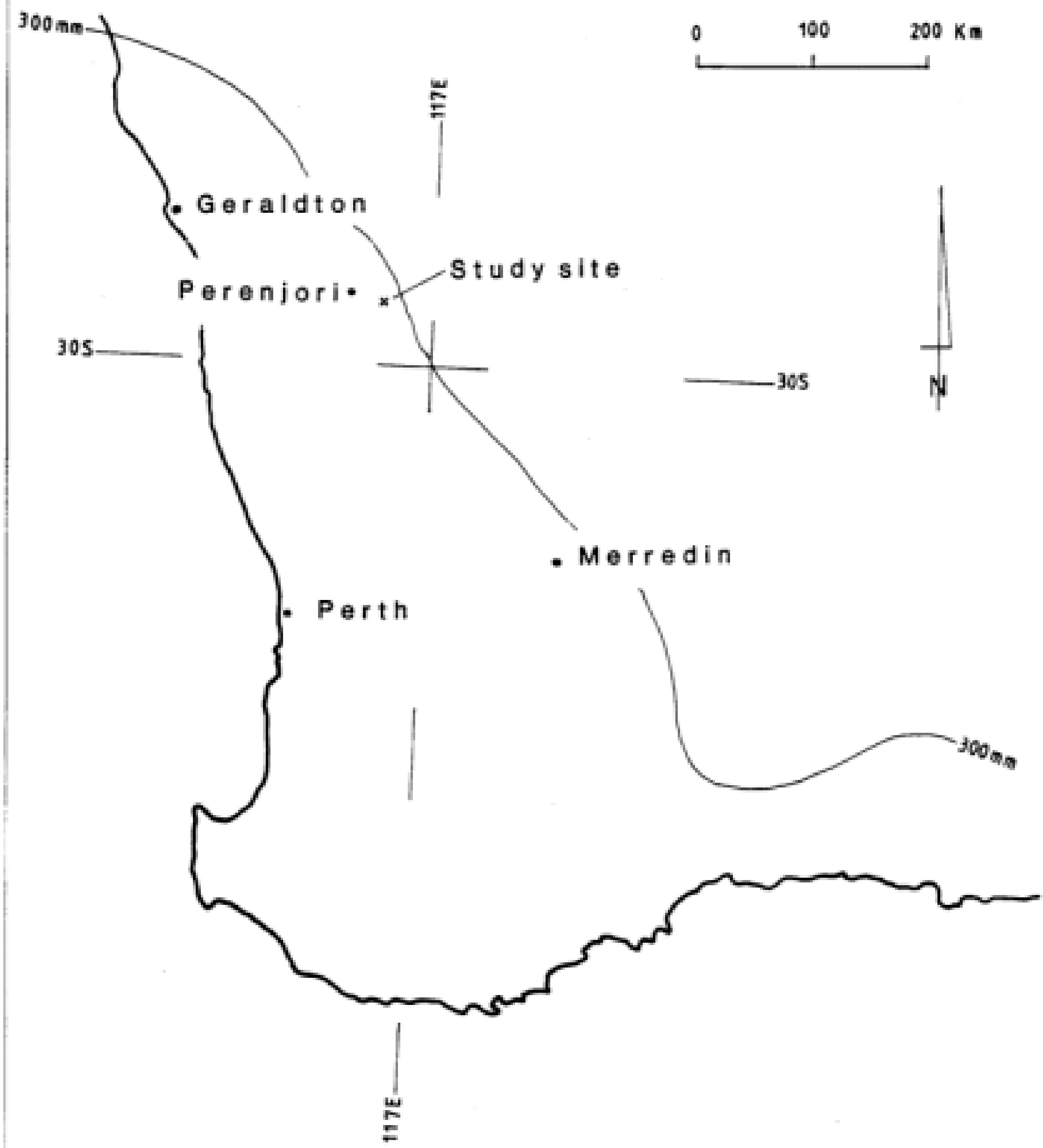

Fig. 1 Location of study area.

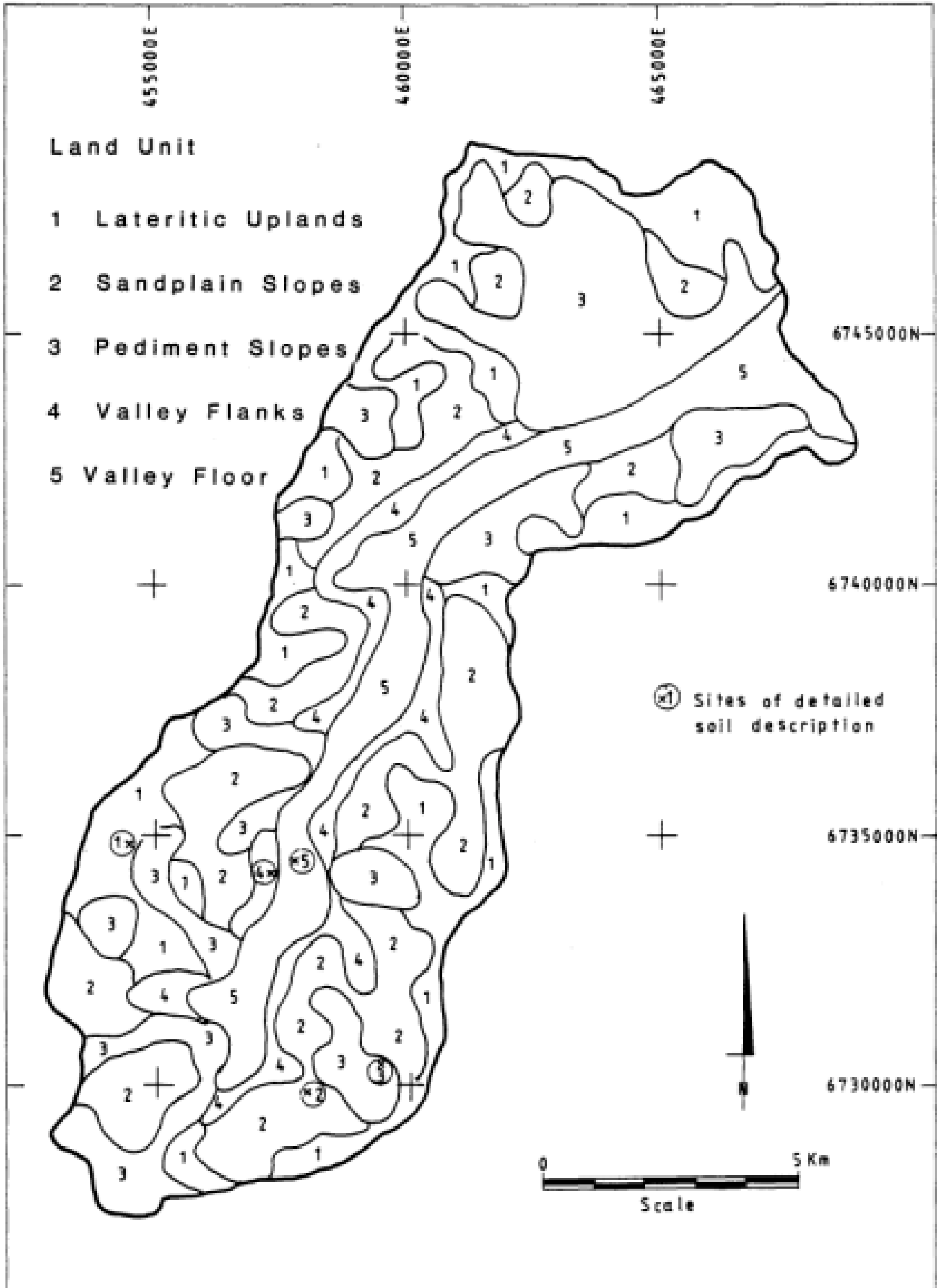

Fig. 2 Land units East Perenjori catchment.

