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FIELD OBSERVATIONS OF THE MOISTURE REGIME OF A YELLOW-GREY EARTH (OTOKIA SILT LOAM) IN EASTERN OTAGO

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ABSTRACT

The moisture regime of yellow-grey earths has in the past been qualitatively inferred from climate analysis and pedologic interpretation. In this study quantitative information was obtained. Field measurements, collected over a 3–4 year period, of the moisture tension and moisture content regimes of a modal Otokia silt loam (Tokomairiro soil set) site provide data on changes in both moisture status and storage opportunity. The overall regime is characterized by periods of high moisture tension (at or drier than wilting point) in the A and B horizons through summer, and periods of low moisture tension (at or wetter than field capacity) in most horizons in winter. Within the limited range of moisture tensions commanded by resistance blocks, neutron probe and resistance block determinations are shown to be compatible.

INTRODUCTION

This paper describes in quantitative terms the moisture regime of an Otokia silt loam site located on the down margin of the Taieri Plain near Dunedin. Prevailing moisture conditions were monitored on a semi-routine basis over a 3–4-year period using neutron-probe, resistance-block and gravimetric techniques.

Although volumes of water stored temporarily or semi-permanently in soil have a large control over both biological and physical processes, measured moisture regimes have not been reported before for New Zealand soils. Some work, however, has been done on a broad scale using climate characteristics and selected soil physical properties, which lead to the specification of moisture classes for soil groups. Cox (1968) calculated water balances from meteorological data for specific climate situations throughout New Zealand using Thornthwaite's method, and correlated the main soil groups with the climate 'classes' so derived. Knowing the available water capacities of the top 46 cm (18 inches) of 54 soil types throughout the country, McDonald (1968) used Cox's water-balance data to assess the average dates of onset and duration of wilting-point conditions and conditions drier than field capacity. On the basis of this study of moisture condition he suggested criteria for six moisture classes already inferred through field observation by Taylor and Pohlen (1962).

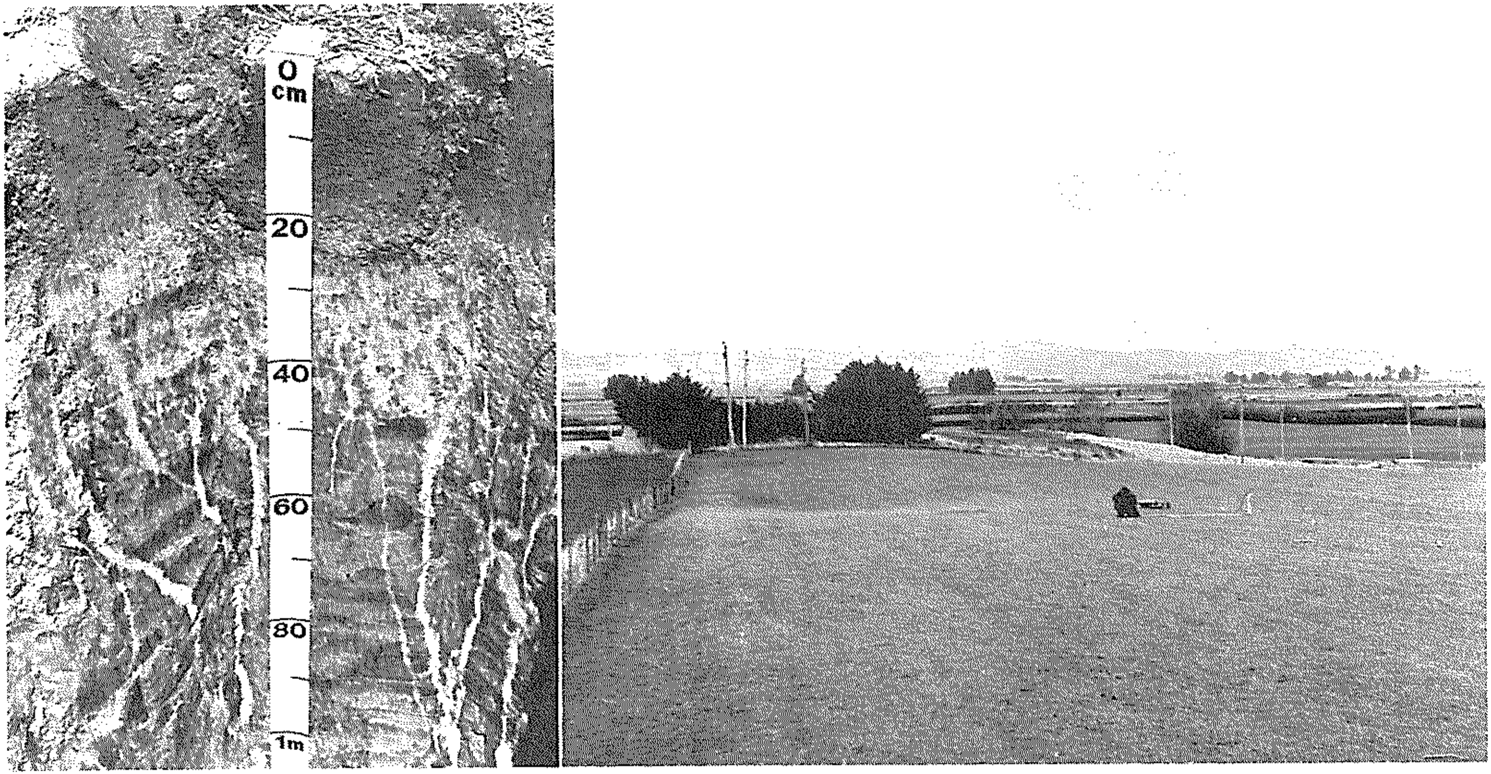

FIG.1 – Study site: Otokia silt loam profile and landscape (view southeast).

In contrast to this earlier work, the study in this paper relates to routine field monitoring of a specific site. Similar studies have been reported overseas by, for example, Aitchison and Holmes (1953), Winkworth (1970), and Franzmeir *et al.* (1973).

SITE DESCRIPTION

The Otokia silt loam soil type (Raeside and Cutler, 1960) is a member of the Tokomairiro soil set (N.Z. Soil Bureau, 1968) which occupies some 11,800 hectares in the Otago counties of Bruce, Clutha, Taieri and Waikouaiti (Long, 1966). This soil set contains yellow-grey earths derived from loess, and has important correlation with the Timaru, Claremont, Te Houka and Warepa soil sets which cover significant areas of South Canterbury and South Otago.

