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Natural Environment Research Council

REPORT TO RIVER AND COASTAL ENGINEERING GROUP, MINISTRY OF AGRICULTURE FISHERIES AND FOOD.

Water Regime of River Meadows : Yarnton Mead Case Study
Project AD2

REPORT PREPARED BY CATRIONA M.K. GARDNER

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July 1991

DRAFT

Response to comments on:

Water Regime of River Meadows: Yarnton Mead Case Study,
IH Report to MAFF on Project AD2, July 1991.

Title page. A botanical survey of the plants in the immediate vicinity of the soil water measurement sites could rpobably be arranged for summer 1992. The work would have to be contracted out, preferably to Dr. A. McDonald, or staff from English Nature who have been concerned with Yarnton Mead.

p. 2,3, and 7. Corrections to references have been indicated on an Errata SHeet, see attached.

p. 3. Pixey Mead is located to the other side of the Thames and the map should have indicated so.

p. 8. Evidence of the occurrance of temporary perched water tables was cited in Section 2.3. This presumably is due to the low conductivity of the deeper alluvium. When this occurs, the saturated zone will be located within the alluvium and the water in this zone will be available to the vegetation. Plant uptake, and/or slow drainage mean that the saturated condition is only short lived.

p. 9, 17,25 etc. The information regarding the measurement methods used was placed in an Annex because it was felt that the report would be more accessible to the non-expert if he/she was not faced with all the detail. However it seems from the comments that certain points should also be mentioned in the main text, in particular the definition of L.A.I. used, the fact that the range of tensiometers is limited and that gypsum blocks, used here to measure soil water potential below tensiometer range, are not very accurate. The "partial" nature of the soil water potential data obtained is, to a large extent, unavoidable with existing equipment. Greater staff input to servicing tensiometers would have improved the data somewhat, but was not feasible in the available budget.

p. 10. In 1987, when the tipping bucket gauge was first installed, there were repeated problems with an unreliable logger which unfortunately were not immediately recognised. Thereafter, data was very occasionally lost due to battery problems or the logger not being changed on time so that its memory was exceeded. The automatic weather station failed very occasionally.

p. 13. The Hydra and automatic weather station were only used at Yarnton in 1989 because the equipment became available due to cancellation of another project. The MAFF budget would not have covered the equipment rental or the staff time for data processing that year.

p. 29. The movement of soil water is explained more fully in

Section 4.4.4 but a simple explanation of the concepts of soil water potential gradients and soil water fluxes with diagrams would help the reader.

p. 30. The lowest soil water potentials occurred where there were most roots, due to plant abstraction of soil water. How these low potentials affected individual species is uncertain. Generally -15000 cm water head is regarded as wilting point but that figure may not be appropriate in the context of river meadow species. Some plants had roots to much greater depth which probably were very important in providing their water needs.

p. 32. The spring samples were virtually all "green material" and no separation was made.

p. 37. There is little information available on the effect of temperature on transpiration rates, and what there is mainly pertains to agricultural species. In general the literature suggests that there is little plant growth at air temperatures below 5 C and so below that temperature, transpiration will be minimal. Above about 10 C there seems to be little or no temperature effect. Mean daytime temperatures at Yarnton in 1990 were between 5 and 10 C for about two weeks in April 1990 and thereafter remained above 10 C until the end of October. If the available information on temperature influences is applicable in the Yarnton context where there is a mixed sward, then low temperatures could well have contributed to the reduced transpiration rates measured early in the growing season. Temperature will have had an indirect effect through its influence on plant growth and so the rate of increase of leaf area.

Water Regime of River Meadows: Yarnton Mead Case Study

Errata

Pages 2, 3, and 7	Reference to "NCC, 1989" should read "NCC, 1990".
Page 7	Reference to "McDonald and Hawker, 1989" should read "McDonald and Hawker, 1988".
Page 38	Reference to "Youngs *et al.* 1990" should read "Youngs *et al.* 1989".
Page 60	Reference to publication by Baker should read: "Baker, H. 1937. Alluvial meadows: a comparative study of grazed and mown meadows. J.Ecol., 25:408-420".
	Reference to publication by Burt and Ventner 1988 should read: "Burt, T.P. and Ventner, P. 1988. Annual Summary of Weather at Oxford for 1987, Radcliffe Meteorological Station, School of Geography, University of Oxford.