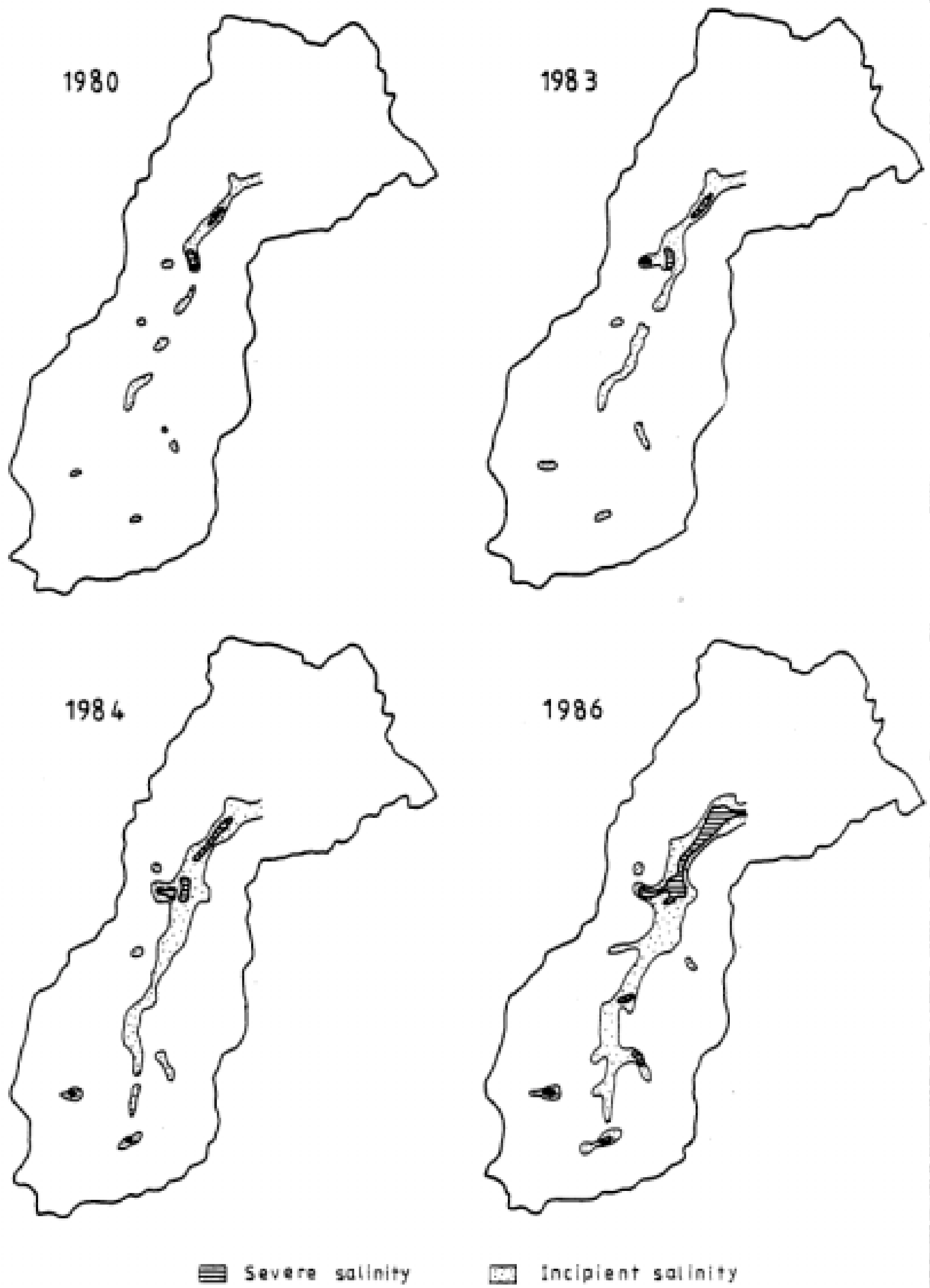

Fig. 3 Maps showing spread of salinity with time

-21-

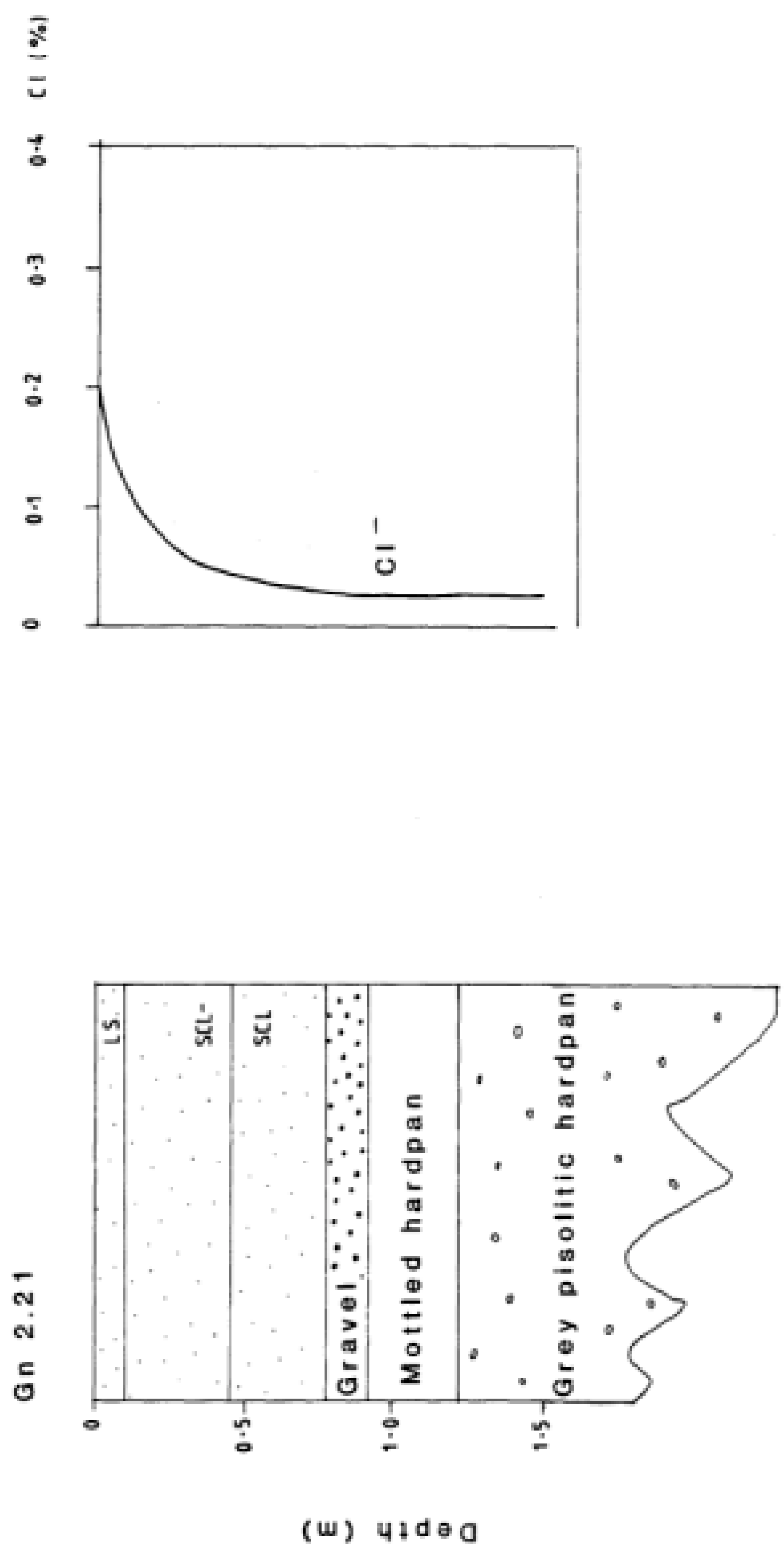

Fig. 4 Soil and chloride profiles within a seepage area of land unit 4.

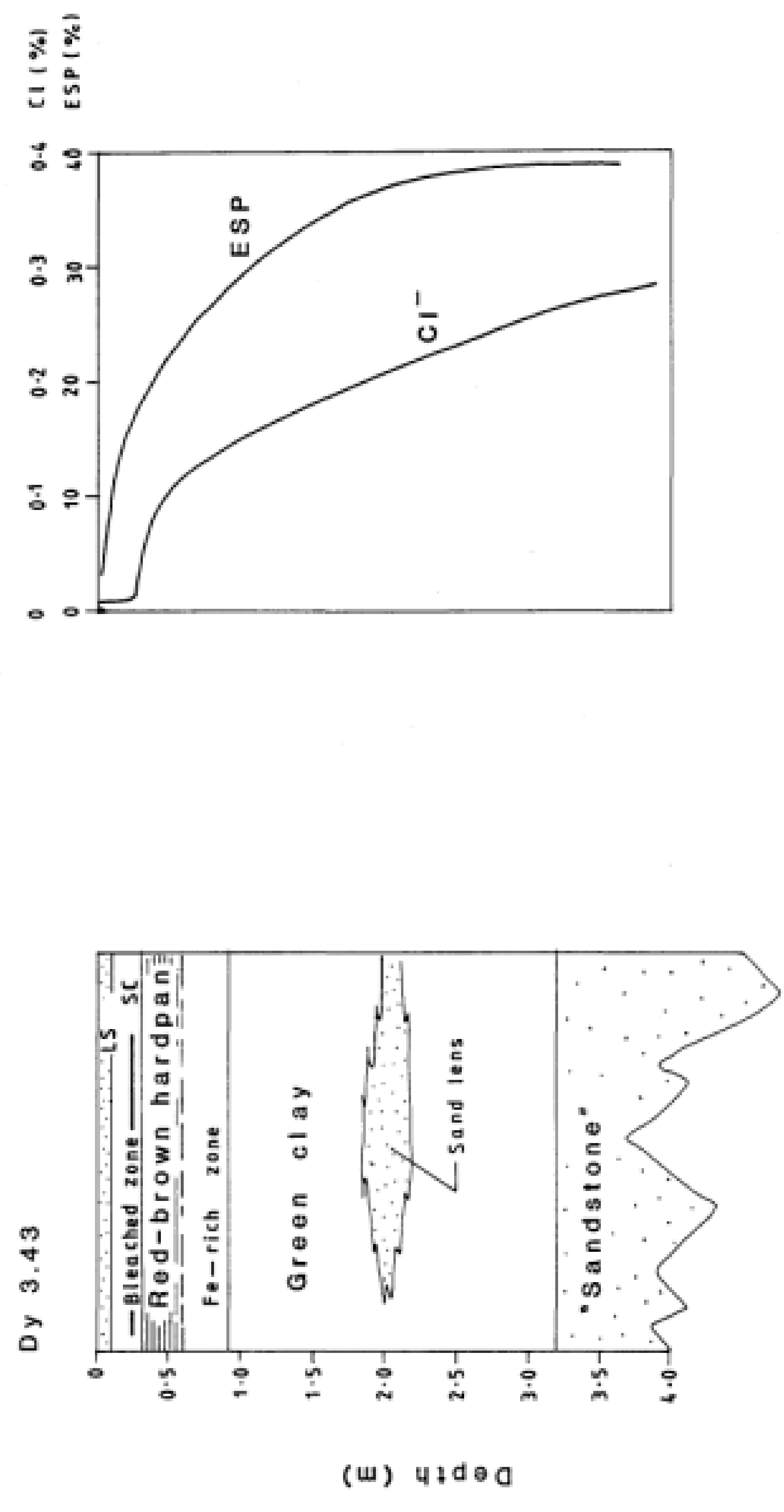

Fig. 5 Soil, chloride and ESP profiles in a salinized area of land unit 5.

Part II Catchment Instrumentation and Hydrogeological Investigation

1. Summary

The objective of the next stage of the study was to define groundwater systems within the catchment and further characterize recharge and discharge areas to gain a better understanding of the processes of salinization.

Three distinct forms of secondary salinization were occurring in the catchment Sandplain seeps resulted from the interaction of two permanent groundwater systems. A relatively fresh perched aquifer developed in sheets of deep yellow sand and discharged as a seepage face at the break in slope of the valley flanks. The perched aquifer was interacting with regional groundwater at this point in the landscape resulting in increasing soil salinization. Hillside seeps (only minor in extent) occurred where regional groundwater was being forced toward the surface by a bedrock high. Valley floor salinity was the result of a salt-waterlogging interaction. The waterlogging was caused by poor drainage characteristics of the valley floor, and salinity was due to upward capillary rise from a shallow saline watertable associated with the deep regional groundwater system.

Extreme rainfall events were recorded in 1984 and 1986 and these had a significant effect on the hydrology of the catchment in terms of increases to soil water storage and groundwater response. Recharge rates were estimated at 20 to 50 mm yr^{1}. Groundwater systems responded in two distinct ways to these events, namely (1) a sharp peaked response usually followed by a steady recession, and (2) a continuous rising trend without any sharp peaks.

2. Introduction

Extensive secondary salinity occurs when the waterbalance is disturbed following clearing from the native state for agriculture. Previous research indicates that there has been an increased rate of recharge following clearing. Peck and Hurle (1973) calculated increases of groundwater recharge under cleared land ranging from 2.3 to 43 cm yr~. George (1978) calculated average recharge under cleared land to be 170 m^3 day~, representing about 7 per cent of annual rainfall, while under native vegetation recharge was estimated to be not greater than 1.5 per cent of annual rainfall.

Groundwater systems subsequently evolve following the destruction of the native vegetation. Examples include documentation by Williamson (1978) of the extensive development of permanent unconfined groundwaters within the deeper sandplain soils of the agricultural areas. Peck (1983) measured responses of potentiometric heads of the deep groundwater aquifers to clearing, and observed rising trends ranging from 0.7 to 1.4 m yr~ in 800 mm yr~ and 1150 mm yr' rainfall areas respectively.

The aim of Part II of the study was to gain a better understanding of the processes involved in salinization of the East Perenjori catcbment. This included definition of groundwater systems and measurement of catchment responses in both the saturated and unsaturated zones.

3. Methods

3 .1 Climatic Data

The catchment was instrumented during the period May to October 1983. Rainfall was measured at five sites using standard 203 mm diameter storage gauges, with rims set at 360 mm above ground bevel. Daily readings were taken by landholders at two of the sites, while at another two sites tipping bucket gauges were located adjacent to storage gauges. At the fifth site monthly readings were taken. Daily Class A evaporation was measured at two sites.

3.2 Soil Moisture

Soil water content was measured at 17 sites in the catchment using a neutron moisture meter (Campbell Pacific Nuclear Corp., model 501). Two sites were located in land unit 1, eleven sites in unit 2, and four sites in unit 3. In cleared areas sites were placed 30 m from fence-lines to avoid edge effects. Four sites were located within belts of native vegetation. Aluminium access tubes of 50 mm diameter were installed to depths ranging from 2 m to 9 m. The tubes were encased in a slurry using method 5, as outlined in Greacen (1981). Tubes were cut at 30 cm below ground level and removable extensions fitted to allow cultivation over the tubes. Routine soil moisture measurements commenced in May 1984, initially at fortnightly intervals and later at monthly intervals. Readings were taken at depth intervals of 25 cm.

Field calibrations of the neutron moisture meter were carried out by using the method of Greacen (1981). Sampling for calibration was done in both a dry and. a wet season. At many sites it was difficult to achieve satisfactory calibration to the required depth because of the presence of gravel and indurated layers. However, for deep sandplain soils (Gn1.21, Uc5.22) in land unit 2, satisfactory calibrations with correlation coefficients of regressions in the range 0.7 0.9 were achieved.

Soil moisture characteristics were obtained in triplicate from three sites. Undisturbed 55 mm diameter cores were collected from the A and B horizons at each site. Water contents were measured at potentials of 0.01, 0.03 and 0.07 MegaPascabs (MPa) using ceramic plates and 0.1, 0.2, 0.3, 0.6 and 1.5 MPa using the pressure membrane apparatus.

3.3 Groundwater

Twenty groundwater monitoring sites were established in the catchment; seven sites were in band unit 4, five sites in unit 2, four sites in unit 5, three sites in unit 3 and one site in unit 1. Additional transects of observation wells were installed at a later date to establish the depth to the watertable beneath the broad valley floor (land unit 5). The Geological Survey of Western Australia (GSWA) drilled and continuously cored three sites for piezometer installation (McGowan, 1984). Cores were analysed for Cl content by the Department of Agriculture, and profile salt storages were calculated assuming a bulk density of 1700 kg rn^3. Historical groundwater information was obtained from GSWA records for 13 bores and wells, which had been abandoned as a stock water supply due to unacceptably high salinity.