The modal site selected for study (Fig. 1; map reference NZMS 1, S163:855670) lies on a gently undulating terrace (site slope 3°, aspect east) on the western margin of the Taieri Plain, 4 km northwest of Dunedin Airport. In the regolith there are three primary loesses which correlate with the Kumara 3_2, 3 and 2_2 stadial advances of the Otiran Glaciation (Bruce, 1973). The loess mantle overlies weakly weathered schist gravels, and extends to a depth of 2.2 m. The 'Yellow A' loess member extends from the surface to a depth of 1 m, the 'Yellow B' member from 1 m to 1.9 m, and the 'Brown A' member from 1.9 to 2.2 m.

The site has been cultivated in the past to a depth of about 15 cm for winter feed crops and wheat, but is currently managed as a semi-permanent pasture of ryegrass and white clover for intensive fat-lamb production. Annual rainfall averages 630 mm (at Dunedin Airport) and is generally well distributed with a slight summer peak and winter low. Mean temperatures (1931–60) at Taieri (Invermay) for January are 14.6°C and for July 4.8°C. Annual sunshine hours average 39 percent of possible, ground frosts occur on average on 115 days and screen frosts on 58 days (N.Z. Meteorological Service, 1973b).

SOIL DESCRIPTION

A photograph of the soil profile at the study site is incorporated in Fig. 1, and a summary of key morphologic features and their interpretation is given in Fig. 2. The topsoil is a dark-grey silt loam with a few small iron/manganese concretions. The grey colour is indicative of reducing conditions that prevail for at least part of each year as a result of waterlogging. Sites that are better drained tend to be browner. The subsoil has a firm to very firm massive to weakly developed prismatic structure intersected and crossed by prominent grey and reddish-yellow veins. It is described as having a net-gammate fragipan of low apparent macroporosity and high dry bulk density. The upper portion of this fragipan is modified by pedological processes which are considered to be currently destroying the fragipan from the top down (Bruce, 1972). In this modified fragipan (B_{2g}) horizon, net-gammate patterns of secondary horizontal veins are developed, probably as a consequence of desiccation followed by uneven penetration of moisture.

In the unmodified (C_x) fragipan horizon, vertical veins follow the joint

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HORIZON	KEY MORPHOLOGICAL FEATURES	INTERPRETATION
A_1	• silt loam texture • dark grey colour • friable consistence • moderately developed fine nut and granular structure • many roots	• organic matter and low clay content manifest in texture, structure, and consistence • colour suggests horizon to be saturated at times
B_{1c}	• clay loam • mottles and small concretions • weakly to mod. developed medium nut structure	• seasonal waterlogging a factor in mobilisation of Fe and Mn
B_{2g}	• clay loam • olive yellow colour • network of light grey vertical and horizontal veins • massive to very weakly developed blocky structure • few thin distinct cutans (clay skins) • few roots	• an horizon of clay illuviation (deposition) • low permeability inferred by texture and structure • colours indicate frequent seasonal saturation
C_x	• clay loam • colour browner • massive structure • prominent gammate fissures between prisms • brown rust-mottled selvedge at edge of prisms • few fine secondary veins • many fine Mn specks • few roots down fissures	• very low permeability inferred by massive structure and high bulk density • fissures an extension of B_{2g} horizon • mobilisation of Fe and Mn suggests optimum moisture levels persist for most of the year
C	• clay • very firm massive structure • spot mottles and small brittle concretions • no roots	• very low permeability
IuB	• clay • very firm massive • continuous spot mottles throughout • primary gammations continue	• hydraulic character similar to C horizons above
IuC	• dark reddish brown concretions	• horizon of water hold-up
2uB	• clay loam • gammate colour patterns still present	• hydraulic character similar to horizons above

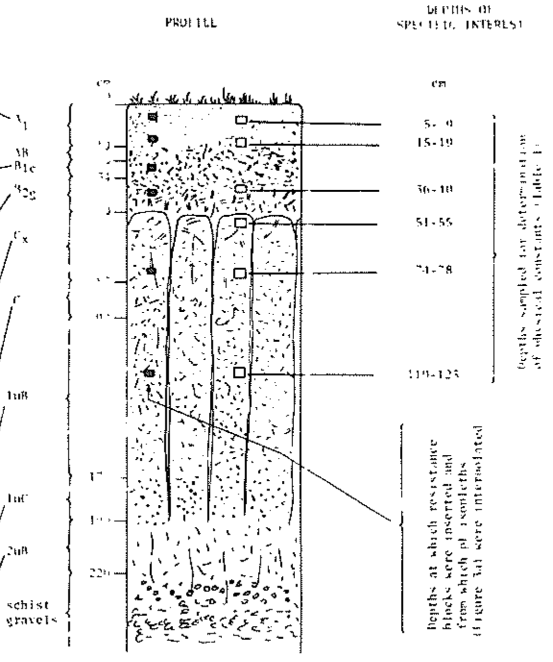

FIG.2 — Profile features and horizon stratigraphy, Otokia silt loam.

systems between prisms of the compact material. Macropores of the modified fragipan (B_{2g} horizon) have cemented walls which enhance the shear strength but reduce permeability. The underlying fragipan lacks cementation. and 'slakes' when moistened at an exposed face. Gleying and mottling occur in the B_{2g} horizon. indicative of a fluctuating moisture regime that seasonally reaches field saturation. The dense and massive structure of both the B_{2g} and C_x horizons imply impermeability. Iron/manganese concretions in the A and B_{1c} horizon are further indications of a contrasting alternately wet and dry (reducing and oxidizing) moisture status.

The morphology of the soil thus indicates, in a qualitative way, important hydraulic controls on the movement of soil water in the profile.

SOIL PHYSICAL PROPERTIES

Bulk densities, particle densities, and the soil moisture characteristic (moisture content versus tension relationship) were determined at six depths representing soil horizons (Table 1). Samples were taken in June 1971, single bulk samples from each depth being carefully hand-carved in the field. Methods used were those described by Gradwell (1972).

METHODS

Gravimetry

On ten occasions selected to cover the full range of surface moisture conditions, samples were obtained for the determination of moisture contents by gravimetric methods. A 28-mm diameter core sampler was used to take ten replicated samples from 0–7.5, 7.5–15, 15–22.5, 22.5–30 cm depth at 1-m intervals along a 10-m line. These were oven-dried, and bulk density and moisture content determined.