The boreholes were drilled with a power rotary auger rig (Gemocodril HM7) using either 50 mm or 100 mm diameter augers and lined with 40 mm or 50 mm diameter

PVC tubing. At five sites, boreholes were developed by surging using a compressor prior to lining with PVC tube. Piezometers were installed to bedrock at cost sites, with observation wells being drilled to penetrate the watertable by one or two metres.

In establishing observation wells, the tubing was fully slotted, while for piezometers the tubing was slotted over the bottom 1.5-2.0 m. A sand-pack was placed around the slotted section followed by a bentonite seal. This procedure was not always effective due to bridging of material on the hole walls or because of rapid filling of the hole with groundwater after removal of the auger flight. Hence it is possible that some piezorneters could behave more like deep observation wells. After placing the bentonite seal, the hole was backfilled with drilling spoil and cement grouted at the surface for sealing and protection.

Waterlevels were monitored and samples collected for analysis for electrical conductivity (BC) and chloride ion (Cl-) at monthly intervals. Six continuous automatic waterlevel recorders were fitted on various wells and piezometers at different times for identifying groundwater response times to rainfall events.

The slug withdrawal method (Bouwer and Rice, 1976) was used to determine the field hydraulic conductivity (K_5) of aquifer materials adjacent to the piezometer and well screens. Laboratory K_5 was determined using a constant—head permeameter technique. Block samples obtained j~ situ from the field were carefully cut to an appropriate size to fit inside a metal cylinder and were then encased in an epoxy compound.

3.4 Geophysics

An airborne time domain electromagnetic (INPUT) and magnetic survey was carried out by Geoterrex Pty Ltd in October 1984. The survey was flown east-west at line spacings of 1.5 km. In August 1985, a north—south ground traverse along the central valley floor using a proton precession magnetometer was undertaken. Total magnetic field intensity in nanoteslas (nT) was measured at 20 rn intervals.

4. Results

4.1 Climatic Data

Rainfall recorded during the period May 1983 to December 1986 was marked by a number of extreme events. During the three month autumn period of March to May 1984, catchment rainfall totalled 307 mm, which is the mean annual rainfall for the area. A storm on May 19, 1984, produced 24 hour totals of 60 to 70 mm throughout the catchment, and the total for the month was 164 mm.

The mean monthly rainfall (1965—1986) and pan evaporation (September 1983 to May 1986) is shown in Table 1. In the absence of a stream gauging station, catchrnent yield was estimated at 20 mm during May 1984. Only one significant runoff event occurring during the monitoring period.

Table 1. Average monthly rainfall (P) pan evaporation (Ep) for the East Perenjori catchment

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
p(mm)	14	15	20	25	42	61	45	35	21	12	11	9	310
Ep (mm)	408	357	259	203	115	70	53	71	134	225	288	351	2534

4.2 Unsaturated Zone Hydrology

The soil moisture characteristics for four textural classes in land units 2 and 3 are shown in Fig. 1, and soil water content profiles for a Gnl.21 soil in land unit 2 (see Appendix, Part I for profile description) are displayed in Fig. 2. Over a three—year period, the upper limit for the soil water store was 398 mm and the lower limit was 278 mm. This represented a total profile water store of 120 mm. The available water storage capacity for plants was only 40 mm m’. The actual rooting depth of annual crops in the highly acid subsoils was uncertain, but was expected to be no greater than 1.5 m for wheat.

Figure 3 is an example of the wetting up of deep yellow sandplain during autumn 1984, five years after clearing of the native vegetation. The site was cleared in 1979 and apart from 1981 all years had below average rainfall. The March 28, 1984 profile shows subsoils having a very low moisture content. The top 1.5 m of the soil profile had wetted up following 65 mm of rainfall earlier in the month. By May 2, after another 75 mm of rain had fallen, the profile water storage increased by 58 mm. During May, 160 mm of rain fell, causing the profile to wet up by a further 63 mm by June 20. The total increase in soil water storage between March and June was 121 mm.

Continued monitoring at this site revealed that gravity drainage was occurring below the root zone. From June 1984 until April 1985 there was a decrease in storage of 17 mm from 150—275 cm. In the following year until March 1986, the soil water storage decreased by a further 6 mm in this depth interval. Hence although plant roots were extracting water to about 1.5 m, the subsoil moisture was being lost to deep drainage.

The specific yield of the perched watertable at site N9 was calculated by relating changes in volumetric soil water content to watertable fluctuations during the period

1984-86. The value of 0.15 was found to be in close agreement to the value of 0.17 used by Williamson (1978) for the perched watertable at Meckering, Western Australia.

4.3 Core Lithology

Drilling bogs, depth to bedrock information and lithobogical descriptions may be found by referring to McGowan (1984).

4.4 Groundwater Systems

Figure 4 is a topographic map of the East Perenjori catchment showing the location of the twenty groundwater monitoring sites and three sites drilled by the GSWA, as well as abandoned farm boreholes used for obtaining additional groundwater information.

Two permanent groundwater flow systems were recognized in the catchment; a local perched system within the deep sands of land unit 2 and an extensive regional system within the weathering material above bedrock. Shallow ephemeral watertables occasionally developed following intense rainfall events. Figure 5 is a hydrogeobogic cross-section showing groundwater systems along the transect A-A[1] in Fig. 4.

(1) Local perched groundwater flow system

Perched groundwaters occur within the yellow sandpbain of land unit 2. They have an areal extent of around 12 km^2, representing 30 per cent of land unit 2 or 9 per cent of the total catchment. The average thickness of the flow system was 1.5 m but “pinches-out” downsbope near the contact with land unit 4. The lateral hydraulic gradient was around 1 per cent and the mean saturated hydraulic conductivity (K_s) was 0.44 m day-^{1} (see Table 2).

This groundwater system occurred in a thin colluvial deposit of poorly sorted angular to subrounded quartz gravel conglomerate. The material was weakly cemented with presumably hydrated iron oxides and secondary silica. Laboratory measurement of K_s from a block of in situ material was 11 m day^{-1}. The perching bed for groundwater was a hardpan of indurated mottled zone and/or pallid zone materials.

The salinity of perched groundwater was generally low and had a mean electrical conductivity (EC) chloride (Cl^-) concentration of 350 mS m^1 and 1000 mg L^{-1} respectively. The sample size was 12 bore holes as an additional four sites had been drilled in 1986. The C1 concentration rose to 7000 mg L^1 in the saline in the saline discharge areas of this groundwater system in land unit 4
.

The local perched groundwater system was monitored at eight sites in land unit 2. Figure 6 is a representative hydrograph and chborograph at site 19 in this land unit. The watertable shows distinct responses to large rainfall events, particularly in May 1984 and June 1986. Automatic waterlevel recorders indicated that waterlevels rose within one to four days following storm events during April 1984. One example was a 45 mm rainfall event, which resulted in a 270 mm rise in the watertable after 2.5 days. The watertable was 3.2 m below the ground surface prior to the event.

The perched watertable showed a long recession of 24 months from June 1984 until June 1986, in response to well below average rainfall. Negligible recharge would have occurred during this period and groundwater dissipated by possibly both lateral flow and vertically downwards leakage.

The chlorograph displayed large seasonal fluctuations with minima immediately after recharge followed by steep rises in C1 concentration. This was followed by gradual recessions prior to the next significant dilution. These fluctuations may be explained by a solution-dissolution interaction in the capillary fringe of the watertable.

(2) Deep regional groundwater flow system

The deep regional groundwater was a low gradient system (0.05 to 0.5 per cent) which was underlying at least 90 per cent of the catchment. Groundwater occurred at depths of 10 to 40 m below ground level under the upper slopes and less than 3 m below the surface in the valleys.

Vertical hydraulic gradients were generally very small in the saline discharge areas of this groundwater system. Slight downward head gradients tended to occur in winter and upward head gradients in summer. The maximum gradients (density corrected) were of the order 0.01 to 0.05. Claypans were zones of strongest upward head gradients (0.05 0.2). Slight downward gradients (0.08) occurred when the claypans became flooded in winter.

The mean K_s of this system (see Table 2) was 0.05 m day~, although this is most likely an underestimation of the real value as piezometers developed by surging gave a mean K_s of almost 0.2 m $^{day-1}$. The salinity was generally in the range 3500 to 4000 mg L^1 Cl, rising to 20,000 mg beneath saline discharge areas of land unit 5.

Table 2. Hydraulic conductivities (K_5) of groundwater systems beneath the East Perenjori catcbment as determined by slug withdrawal tests

Groundwater system	Number of measurements	Mean depth measurement (m)	K_s ($m\ d^{-1}$)
local perched	20	4.2	0.44
deep regional[A]	18	2.7	0.14
deep regional[B]	9	13.2	0.05
deep regional[C]	7	21.2	0.19

[A] Top of flow system (watertable)
[B] Base of flow system (undeveloped bores)
[C] Base of flow system (developed bores).

A composite of hydrographs for piezometers penetrating the deep regional groundwater system is shown in Fig. 7. Groundwater levels in land units 1 and 2 showed a continuous rising trend with very damped seasonal responses. The trend steepened significantly two months after the May 1984 rainfall event. The average rate of rise was 0.8 m yr^{-1} in 1984 and this had slowed to about 0.2 m yr^{-1} in 1986. The mean rise in waterlevel in the 1984—86 period was 0.5 m yr^{-1} and this represented 50 per cent of the catchment area. The recharge rate during this period was calculated at 20 mm $^{yr-1}$ or 6.5 per cent of rainfall (a specific yield of 0.04 was assumed for the deep groundwater system). In the remainder of the catchment (land units 3, 4 and 5) groundwater showed distinct although damped and buffered seasonal responses.

Table 3 swmnarizes the responses of the local perched and the deep regional groundwater systems to two major recharge events occurring in this catchment. Again, using a specific yield of 0.04, the recharge to the deep groundwater in 1984 was 50 mm (10.5 per cent of rainfall) and in 1986 was 24 mm (7.5 per cent of rainfall).

Table 3. Response of groundwater systems to two major recharge events

Groundwater system	1984 event[A]	Groundwater response (mm)		Ratio[C]
		Ratio	1986 event[B]	
Local perched	1430	0.21	540	0.23
Deep regional	1240	0.24	590	0.21

[A] March 1 - May 31, 1984 (300 mm rainfall)
[B] May 1 -June 30, 1986 (125 mm rainfall)
[C] Ratio = Rainfall/water level rise

Chlorographs of deep groundwater in band units 1 and 2 showed steadily rising trends, with minima occurring one or two months after large rainfall events in some cases. Chlorographs showed relatively constant trends in land units 3 and 5.

(3) Ephemeral watertables

Ephemeral perched watertables occasionally developed over much greater areas of the catchment in soils where a permeability contrast was caused by clay or a shallow indurated layer. For example, in band unit 3, perched watertables developed in waterlogging prone areas on the upper pediment below breakaways. Similarly, where fresh granite bedrock was overlain by skeletal soils, winter seepage was observed to develop along then rock/soil interface. These ephemeral perched watertables only persisted for short periods (eg. two months) in the wetter winters.

4.5 Historical Groundwater Data

A total of 27 farm and pastoral bores and hand-dug wells were located in this catchment. Of these, 44 per cent had been abandoned due to low yields or unacceptably high salinity. Most of the bores and wells were registered by the GSWA to be included in their statewide monitoring programme. Five bores/wells were selected in the agricultural part of the catchment and five in the pastoral land for comparison, as these bores/wells had reliable data for the years 1978, 1979, 1983, 1984 and 1987. The bores/wells were grouped according to band units and the data is shown in Table 4. The data indicated that groundwater has been rising by around 0.2 m yr^{-1} in the agricultural land and falling by 0.15 m yr' in pastoral land.

Table 4. Long term groundwater trends in cleared and uncleared areas of the East Perenjori catchment

Land unit	Groundwater trend (m year~) Cleared	Uncleared
1	+0.20	-0.8
2	+0.25	-
3	-	-0.20

+ = rising waterlevel - = falling waterlevel

4.6 Landscape Salt Storage

Salt storage was calculated for cores retrieved by GSWA were as follows: site PN1 (land unit 2) was 5 kg m~ to 15 m depth; site PN2 (land unit 3) was 25 kg m^2 to 23 m depth; site MP1B was 115 kg m^2 to 34 m depth.

4.7 Classes of Soil Salinity

Soil salinity was categorized into five classes, based on genesis, as shown in Table 5. Primary or pre-cbearing salinity (classes 1 and 4) occupied more than 4 km^2 and was mainly associated with braided streams on a large floodplain in the pastoral land adjacent to Mongers Lake. A discussion of high—level salt scalds occurs in Part I of this report.

Table 5. Soil salinity classes in the East Perenjori catchxnent

Class	Name	Primary (I) or secondary (II)	Land unit		AreaA affected (km^2)
1	Salt scald	I	3	(upper)	0.10
2	Hillside seeps	II	3		0.01
3	Sandplain seeps	II	4		0.50
4	Valley floor salinity	I	5	(lower)	4.20
5	Valley floor salinity	II	5		1.99
	Total saline land				6.80

[A] As at September 1986.

Secondary (post-clearing) salinity was affecting 2.5 km^2 of land and sandplain seeps (class 3) and valley floor salinity (class 5) showed the greatest potential for future spread. Investigations of hillside seeps (class 2) suggested that irregularity of the bedrock surface beneath the pediment slopes could cause salinity where a bedrock high was forcing groundwater toward the soil surface. Only small areas in the catchment were affected by this class of salinity and the seeps were relatively static. The cause and effects of salinity classes 3 and 5 will now be discussed in more detail.

- Sandplain seeps

This class of salinity occurred in land unit 4 where deep yellow sandplain was rapidly thinning at the break-in-slope. A typical soil and salt profile are shown in Fig. 4 in Part I of this report. The perched watertable occurred in gravel overlying a massive blue—grey silicified hardpan. Macropores within the hardpan were transmitting saline water, presumably from the deep regional groundwater system.

Figure 8 shows hydrographs and chlorographs of the perched and deep groundwater systems of a sandplain seep at site 4 in land unit 4. At this site, salinity expanded rapidly from 2 ha in 1983 to 6.5 ha being affected in 1986.

The perched watertable showed strong seasonal responses and automatic waterlevel recorders indicated that the watertable responded within a few hours of a storm. The watertable fluctuated from 1.3 m below ground level (BGL) during summer to 0.01 m BGL in the 1986 winter.

The deep regional groundwater rose rapidly during late 1983 through to mid 1984. This resulted in a gradient reversal between the two groundwater systems, with an upward component of flow for a continuous eight month period in 1984—85. A convergence of the two systems is indicated by the almost identical responses in 1986, so that the previous two hydraulically separate groundwater systems were now in hydraulic connection.

The upward hydraulic gradient (0.15) would be expected to cause an injection of salt into the system and, as shown by the chlorographs, groundwater salinity increased rapidly (as did the area of saltland) from 1985 onwards.

- Valley floor salinity

By 1986, valley floor salinity was affecting 2 km^2 in land unit 5. A typical valley floor profile is shown in Fig. 5 in Part I of this report. The main feature of the profile was the presence of two indurated layers or hardpans. The “upper hardpan” known as the red brown hardpan was found at 0.3 . 1.0 m depth, while the “lower hardpan” occurred at 3.0 . 6 m depth.

Laboratory measurements of vertical infiltration through the surface of the red brown hardpan gave values of $^{10-3}$ to $^{10-}$4 m day^{-1}. This very slow infiltration rate would account for the severe waterbogging problems occurring in the valley floor. On the positi-ve side, capillary rise of water and salt from the shallow regional groundwater table was apparently truncated to some extent during summer and autumn by the presence of this hardpan, thus reducing the severity of salinity at the soil surface.

Figure 9 shows hydrographs and chlorographs of the deep groundwater system at site 3 in land unit 5 which is affected by valley floor salinity. Although the waterlevels showed a static trend with time, there were distinct seasonal responses. The “sinusoidal” fluctuations were strongly correlated to winter recharge by rainfall and to summer discharge by evapotranspiration.

Continuous waterlevel recorders on the deep piezometer showed that waterlevels responded within 4—24 hours of the rainfall event. The similarity of responses between the top and bottom of the flow system suggests a good hydraulic connection throughout the depth of the flow system. The hydraulic head differential between the top and bottom of the flow system was small (0.006 in the upwards direction).

The simultaneous rise of groundwater levels throughout the flow system during the 1984/85 summer, in the absence of rainfall, suggests the arrival of water from an upslope recharge area. However, it would appear that local or in-situ recharge also occurs as evidenced by troughs in the chlorographs within one month of rainfall events. Surface water is evidently able to leak downwards through the red brown hardpan, most likely through preferred channels once the topsoil is saturated.

4.8 Geophysical Surveys

Figure 10 (after Butt, 1985) shows apparent resistivity contours determined from an airborne electromagnetic survey flown by Geoterrex Pty Ltd (Schneider, 1985). The survey gives a broad regional picture of the distribution of salinity in the catchment. Low resistivity (high EC) zones highlight saline and potentially saline areas. Apparent resistivity was correlated with groundwater salinity and a reasonable relationship ($r^2 = 0.61$) was found between resistivity and groundwater salinity at depths of 3-5 m.

Zones of high resistivity (low EC) tended to relate to shallow bedrock and to areas of low groundwater salinity. The batter could represent useful target areas for farmers searching for potable groundwater supplies.

The resistivity low in the southern half of the catchment indicates the potential for future salinization of the valley floor, if the saline regional watertable comes closer to the ground surface in this area. Examination of a simplified geologic map (Fig. 11) indicates bedrock highs at the extremities of the central part of the catchment could be constricting deep groundwater flowing northwards out of the catchment. Hence geologic control on development of salinity in the up-stream end of the catchment may exist.

Furthermore, Schneider (1985) found increased magnetic activity in the northern part of the catchment indicating the presence of deeply buried dolerite dykes. This was confirmed by ground magnetometer traverses (Fig. 12). Dolerite rock detritus occurred at a number of places on the catchment slopes. Engel (1987) provide data which show that dolerite dykes can act as hydraulic barriers, impeding the flow of groundwater out of catchments and resulting in saline seeps. The possibility of dolerite dykes acting as hydraulic barriers in this section of the catchment would require further investigation.

5. Discussion

Major rainfall events, such as the May 1984 event and to a lesser extent the 1986 storm events, were found to have a significant effect on the hydrology of the catchment in terms of increases to soil water storage and groundwater responses. The occurrence of flooding, waterlogging and the rapid spread of saline seeps resulted from these events. Williamson (1978) indicated the significant impact that a wet year could have on the hydrology of a catchment. While recharge might average approximately 10 per cent of rainfall, it would be considerably greater in wet years (up to 22 per cent of rainfall) and much less in dry years.

Although the overall net recharge rate at East Perenjori was estimated at 6.5 per cent of the annual rainfall, the recharge rate was likely to be highly variable both spatially and temporally. Recharge will vary with land use, soil type and landscape position. In dry years such as 1985, recharge was negligible, while in wet years such as 1984, recharge was greater than 10 per cent of annual rainfall.

Although recharge occurs across the whole catchment in extreme rainfall events (e.g. May 1984), the deep sand pockets (spillways) of the sandplain slopes could be considered as preferential recharge areas. They satisfy most of the criteria of a preferential recharge area, including, readily drainable soils, low soil salt storages and low salinity groundwater. The perched groundwater system contributes water to sandplain seeps and may be an additional source of water for recharging the deep groundwater system.

The presence of perched watertables, particularly in land unit 2, was significant in terms of recharge. Hydrograph decay suggested that perched groundwater dissipated either by lateral flow downslope and/or by vertical movement downwards into the pallid zone. Johnston (1983) considered the role of a shallow aquifer in the more permeable sandy surface soils in recharging deeper groundwater systems. They concluded that recharge could be significant in the presence of preferential flow paths and the vertical channels of remnant tree roots appeared to fulfill the role of providing a connecting link between groundwater systems. Williamson and Bettenay (1979) identified a significant upland recharge area where a perched watertable had developed at the gravel/clay interface. The volume change was sufficient to provide the recharge necessary for the measured rise of the deeper groundwater. Williamson (1978) measured a vertical drainage component of 45 mm yr~ below the perching bed of the shallow aquifer on deep sands at Meckering.

Engel et al.(1987) identified two possible mechanisms of recharge in wheatbelt catchments. These were piston—type (or matrix flow) and preferred pathway (or macropore flow). It is quite likely that both mechanisms are operating in the East Perenjori catchment. Matrix flow appears to be the principal recharge mechanism occurring in the coarse textured soils of land units 1 and 2. This is evidenced by soils which show low salt storages and relatively high K_3. Deep groundwaters beneath these soils show steadily rising trends without sharp peaks. Examination of soil cores treated with rhodamine dye showed that water flow was relatively uniform through sandplain soils.

Macropore flow seemed to be the main recharge mechanism in the finer textured. soils of land units 3 and 5. This was evidenced by soils showing higher salt storages and a relatively bow K_5 of the soil matrix. Examination of soil cores treated with rhodamine dye showed that most of the water flow occurred through natural fractures and fine root channels. In the native state, *Eucalyptus* spp. were growing on these soils and this would account for the root channels which are now acting as conduits for flow. There appeared to be two components of recharge to the deep groundwater system (1) in situ recharge when large rainfall events resulted in almost instantaneous responses to water levels and (2) delayed responses due to arrival of a pulse of water from upslope.

The concept of valley flats acting as significant recharge areas was discussed by McFarbane (1988). The near instantaneous response of deep piezometers could be caused by aquifer loading the result of addition of surface water causing an increase in pressure to the flow system. Alternatively the response could result from equilibration of pressure following cessation of evapotranspiration.

The regional groundwater system, for at least 50 per cent of the catchment is still in an unsteady state, with water levels slowly rising toward a new equilibrium. A rise of the watertable below the slopes will increase hydraulic gradients towards the valley floor and this will produce further increases in area of salinity.

In the lower regions of the valley floor, there is evidence of previous high watertables in the pre-cleared state indicating the catchment may have been saline in the past. This includes the presence of clay pans, silcretes, iron and manganese precipitates in shallow hardpans and green clays indicating reducing conditions. These fossil saline discharge sites could be considered high risk areas in terms of present and future salinity development. Landholders reported pre-clearing watertables at 2.5 m depth in the valley indicating high watertables even in the native state. There would seem to be a gradual transition between primary and secondary salinity along the length of the broad valley floor.

6. Conclusions

The following causes of secondary salinization are identified in the East Perenjori catchment and these involve involving both geologic and geomorphic controls.

(1) Hillside seeps where bedrock highs force saline regional groundwater toward the soil surface in land unit 3.

(2) Sandplain seeps in band unit 4 result from the interaction of a relatively fresh local perched watertable (originating from spillway sands in land unit 2) and the saline regional groundwater system.

(3) Valley floor salinity results from a combination of surface waterlogging and shallow regional groundwater. A shallow natural hardpan acts as a perching bed for rainfall and possibly as a choke for upward capillary rise from the saline watertable during summer.

Some geologic control of the regional groundwater in the valley floor is evident from a “bottleneck” situation caused by granite bedrock highs and the inferred presence of deeply buried dolerite dykes.

Extreme rainfall events, characteristic of this region, have a significant effect on the hydrology of the catchment in terms of surface runoff; increases to soil water storage and groundwater response.

7. Acknowledgments

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8. References

Bouwer, H. and Rice, R.C. (1976). A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells. Water Resour. Res. 12, 423-8.

Butt, G.R. (1985). Case histories showing various applications of a combined INPUT magnetometer-spectrometer airborne geophysical system in Australia. (4th ASEG Conference).

Engel, R., McFarbane, D.J., and Street, G. (1987). The influence of dolerite dykes on saline seeps in South—western Australia. Aust. J. Soil Res. 25, 125—36.