Neutron Probe

Neutron probe readings were obtained using a Troxler Model 105A probe. Two access tubes were installed some 15 m apart to a depth of 2.3 m. On each day that observations were made, readings were generally taken at 5-cm intervals from 0 to 30 cm, at 10-cm intervals from 30 to 60 cm, and thereafter at 10-cm or 20-cm increments depending on the rate of moisture change with depth. The effective radius of the 'sphere of influence' (i.e. the volume of soil on which the measurement is made) is not less than 10–15 cm for a wet soil containing 50–60 percent of moisture by volume, and is about 30–40 cm for a dry soil (*c.* 10 percent moisture volume) (Bell, 1973; Kristensen, 1973). The optimum spacing of readings is therefore about 10–15 cm for wet soils and 15–20 cm for dry soils; decreasing this figure will not improve resolution. However, 5-cm intervals were taken at the surface to determine which specific readings had the best empirical correlation with gravimetric determinations of moisture content in the top 30 cm.

To convert the probe count ratio at a specific depth to a moisture content, the manufacturer's lineal calibration was used up to a count ratio of 0.8 (0.38 moisture volume fraction – MVF). Above this value a quadratic relation was used to extend the calibration to a count ratio of 1.55 (1.00 MVF). This combination calibration was found to give moisture volumes in excess of gravimetric determinations by an amount equal to the volume of 'bound' water

TABLE 1 – Physical relationships, Otokia silt loam.

Horizon & depth sampled (cm)	*Dry bulk density (g / cm³)*	*Particle density (g/cm³)*	*Total porosity (%)*	*Moisture loss 105-600°C (v/v %)*	*Water contents at various tensions (w/w%; v/v% in brackets)*						
					0.05 bar pF 1.7	*0.1 bar pF 2.0*	*0.2 bar pF 2.3*	*0.4 bar pF 2.6*	*1.0 bar pF 3.0*	*4.0 bar pF 3.6*	*15.0 bar pF 4.2*
A_1, 5–9	1.22	2.62	53.3	9.9	34.1 (41.7)	32.9 (40.2)	31.6 (38.6)	30.0 (36.7)	25.8 (31.5)	20.5 (25.1)	14.7 (18.0)
A_1, 15–19	1.34	2.65	49.5	9.4	29.2 (39.1)	28.2 (37.7)	27.2 (36.4)	25.8 (34.5)	22.4 (30.0)	18.4 (24.6)	15.2 (20.3)
B_{2g}, 36–40	1.65	2.73	39.5	5.6	21.3 (35.2)	20.9 (34.5)	20.1 (33.2)	19.8 (32.7)	18.2 (30.1)	16.0 (26.4)	14.3 (23.6)
C_x, 51–55	1.80	2.76	34.8	4.7	18.3 (32.9)	18.0 (32.4)	17.7 (31.8)	17.3 (31.1)	15.9 (28.6)	14.8 (26.6)	12.0 (21.6)
C_x, 74–78	1.84	2.74	32.8	5.1	17.1 (31.5)	17.0 (31.3)	16.8 (30.9)	16.6 (30.5)	15.8 (29.1)	14.2 (26.1)	12.2 (22.4)
IuB, 119–123	1.80	2.74	34.4	5.3	17.7 (31.8)	17.6 (31.6)	17.5 (31.4)	17.3 (31.1)	17.1 (30.7)	17.0 (30.5)	14.0 (25.1)

or 'water equivalent' retained at 105°C but lost at 600°C. This relationship was established:

(1) By comparison of moisture characteristic values (pF = 0. and 4.2) with moisture logs on dates when specific depths were known to be near saturation or wilting point.

(2) By comparison with gravimetric determinations.

(3) From experience on other soils.

Correction values were obtained by drying to 600°C samples from selected depths (Fig. 2). The loss in weight from 105° to 600° was attributed to loss of 'bound' water in the clay minerals together with loss of organic matter. For practical purposes the loss of weight through organic matter ignition may probably be regarded as a 'water equivalent' of the organic matter, since the atomic weight ratios of hydrogen to that of water, and of hydrogen to that of the dominant forms of organic matter are similar. 'Moisture' values by which the probe might be expected to exceed gravimetric values were thus determined and are shown in Table 1.

Neutron-probe readings from both tubes were averaged. At specific depths the difference between tubes was generally less than 2 percent of soil volume, but occasionally in the autumn during rewetting differences of up to 5 percent were noted. The limit of accuracy of the probe is considered to be about ± 1 percent (i.e. ± 10 mm per 1 m depth). Readings commenced in July 1971 and continued through April 1974 at intervals relevant to the weather pattern.

Water contents determined by the neutron probe in the 'A' (0–15 cm) and 'AB' (15–30 cm) horizons were calculated on a different basis to other horizons since in the vicinity of the surface the 'sphere of influence' of the neutron probe is not fully submerged and the normal calibration of count ratio to moisture content cannot apply. Empirical relationships were therefore established between probe readings and gravimetric moisture determinations for a range of dates and moisture conditions when both neutron-probe and gravimetric readings were taken simultaneously. With the neutron-probe determination of moisture volume at one specific depth the independent (X) variable, and with the gravimetric determination of moisture in a depth increment the dependent (Y) variable, the linear regressions of Y on X were computed for six depth increments. The regression equations were as follows:

'A' horizon:
(1) 0–7.5 cm $Y'_1 = 1.3791\,X_1 + 0.0784$ $(r = 0.977)$
(2) 7.5–15.0 cm $Y'_2 = 0.8486\,X_2 + 0.0187$ $(r = 0.984)$
(3) 0–15.0 cm $Y'_3 = 0.9094\,X_3 + 0.0320$ $(r = 0.990)$
'AB' horizon:
(4) 15.0–22.5 cm $Y'_4 = 1.0548\,X_4 - 0.0970$ $(r = 0.964)$
(5) 22.5–30.0 cm $Y'_5 = 0.9011\,X_5 - 0.0613$ $(r = 0.924)$
(6) 15.0–30.0 cm $Y'_6 = 0.9869\,X_6 - 0.0827$ $(r = 0.954)$

where Y' is the predicted value of the gravimetrically determined moisture volume fraction (MVF), X_1 is the MVF from a probe centred at 0 cm from the surface, X_2 at 10 cm, X_3 at 7.5 cm, X_4 at 20 cm, X_5 at 25 cm, and X_6 at 22.5 cm, and r is the correlation coefficient.