George, P.R. (1978). The hydrogeology of a dryland salt seepage area in South western Australia. Proc. Subcomm. Salt Affected Soils. 11th mt. Soil Sci. Congr., Edmonton. pp. 3.10 3.13

Greacen, E.L. (1981). Soil water assessment by the neutron method. Div. of Soils, CSIRO, Adelaide. 140 pp.

McFarlane, D.J., Engeb, R., and Ryder, A.T. (1988). Location of recharge areas responsible for valley salinity in the Lake Toolibin catchxnent, Western Australia. J. Hydrol. (in press).

Johnston, C.D., Hurle, D.H., Hudson, D.R. and Height, M.I. (1983). Water movement through preferred paths in lateritic profiles of the Darling plateau, Western Australia. CSIRO Div. Groundwater Res. Tech. Pap. No. 1, 34 pp.

McGowan, R.J, (1984). Report on multiport monitoring bore and piezometer nest construction in the East Perenjori catchment. Hydrogeology Report No. 2572 (unpublished). West. Aust. Geol. Surv., Perth.

Peck, A.J. (1983). Response of groundwaters to clearing in Western Australia. Papers of the International Conference on Groundwater and Man, Sydney. Australian Govt. Publishing Serv. Canberra. pp. 327-335.

Peck, A.J. and Hurbe, D.H. (1973). Chloride balance of some farmed and forested catchiuents in South western Australia. Water Resources Res. 9, 648—57.

Schneider, M. (1985). Interpretation report for an electromagnetic and magnetic survey using the Barringer “INPUT” system of the Monger’s Lake East Perenjori catchment area for the West Australian Department of Agriculture. Geoterrex report Job No. 83—569.

Williamson, D.R. (1978). The waterbalance of deep sands near Meckering, W.A. MSc. Thesis. Institute of Agriculture, University of Western Australia, Perth.

Williamson, D.R. and Bettenay, E. (1979). Agricultural land use and its effect on catchrnent output of salt and water evidence from Southern Australia. Prog. Wat. Tech. 11(6), 463—80.

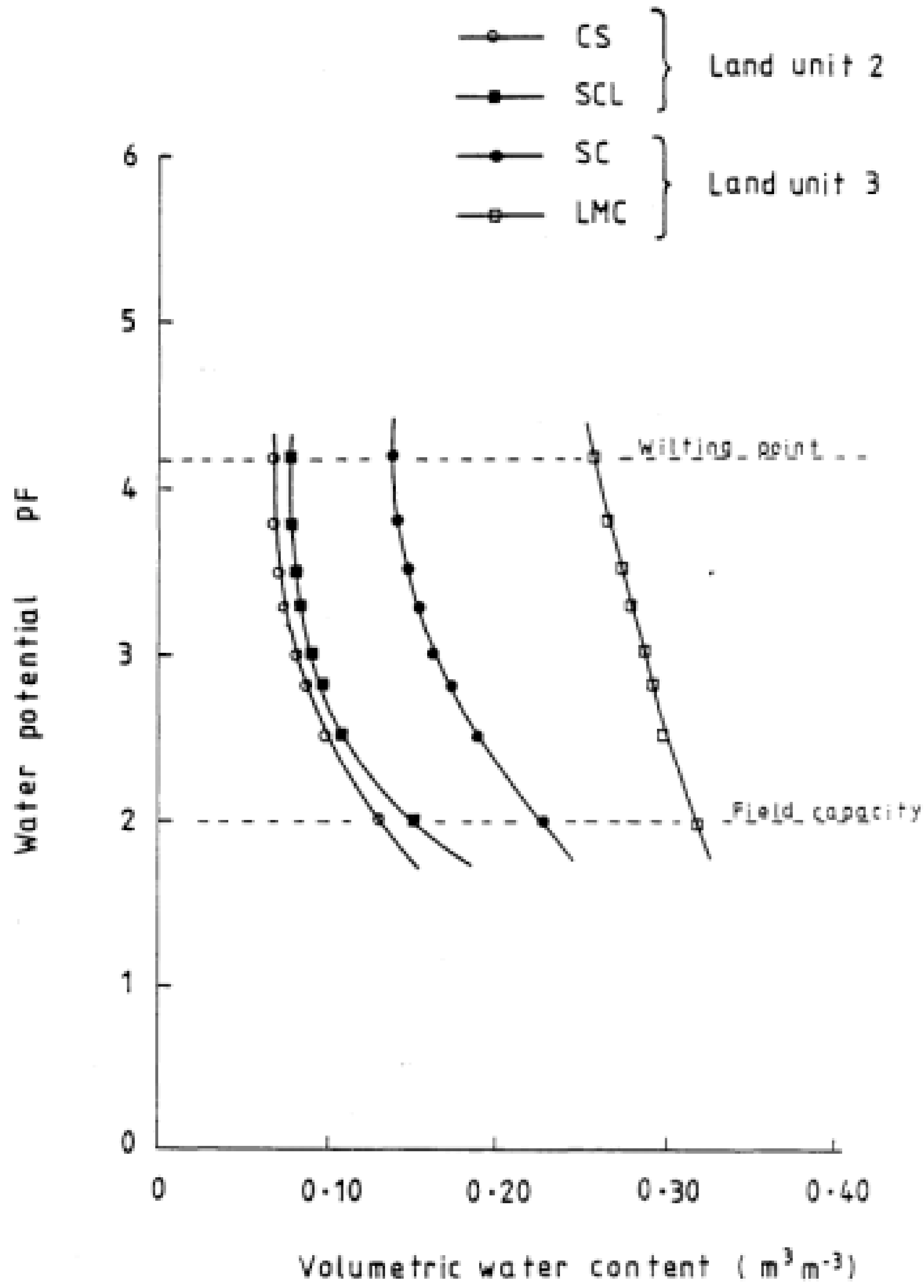


Fig. 1 Soil moisture characteristics of four textural classes between wilting point and field capacity.

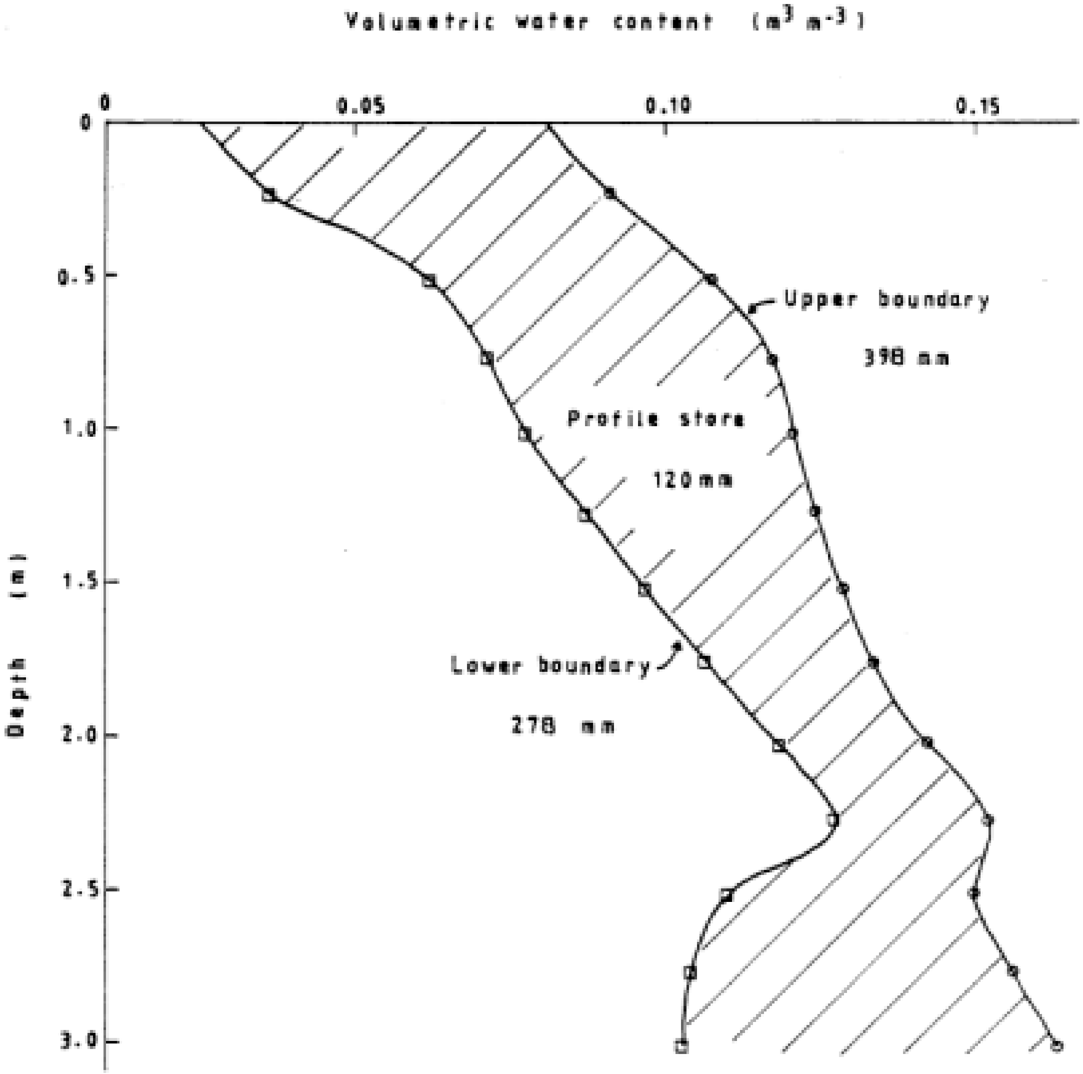


Fig. 2 Limits of soil water storage for the top 3m of a Gn1.21 soil at site N9 for the period 1984-86.

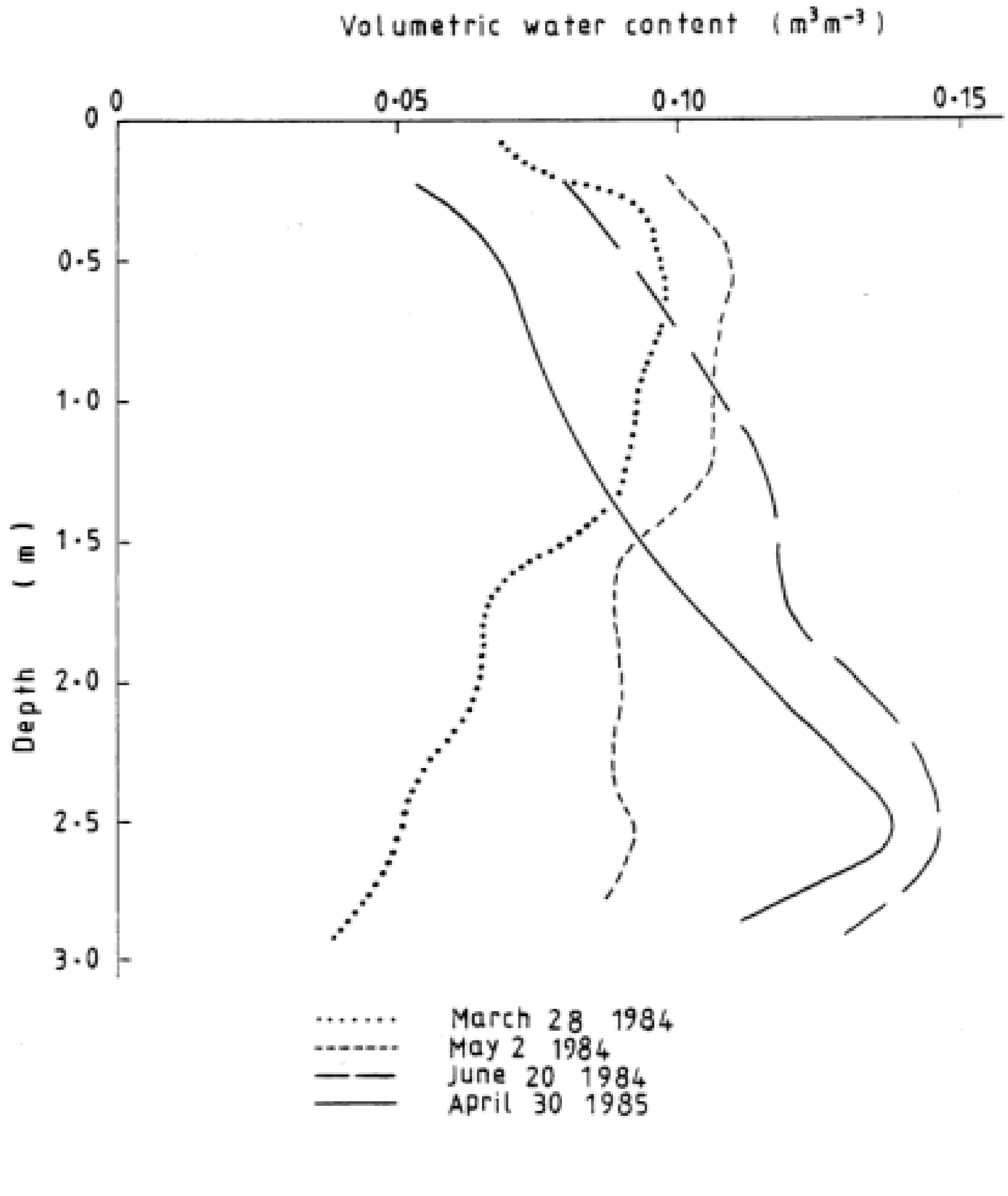


Fig. 3 Wetting and drying cycles in recently cleared sandplain.