In the final analysis, equations (3) and (6) were used to predict the mean moisture volume fraction of the 0–15 cm and 15–30 cm depth increments. For the 0–15 cm depth increment, at $X = 0.317$ MVF (mean probe value), the population mean (u) of the estimated gravimetric MVF is 0.320 and 0.95

confidence limits from 0.309 to 0.331; at $X = 0.129$ MVF (driest probe value), $u = 0.149$ (0.126 to 0.172); at $X = 0.434$ MVF (wettest probe value), $u = 0.427$ (0.410 to 0.444). For the 15–30 cm depth increment, at $X = 0.364$ (mean probe value), $u = 0.276$ (0.257 to 0.295); at $X = 0.243$ (driest probe value), $u = 0.157$ (0.117 to 0.197); at $X = 0.462$ (wettest probe value), $u = 0.373$ (0.346 to 0.400).

Although four pedologic horizons are recognized between 0 and 50 cm (Fig. 2), moisture analysis of neutron-probe data has been done for only three depth increments to 50 cm (viz 'A', 'AB' and B_{2g}). This is justified, as the true AB horizon is only intermediate between the A and B horizons, and the B_{1c} occurs only as discontinuous lenses.

Resistance Blocks

Plaster-of-Paris resistance blocks (61 × 34 × 5 mm) were installed at depths chosen to represent each important soil horizon, i.e. at 5, 15, 28, 41, 76 and 122 cm (Fig. 2). At each of the first three depths three blocks were installed by digging shallow pits, hand-carving a horizontal position for the blocks in the pit sides, and carefully repacking the soil material. Each pit contained one block at each of the three depths. At the last three depths, two blocks were installed at each depth, each being installed vertically at the bottom of a 34-mm-diameter auger hole. Insertion was aided by a two-pronged fork attachment to the auger which also served to repack material around the block. The auger hole was then carefully backfilled and packed. Leads from all blocks ran radially just beneath the turf to a centrally placed Toby box located flush with the soil surface. Damage to leads by stock was thus avoided. Readings were taken using a Barlow and Kelly Mk7A a.c. resistance bridge at intervals ranging from a few days to several weeks, depending on circumstances, from December 1970 to April 1974. Conversion from resistance to moisture tension involved calibration of the blocks using the method described by Tanner and Hanks (1952). In all instances the drying limb of the calibration curve was used, as it was considered that the wetting limb applied only transiently during drainage. The tensions were expressed in p*F* units, i.e. the logarithm to base 10 of the moisture tension expressed as centimetres of water head.

RESULTS AND DISCUSSION

Soil Moisture Content – Neutron Probe

Results from the neutron probe are shown in Table 2. The monitored water contents (mm) were computed by summing the products of moisture volume fraction times depth interval, for the relevant horizon depth.

Maximum, minimum and 'datum' values are compared in Table 3 with calculated storage values. The calculated values were determined by integrating and weighting the moisture characteristic data of Table 1*. Maximum probe values are close to the calculated total porosity values, except in the upper horizons where they are less by amounts ranging from 8–18 percent of the pore volume. There may be two reasons for this. Firstly, trapped air prevent the full pore volume from being occupied by water. Romanov (1974) has observed that "even with very slow capillary saturation from below, trapped gas fills 15–21 percent of the pore volume". Secondly, probe estimates of water content in the 0–30-cm range depend on an empirical relationship with gravimetric deter-

TABLE 2 – Water contents (mm) determined by neutron probe. Water contents in this table are expressed as 'gravimetric equivalents.' For the 'A' and 'AB' horizons the water contents are derived from probe versus gravimetric regressions: for all other horizons they are derived from neutron-probe determinations from which has been subtracted a 'bound water' value (see column 5. Table 1). Depth increments used in this table differ only slightly from pedologic horizons recorded in adjacent field pits (see Fig. 2). Note that the B_{1c} horizon is incorporated in the 'AB' and 'B_{2g}'.

Horizon: *Depth (cm):*	*'A'* 0–15	*'AB'* 15–30	*'B_{2g}'* 30–50	*C_x* 50–80	*C* 80–100	*IuB* 100–170	*IuC* 170–190	*2uB* 190–200
Date:								
22 Jul 1971	56	55	71	99	64	232	—	—
7 Sep 1971	57	54	71	97	64	224	68	90
20 Oct 1971	51	49	66	93	61	215	67	89
1 Dec 1971	39	45	69	97	64	227	70	95
12 Jan 1972	39	39	59	93	62	228	70	96
6 Mar 1972	26	28	49	80	58	214	68	89
24 Apr 1972	42	36	52	81	58	214	67	91
14 Jun 1972	66	57	71	97	64	244	73	96
4 Jul 1972	65	56	71	96	64	242	74	99
26 Jul 1972	64	56	71	96	65	242	75	97
4 Aug 1972	65	55	71	96	64	237	74	96
11 Aug 1972	62	54	71	97	65	235	73	96
18 Aug 1972	67	56	73	98	65	243	74	98
27 Sep 1972	58	52	70	98	65	233	74	98
6 Oct 1972	54	48	69	96	65	231	73	96
20 Oct 1972	56	51	70	97	64	231	74	97
5 Dec 1972	41	36	61	96	66	232	72	97
14 Dec 1972	38	35	59	94	65	229	71	96
21 Dec 1972	40	37	60	94	65	233	72	96
8 Jan 1973	36	34	56	90	64	229	70	95
15 Jan 1973	33	33	55	89	64	232	72	96
14 Feb 1973	22	23	43	76	56	215	72	93
1 Mar 1973	23	23	43	74	56	212	70	92
19 Mar 1973	25	26	46	75	56	212	69	92
2 Apr 1973	29	27	46	77	57	213	68	91
19 Apr 1973	31	30	47	76	57	212	67	89
30 Apr 1973	48	41	57	80	57	213	67	89
24 May 1973	61	54	71	95	64	232	71	92
6 Jun 1973	61	53	69	93	62	226	70	90
20 Jun 1973	58	51	69	96	63	222	69	91
16 Jul 1973	57	49	68	94	63	219	67	90
20 Aug 1973	66	55	71	98	65	240	72	95
17 Sep 1973	57	49	69	96	63	226	70	92
24 Sep 1973	58	50	68	95	64	229	71	93
1 Oct 1973	55	48	67	95	64	225	70	93
10 Oct 1973	55	49	68	95	64	228	70	93
2 Nov 1973	67	53	70	98	64	228	71	93
23 Nov 1973	59	51	69	97	64	226	71	93
6 Dec 1973	49	45	68	96	64	229	71	95
20 Dec 1973	35	38	63	95	64	226	72	93
14 Jan 1974	28	28	51	86	62	227	71	93
28 Jan 1974	28	29	50	84	61	228	71	95
25 Feb 1974	32	32	51	82	59	223	71	94
22 Mar 1974	31	31	50	81	59	220	70	94
19 Apr 1974	38	32	50	80	59	218	69	91
2 Aug 1974	68	54	71	97	65	242	71	95

TABLE 3 — Comparison of calculated and measured storage values.

Horizon:	'A'	'AB'	B_{2g}'	C_x	C	1uB	1uC	2uB	Profile	
Depth (cm):	0–15	15–30	30–50	50–80	80–100	100–170	170–190	190–200	0–100	0–220
Calculated storage (mm) *(from Table 1)*										
1) Total porosity (TP):	80	69	79	101	66	241	69	103	395	808
2) 0.05 bar:	63	57	70	97	63	223	64	95	350	732
3) 0.1 bar:	60	55	69	96	63	221	63	95	343	722
4) 15 bar:	27	32	47	66	45	176	50	75	217	518
5) Drainage capacity: (TP–0.1 bar)	20	14	10	5	3	20	6	8	52	86
6) Available water capacity: (0.1–15 bar)	33	23	22	30	18	45	13	20	126	204
Measured storage (mm) *(from Table 2)*										
7) Maximum value:	68	57	73	99	66	244	75	99	363	781
8) Datum value*:	66	54	71	97	64	242	72	95	352	761
9) Minimum value:	22	23	43	74	56	212	67	89	218	586
10) Maximum abstraction: (Datum–min. value)	44	31	28	23	8	30	5	6	134	175

* Datum value is the moisture content taken to represent zero storage opportunity.

minations and are therefore subject to any error in the latter. The small diameter and the high area (kerf) ratio of the cutting head of the gravimetric sampler possibly contributed to disturbance of the samples. In wet conditions particularly this may have resulted in under-estimation of moisture volumes. However, these characteristics of the auger could also increase the possibility of entrance of excess soil, and this would have the opposite effect of increasing the apparent bulk density and therefore the moisture volume.

Minimum probe values in Table 3 are noted to fall below the calculated 15-bar values in the 0–50 cm depths, but not at greater depths. This is discussed later.

An interesting feature of the probe data (Table 2) is the return each winter to a reasonably consistent level. This 'datum' level is a little less than the maximum values recorded, and is considered to represent the 'field capacity' of the site, having been recorded on several occasions at least three days after rain. Reference to the calculated values indicates field capacity for this site to be therefore near the 0.1-bar tension, or slightly less. A field capacity of this order is in accord with the low slope of the site and the low, morphologically inferred, hydraulic conductivity of the subsurface horizons.

The 'datum' level was used to calculate 'storage opportunity' for each observation date. 'Storage opportunity' is the difference between the moisture content on a particular date and the 'datum' moisture content. It is plotted against time in Fig. 3a. The values illustrate the potential of each horizon, and combination of horizons, to absorb rainwater. In the whole profile, storage opportunity reached maxima of 149, 168 and 125 mm in the three summers monitored, and fell to zero each winter.

Relationships between measured and calculated storage values are also illustrated in Fig. 4 where a sequence of moisture profiles from wettest to driest are plotted in relation to the total-porosity and wilting-point values of Table 1. The relationship to total porosity has already been discussed. At the dry extreme, 15-bar (wilting point) values were exceeded to a depth of about 50 cm in the summer of 1973. Resistance-block data (Fig. 3b), less influenced by vertical resolution, suggests depths of 60–70 cm for the same period – a satisfactory agreement. Between the wet and dry extremes, Fig. 4 shows seasonal drying to be most marked in the A and B horizons, with initially only minor moisture changes below 50 cm. However, once the surface horizons approach wilting point, moisture losses do occur in the C_x and lower horizons.

Soil Moisture Tension – Resistance Blocks

Results from the resistance blocks are plotted in Fig. 3b as p*F* isopleths. These lines were interpolated from mean p*F* values derived from resistance blocks at each of the six depths, together with interpretation of wetting-front penetration suggested by daily rainfall records. The data fail to explore the moisture regime at both the wet end of the scale (pF<2.7) and the very dry extreme (pF>4.2). Therefore in this soil where an important part of the moisture regime occurs in

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* Calculated values for the 'A' horizon are based on the 5 9 cm determination; 'AB' from 15 19 and 36-40 cm; B_{2g} from 36-40 cm; C_x from 51-55 and 74-78 cm; C from 74 78 cm; IuB, IuC, 2uB from 119-123 cm.

the low tension range, resistance blocks alone provide data on only part of the overall regime.

The p*F* isopleths for the period September 1971 to July 1974 are shown in Fig. 3b: additional data for the period December 1970 to August 1971 are not shown but were used in the analysis. Fig. 3b shows this soil to be one characterized by two distinct soil-moisture seasons: a 'dry' season extending through the summer months into autumn, and a 'wet' season extending through the winter months into spring. The figure also demonstrates the pattern of the seasonal wetting and drying sequences. Depending on spring (September, October, November) rainfall, seasonal drying may start in September or be delayed through November. December appears to be a month of active drying with wilting point conditions usually commencing in late December or January in the A horizon. However, unusually wet weather in January may delay the onset of drought until as late as mid February. Values for p*F* of 4.2 (wilting point) have been recorded to a depth of 30 cm each year for periods of at least 10 days. In 1973, when summer precipitation was less than that recorded for any year between 1943 and 1969 (Taieri – Invermay climate station), p*F* values of 4.2 were recorded to 70 cm below the surface (mid depth of C_x horizon) and persisted at 40 cm (B_{2g} horizon) for 75 days. Recharge usually commences in March (occasionally April) and profiles approach the wet limit for resistance-block readings (p*F* = 2.7) by early June or, at the latest, August.