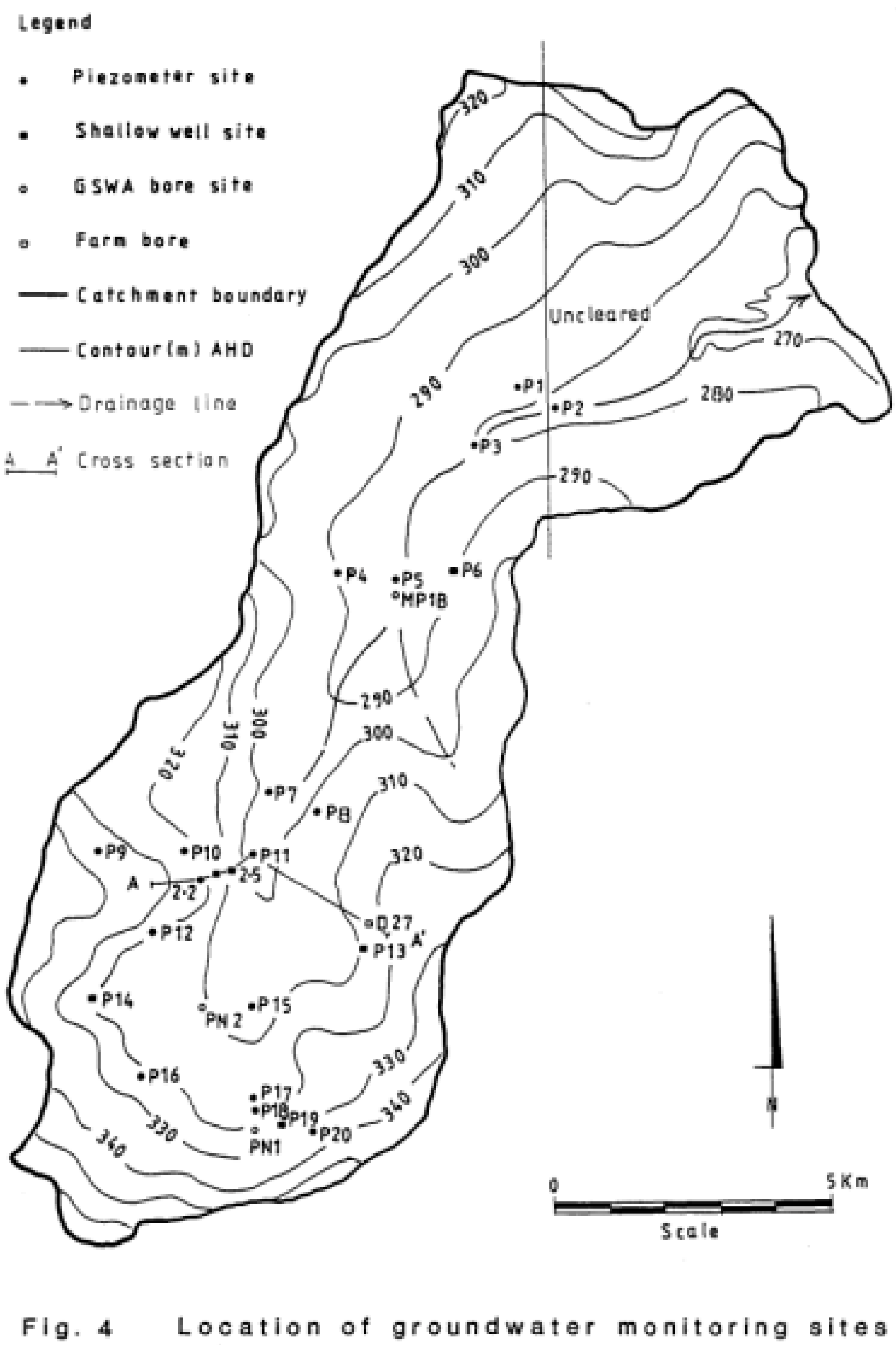
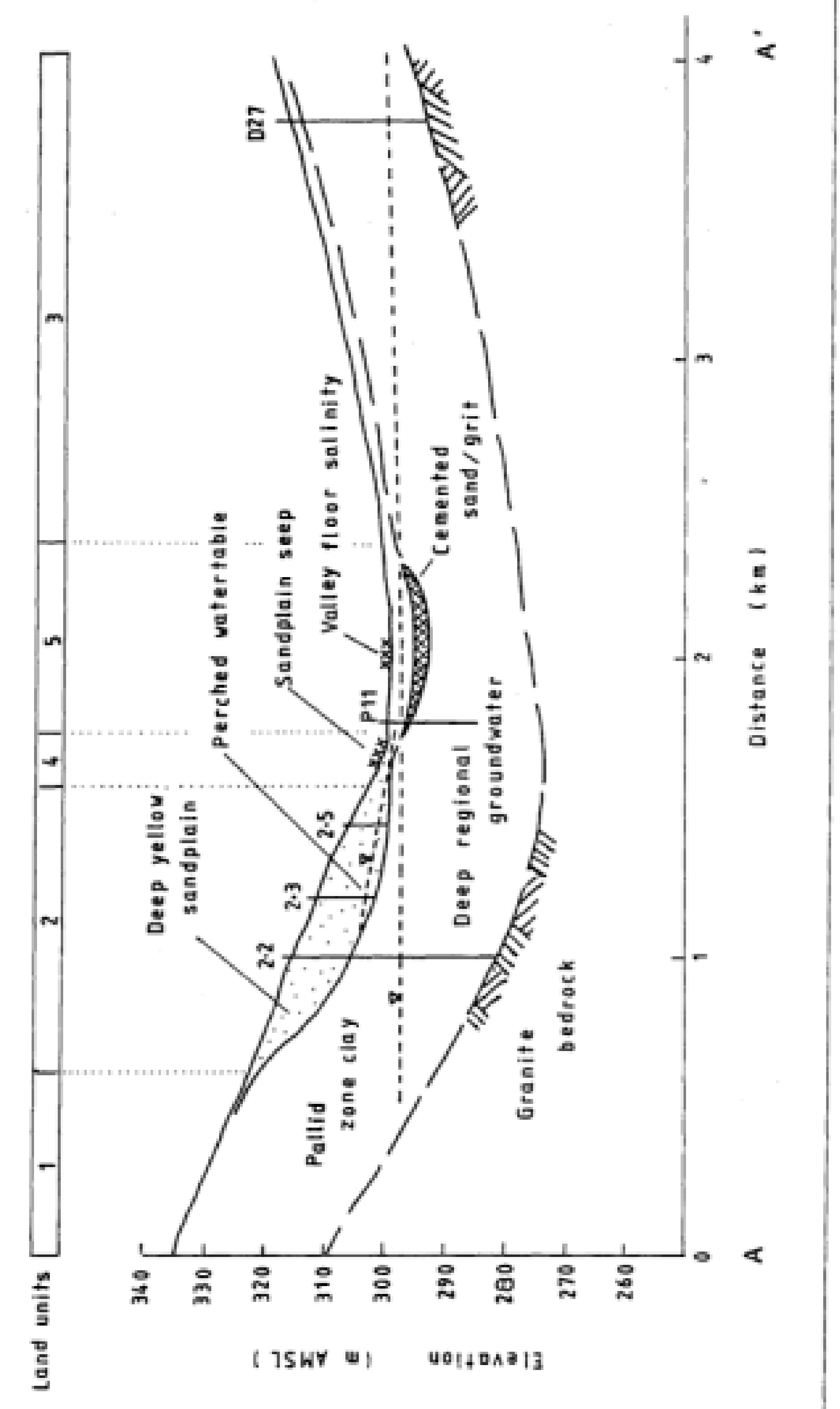


Fig. 4 Location of groundwater monitoring sites and topography of the East Perenjori catchment.

Fig. 5 Hydrogeologic cross-section showing groundwater systems and development of salinisation in the landscape.



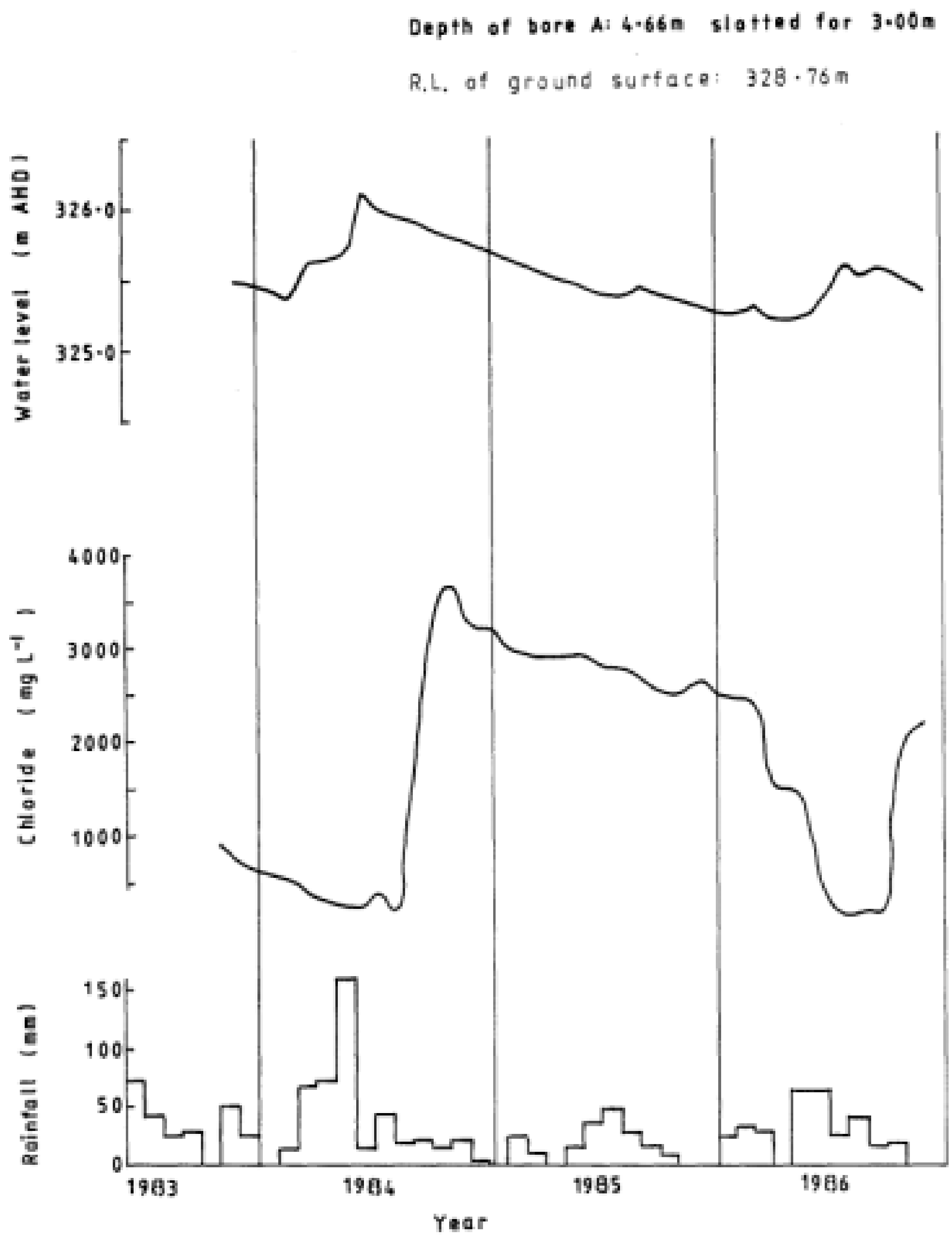


Fig. 6 Hydrograph and chlorograph of the perched groundwater system from observation well P19A in land unit 2.