Duration of Specific Moisture Conditions

The number of days in which the storage opportunity fell within 25-mm classes is analysed from Fig. 3a in Table 4. Because the values above various horizon boundaries may be useful for different purposes, the data are presented

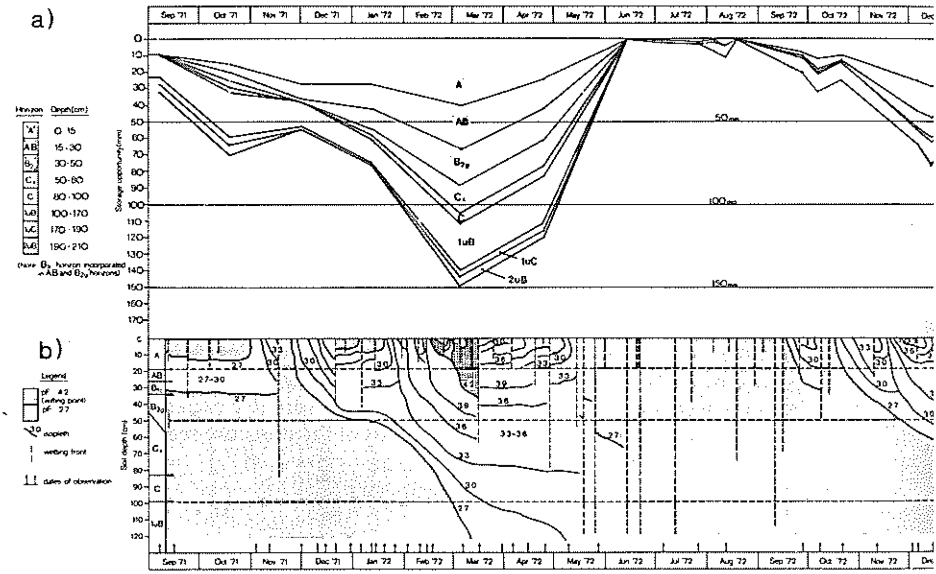


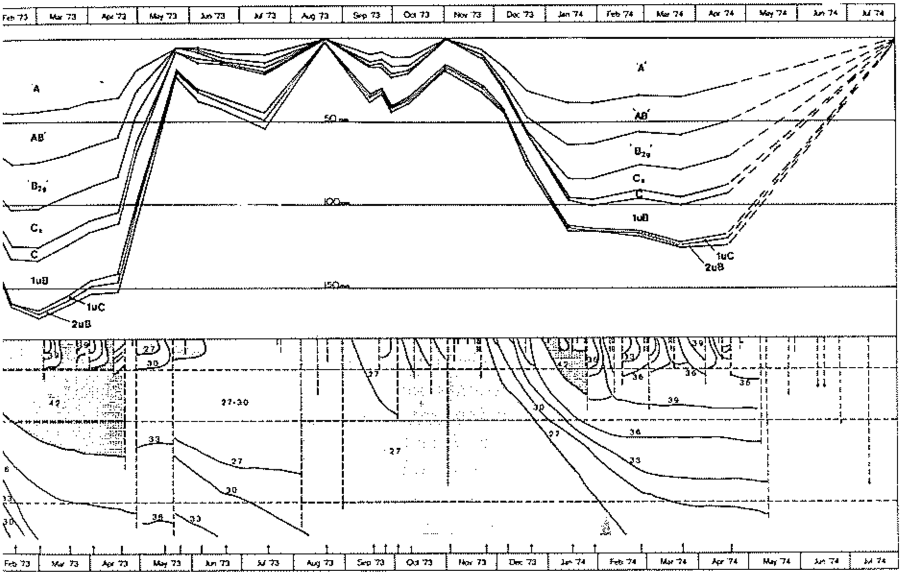
FIG.3 – Soil moisture regime during study period. (a) Storage opportunity calculated from neutron-pr

in various horizon combinations. Data for the 1973–74 year lack the detail for the previous two years since few records were taken in the 1974 winter. Table 4 is based on analysis of the water year, September to August.

The duration of specific moisture conditions for individual horizons is given in Table 5 on a moisture-season basis. Three moisture conditions are analysed. The periods 'drier than 15-bar tension' (Table 5a) and 'wetter than 0.5-bar tension' (Table 5b), were evaluated from the resistance-block data of Fig. 3b. The durations relate to the two general moisture seasons (p$F<2.7$ and p$F>2.7$) that occur each year. Thus the '1973' season in Table 5a refers to wilting-point conditions in January–April 1973, while the '1973' season in Table 5b refers to the period August to December, 1973. A moisture season may be of variable duration, and the date of onset varies from year to year. The distinction between consecutive days (days in a row) and cumulative days (days in a season, not necessarily in a row) for specifying duration of conditions is especially relevant to the A horizon, where small increments of precipitation or drying can break a continuous run.

The number of days when the soil was estimated to be 'wetter than *c*. 0.1-bar tensions' (Table 5c) were assessed from the duration of zero storage opportunity for each horizon (Fig. 3a). The precision of this analysis is limited by the frequency of observations, and some interpretation was of necessity based on contemporary field experience. This was particularly so in the A horizon, where field observation indicated that very wet conditions rarely persisted longer than 10 days except in exceptionally wet periods, lateral movement presumably occurring.

Obviously the information collated during the period of study was fundamentally related to the prevailing weather patterns during that period.



(b) p*F* isopleths interpolated from resistance-block data.

Long-term analyses of climate and water balances at this site will be the subject of further work. but to indicate how precipitation deviated from the normal during the study. seasonal precipitation is related to percentile values in Table 6.

TABLE 6 – Number of years each century when precipitation for season would be less than that recorded. Data based on rainfall percentiles for Taieri–Invermay 1943–69, (N.Z. Meteorological Service, 1973a).

	Summer (Dec-Jan-Feb)	*Autumn (Mar-Apr-May)*	*Winter (Jun-Jul-Aug)*	*Spring (Sep-Oct-Nov)*
1971	60	70	*c.*85	90
1972	30	80	>90	60
1973	<10	*c.*65	40	70
1974	30	30	–	–

Comparison of Methods

Figs. 3a and 3b may be related using the moisture characteristic values detailed in Table 1. Examination reveals an apparent general agreement within the limits of operation of the resistance blocks; moistures contents for specific depths and moisture contents integrated for soil horizons from data in Fig. 3a (neutron probe) suggest moisture tensions that are in general accord with those recorded in Fig. 3b (p*F* isopleths from resistance blocks).

A depth 40 cm below the surface (the centre of the B_{2g} horizon) was selected for further analysis. This was deep enough to be independent of surface effects for the neutron probe, yet was near enough to the surface to experience major seasonal changes of moisture content. For 41 dates from September 1971 to April 1974, p*F* values at 40 cm were taken from resistance-block data. These were converted to moisture contents (using the moisture-content/tension data of Table 1, row 3). and plotted against time (Fig. 5) along with 'corrected' neutron-probe determinations of moisture content where the sphere of influence was centred at 40 cm. The figure illustrates the limited range of the resistance blocks between p*F* values of 2.7 and 4.2, but within this range an acceptable agreement between the resistance-block data and the neutron-probe data is noted.

Extending the comparison from a point depth to a depth increment, moisture contents for the 0–30 cm depths were estimated from resistance-block data and compared in Fig. 6 with moisture contents measured with the neutron probe. This was done for all dates when both measurements had been taken contemporaneously. Estimated moisture contents were obtained from the resistance blocks at 5, 15 and 28 cm by converting tensions to moisture contents through the use of the moisture-characteristic data of Table 1. Where bulk densities were measured on the day of record, they were used to convert the moisture weight fraction to a moisture volume; on all other occasions the bulk densities of Table 1 were used. Moisture contents (mm) were obtained by integrating the moisture volume fraction with depth. The comparison (Fig. 6) indicates the broad relationships between the two methods, specific agreement being restricted by several considerations which include:

1. The restricted range of moisture contents to which resistance blocks are sensitive: a poor correlation at high moisture contents is particularly noticeable.
2. The integration procedure of estimating the 0–30-cm moisture content from a few tensions measured at specific depths, which necessitates interpolation of the moisture-characteristic data.
3. A need for a more accurate assessment of the variability of bulk density, both spatially and from season to season, so that the validity of applying the moisture-characteristic data of Table 1 over all seasons may be tested.

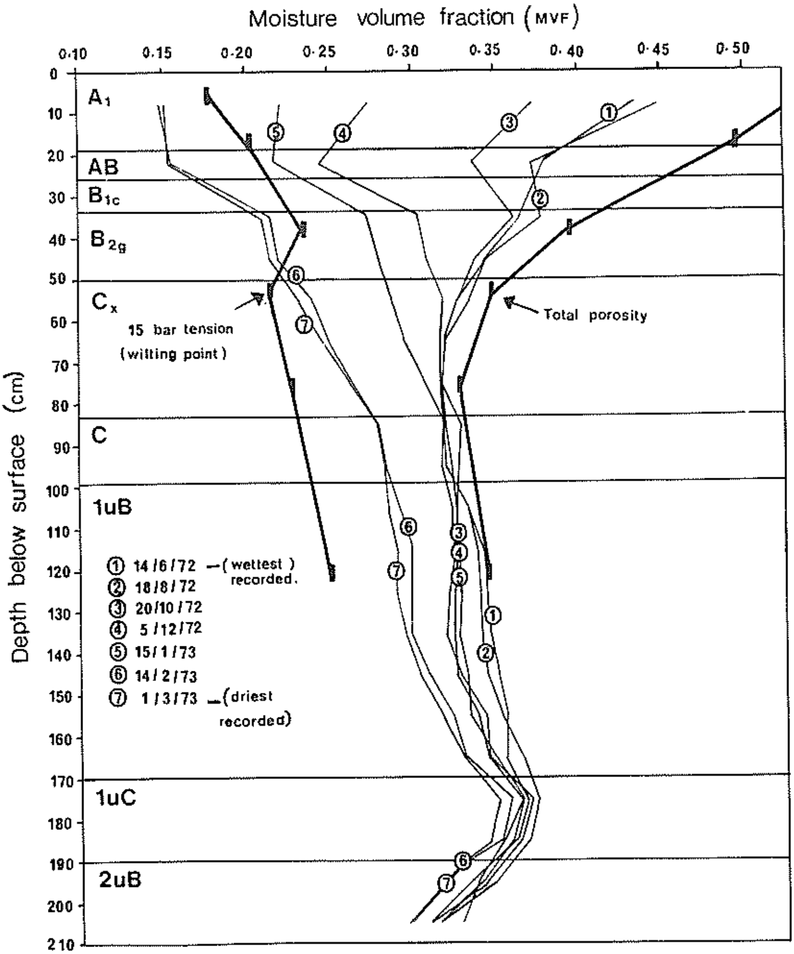


FIG.4 – A drying sequence of moisture profiles from wettest to driest conditions in relation to total porosity and wilting point.

TABLE 4 – Number of days in year when specific horizon combinations had storage opportunities within size classes indicated.

Storage opportunity class (mm)	*Year (Sept–Aug)*	*Horizon (cm)*			
		A *0–15*	*A + B* *0–50*	*A + B + C* *0–100*	*Whole profile* *0–220*
<1	71/72	80	80	80	60
<1	72/73	20	20	20	0
<1	73/74	>10	>10	>10	0?
1–25	71/72	130	60	40	20
1–25	72/73	200	150	150	60
1–25	73/74	<120	<210	*c.*220	*c.*160
26–50	71/72	150	100	100	40
26–50	72/73	140	40	30	110
26–50	73/74	>130	<10	<20	<70
51–75	71/72	–	80	50	120
51–75	72/73	–	60	50	50
51–75	73/74	–	>40	<10	<10
76–100	71/72	–	40	60	20
76–100	72/73	–	70	20	40
76–100	73/74	–	90	>110	<10
101–125	71/72	–	–	30	40
101–125	72/73	–	20	50	10
101–125	73/74	–	–	–	>110
126–150	71/72	–	–	–	60
126–150	72/73	–	–	40	20
126–150	73/74	–	–	–	–
151–175	71/72	–	–	–	–
151–175	72/73	–	–	–	70
151–175	73/74	–	–	–	–

In comparing all methods used in this study, three general conclusions are drawn. Firstly, in comparing neutron-probe data with gravimetric data, allowance must be made for that volume of 'bound' water, or 'water equivalent' still held at 105°C. This volume is monitored by the probe but not by gravimetrics. Secondly, a comparison of resistance-block data with neutron-probe data is limited by the fact that two different properties are being measured. Comparison requires conversion through moisture content–tension relationships, with consequent compounding of errors. Furthermore, resistance-block data refer to specific depths whereas probe values refer to a soil volume. Thirdly, total porosity as determined from dry bulk and particle densities cannot be reliably used as an accurate measure of pore space occupied by water at field saturation. Within these limitations, and given reasonably stable moisture conditions, the methods show satisfactory agreement.

TABLE 5a – Number of days in soil-moisture season when each horizon was at or drier than 15-bar tension (i.e. wilting point, p$F \geqslant 4.2$): resistance-block data.

		Max. consecutive				*Total cumulative*			
Horizon	*Depth (cm)*	*1971*	*1972*	*1973*	*1974*	*1971*	*1972*	*1973*	*1974*
A'	at 10	20	15	40	20	35	20	55	25
AB'	at 30	15	10	85	5	25	10	85	5
B_{2g}	at 40	10	0	75	0	25	0	75	0
	at 60	10	0	50	0	10	0	50	0
[illegible]	at 90	0	0	0	0	0	0	0	0

TABLE 5b – Number of days in soil-moisture season when each horizon was at or wetter than 0.5-bar tension (p$F \leqslant 2.7$): resistance-block data.