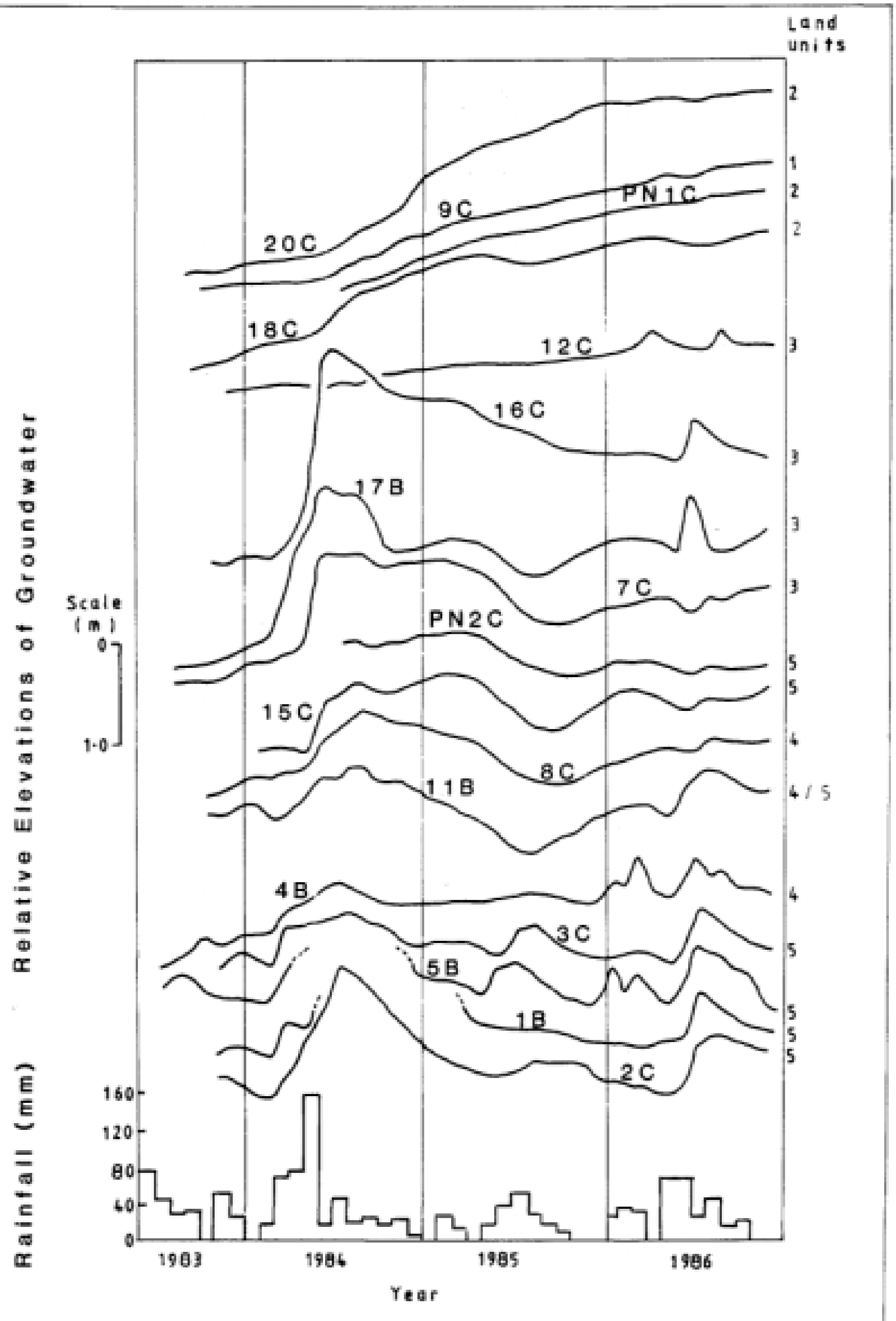


Fig. 7 Hydrographs showing responses of the deep regional groundwater system throughout the catchment.

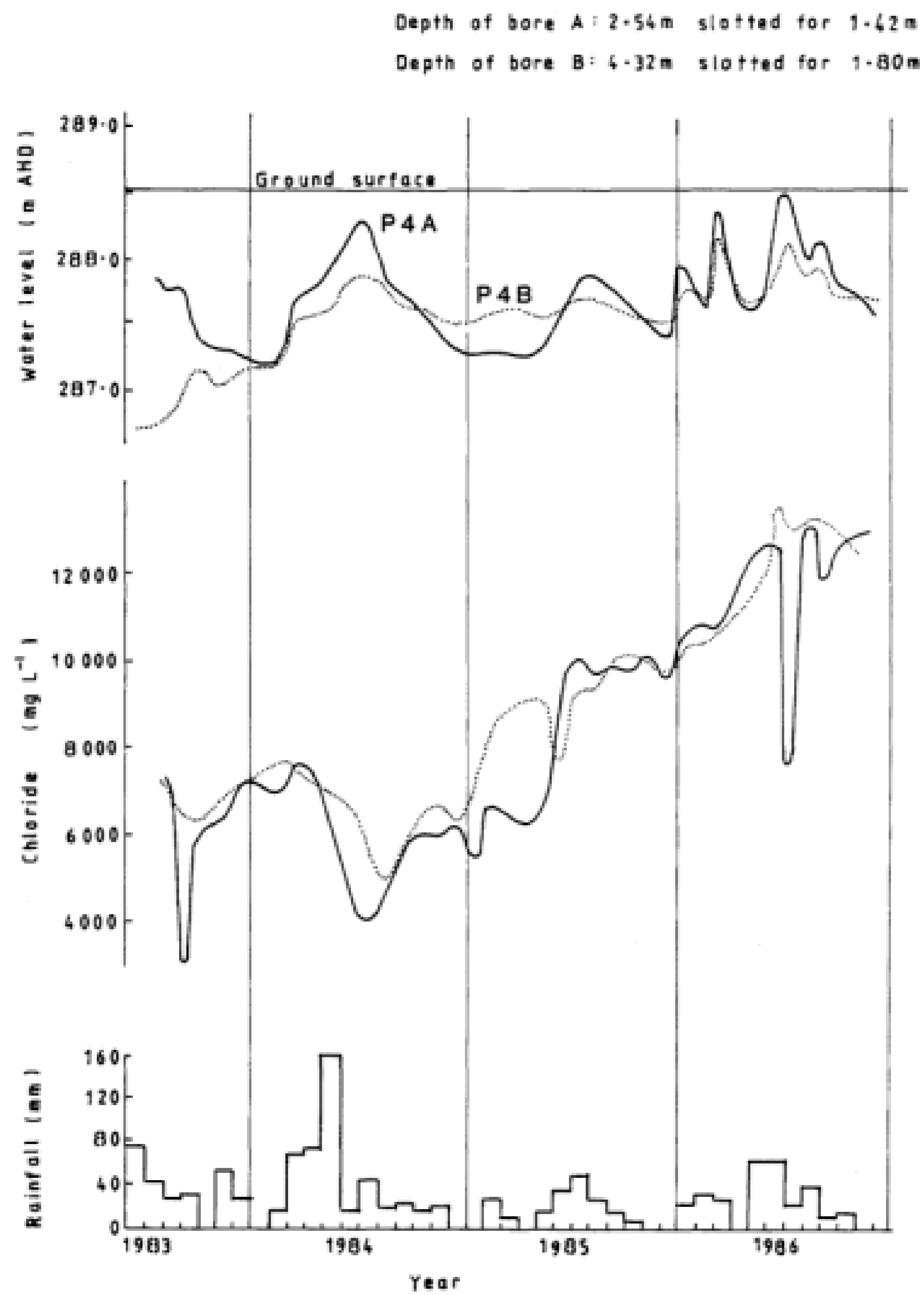


Fig. 8 Hydrographs and chlorographs of the perched and deep groundwater systems from well P4A and piezometer P4B in land unit 4.

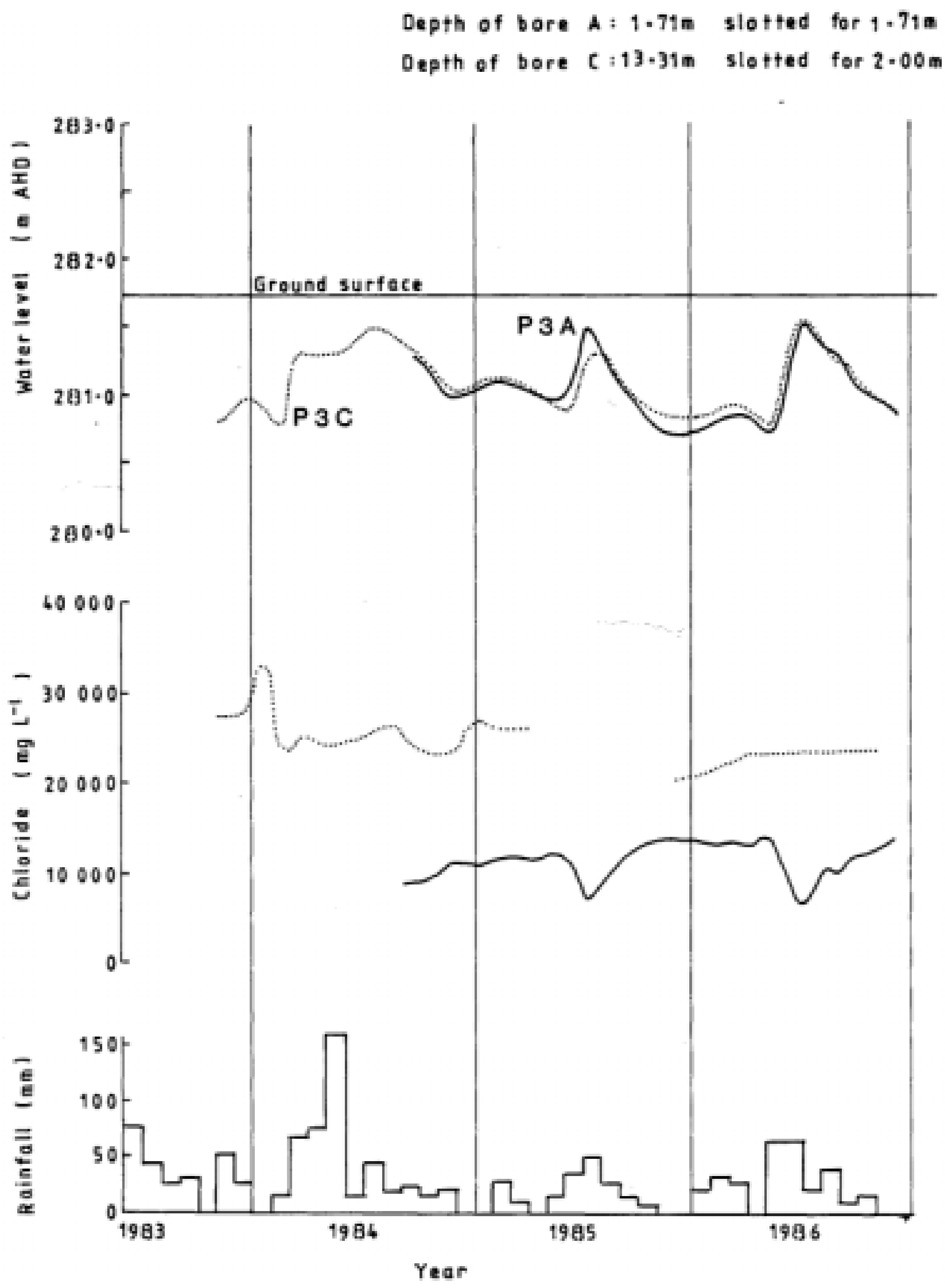


Fig. 9 Hydrographs and chlorographs of the deep groundwater system from well P3A and piezometer P3C in land unit 5.