		Max. consecutive			*Total cumulative*		
Horizon	*Depth (cm)*	*1971*	*1972*	*1973*	*1971*	*1972*	*1973*
A'	at 10	85	120	35	135	140	75
AB'	at 30	175	160	65	175	160	110
B_{2g}	at 40	185	170	70	185	170	115
	at 60	230	190	150	230	190	150
[illegible]	at 90	255	220	170	255	220	170

TABLE 5c – Number of days in soil-moisture season when each horizon was at or wetter than c.0.1-bar tension (i.e. field capacity, p$F \leqslant 2.0$): neutron-probe data and field observation.

		Max. consecutive		*Total cumulative*	
Horizon	*Depth (cm)*	*1972*	*1973*	*1972*	*1973*
A'	0–15	<10	<10	30	20
AB'	15–30	80	10	80	30
B_{2g}	30–50	140	10	140	30
	50–80	180	60	180	110
[illegible]	80–100	220	170	220	180
uB	100–170	50	10	60	10
uC	170–190	200	30	230	40
uB	190–210	250	10	250	10

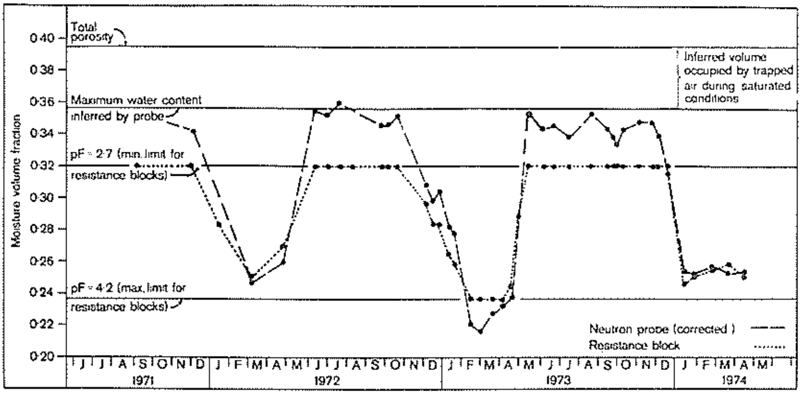


FIG.5 – Comparison of resistance-block and neutron-probe data at 40 cm.

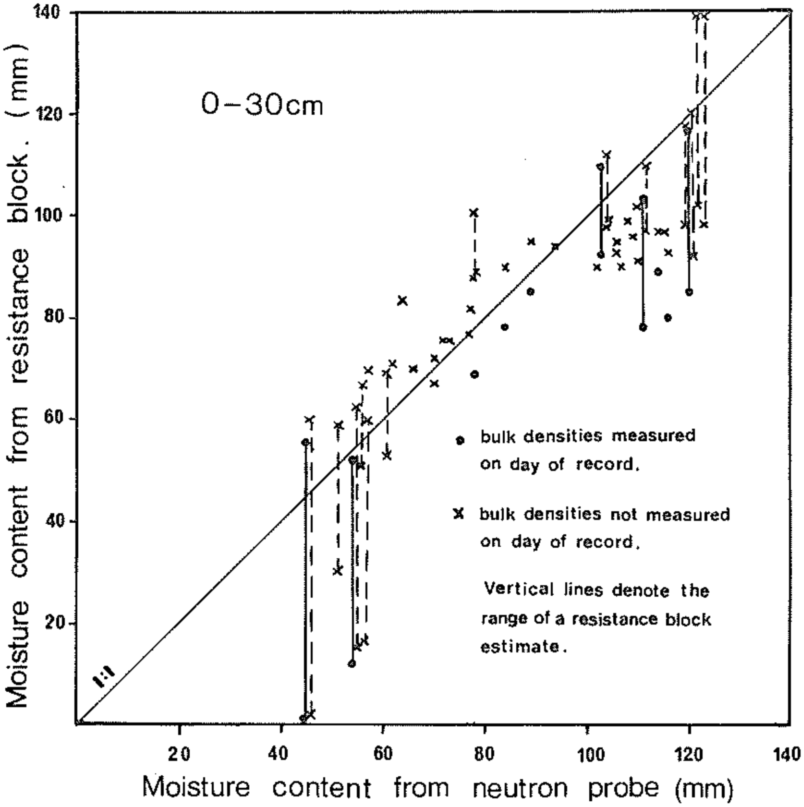


FIG.6 – Comparison of storage estimates in 0–30-cm depth (neutron probe versus resistance block).

CONCLUSIONS

The moisture regime at the Otokia silt loam study site is characterized by two distinct soil-moisture seasons, one dry and the other wet. Their intensity and duration varies depending on weather patterns, but the basic cycle repeats each year.

The dry season, which may extend from December to April, is characterized by a period of wilting-point tensions which, during the study period, extended at least to 30 cm for at least 10 days. In the exceptionally dry summer of 1973, wilting-point tensions extended to a depth of 70 cm and persisted in the C_x horizon for approximately 50 days. In the B_{2g} horizon that year wilting point conditions persisted for 70–80 days. Storage opportunities of more than 50 mm existed each year in the 0–30 cm horizons for 60–100 days and for the A plus B horizons reached a maximum of 100 mm in 1973. In the entire profile (0–220 cm), storage opportunities of 149, 168 and 125 mm were recorded during the three summers of observation.

The wet season, which may extend from May through November, is characterized by tensions at or wetter than p*F* 2.7 for all horizons. Conditions wetter than field capacity (p*F* 2.0) also existed during the two winters for which data were analysed. It is concluded that the C_x horizon imposes important control on vertical movement of moisture and that above this horizon a perched water table can exist for up to 140 days in the B_{2g} horizon, as occurred in the exceptionally wet winter of 1972. While the C_x and upper horizons are at or wetter than field capacity, lower horizons, and especially the luB, may have some storage opportunity.

The data reported in this study are probably unique to both the slope angle and slope position of the particular study site. Extrapolation of the results to other slope situations should be done with caution. While the overall seasonal pattern of the moisture regime may be similar on other sites, future studies should establish particularly the relationships of slope angle and slope position to the frequency and duration of conditions wetter than field capacity in both the A and B horizons.

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