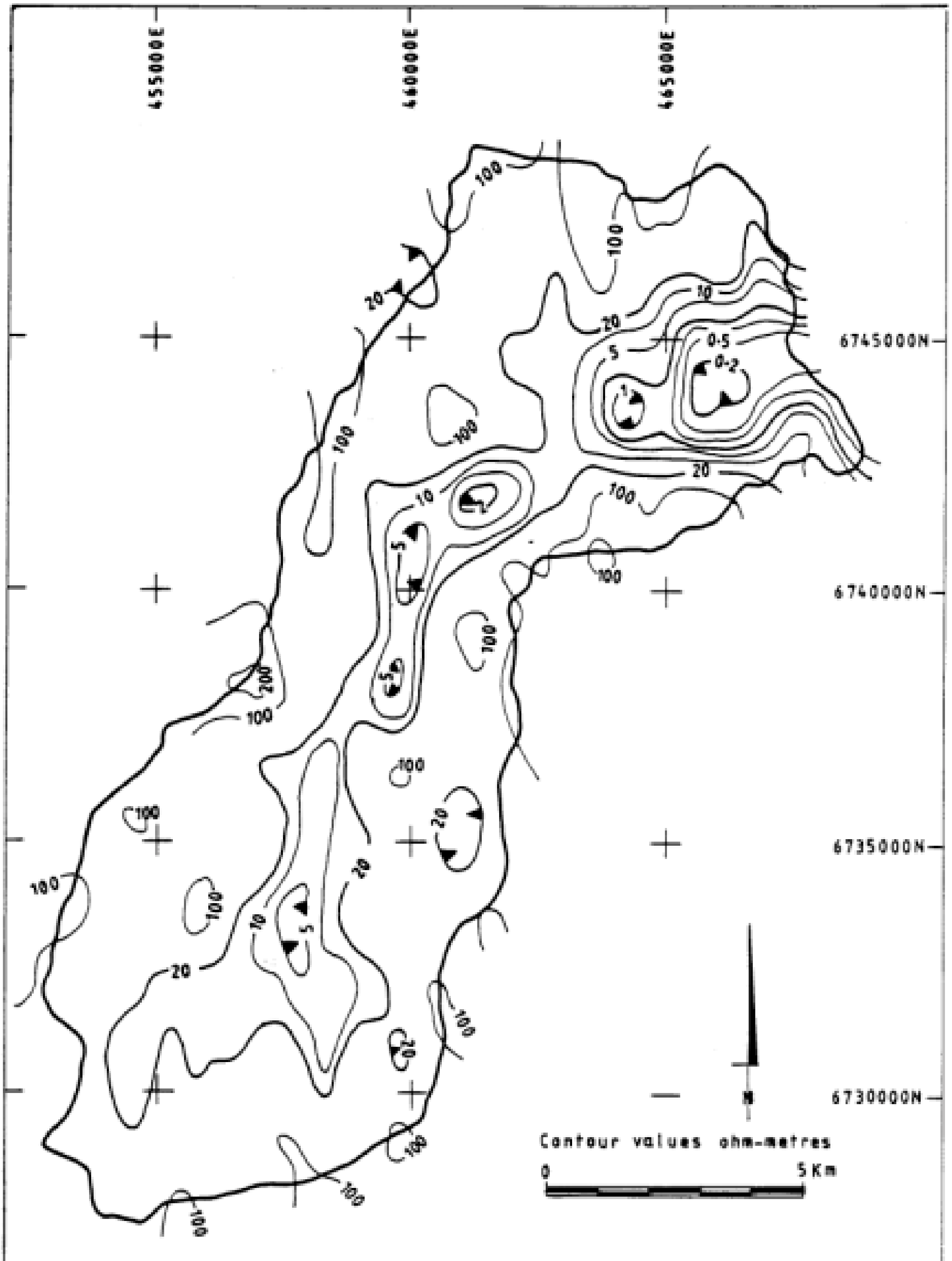


Fig. 10 Contour map of apparent resistivity derived from INPUT data (after Butt, 1985)

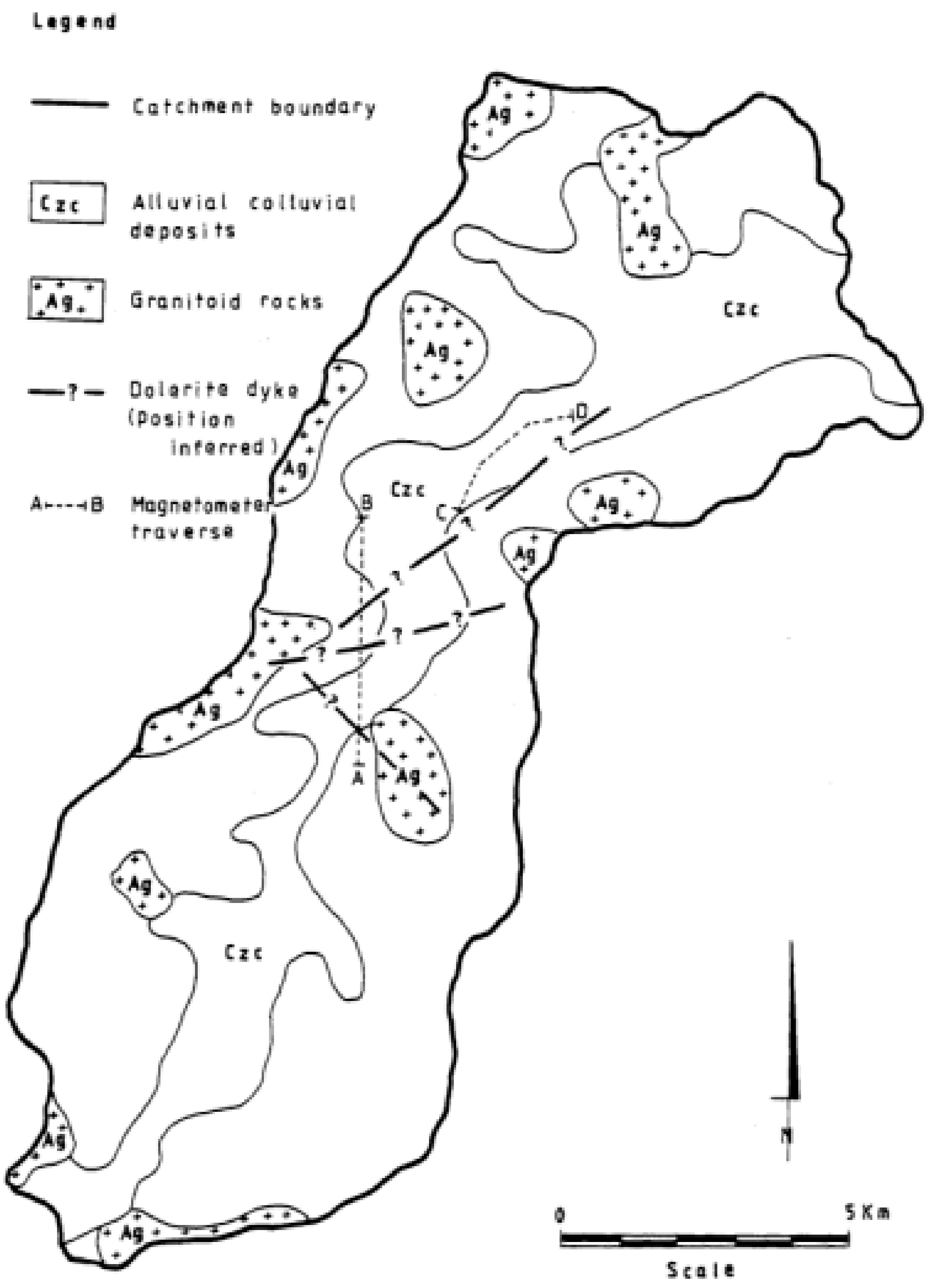


Fig. 11 Geology of the East Perenjori catchment (after Baxter and Lipple, 1985).

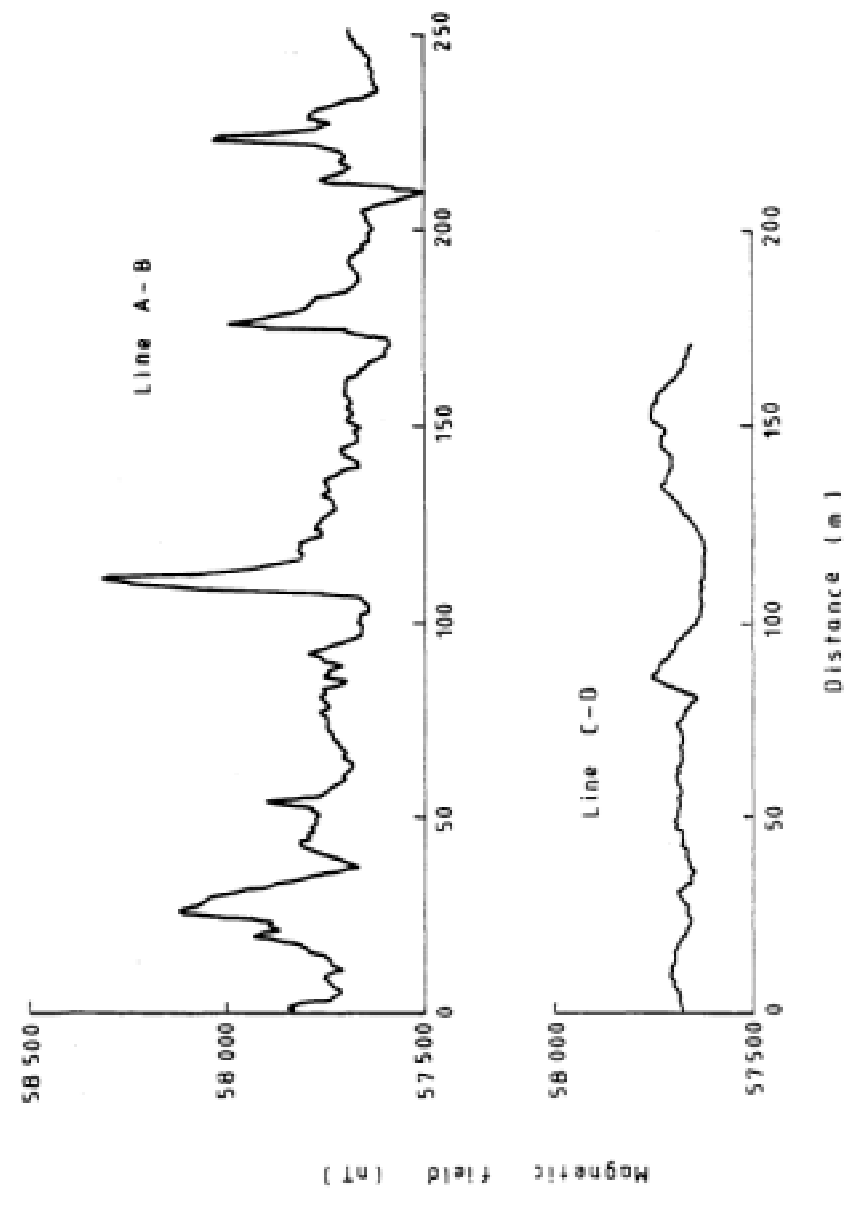


Fig. 12 Magnetic profiles along valley floor.