Executive Summary

1. The report presents the results of an investigation of the water balance and soil water regime at Yarnton Mead. The Mead, an ancient floodplain hay meadow beside the River Thames near Oxford, is part of an SSSI.

2. Water table levels, soil water content and soil water potentials have been monitored to establish the normal range of soil conditions which the plant community experiences. The response of the vegetation to these was recorded by measuring bulk evaporation rates using a Hydra, an instrument designed and developed at the Institute of Hydrology. Rates of influx of water to the unsaturated zone from the groundwater were estimated using the measurements of rainfall, actual evaporation and soil water content change in a simple water balance.

3. Even when the water table was at its lowest position at the soil water measurement sites (deeper than 1.1 m below ground level.) in the dry summer of 1990, soil water potentials at 0.5 m depth and below remained higher than -1000 cm water head. Low potentials, i.e. less than -3000 cm water head, developed between the surface and 0.3 m but generally did not persist for periods exceeding 3 weeks because rainfall events caused potentials to increase rapidly at the surface.

4. In summer, when the soil profile was not draining, an upward gradient of soil water potential developed in the unsaturated zone indicating that upward flow from the groundwater could occur. Estimates of plant use of groundwater indicated that in both 1989 and 1990, uptake accounted for more than 39% of actual evaporation between the hay cut in early July, and the end of September. Daily rates of influx reached 2.5 mm d^{-1} over short periods.

5. Actual evaporation rates were less than the Penman potential demand during most of the spring and summer of 1990, and the summer and early autumn of 1989. The maximum actual evaporation rates recorded were 5.5 mm d^{-1} and 3.9 mm d^{-1} in July 1989 and 1990 respectively; these were amongst the first such direct field measurements of evaporation in Britain. Penman potential evaporation rates occasionaly reached 6 mm d^{-1} in July each year.

6. Measurements in 1990 showed that the leaf area index (LAI) had reached 3 by mid-May. It was reduced to less than 1 by the hay cut and remained so, due to subsequent grazing, until at least early October. It is probable that the LAI is also small through the winter months when there is little growth. The amount of vegetation present must therefore be an important factor in controlling actual evaporation rates at Yarnton Mead because a LAI of about 3 is generally required to obtain potential evaporation rates.

7. Measurements from other shallow water table habitats are required to determine how representative these results are but there is no obvious reason why they should not be generally applicable in the English lowlands.

Contents

1. Introduction

1.1 RESEARCH SCOPE

Flood protection schemes inevitably disturb natural floodplain vegetation and this warrants monitoring and mitigation techniques.

This case study has investigated how the shallow water table/soil/plant system operates in the field at Yarnton Mead. The objectives were:

1. to determine the range of water table and corresponding soil water conditions which the plant community usually experiences;
2. to record the response of the vegetation to these conditions by measuring transpiration rates;
3. to estimate rates of groundwater discharge to the unsaturated zone caused by plant abstraction.

The study provides a baseline under 'normal' conditions to allow models of the system to be evaluated. This is an essential precursor to the use of models to predict the effect of river level changes on floodplain vegetation.

This report presents the results of the field measurements at Yarnton Mead from 1987 up until October 1990.

1.2 BACKGROUND TO THE RESEARCH

Water table level changes in river meadows may occur for various reasons. However, knowledge of the depth by which a water table may change is, alone, insufficient to understand the possible impact on the meadow flora. The effect of such a change depends upon the character of the soil and the tolerance of the plants to fluctuations in soil water conditions.

The principles of water behaviour in shallow water table soils have long been discussed (e.g. Gardner, 1958). As a consequence of necessity, the Dutch in particular have put a lot of effort into the development of models, based upon theoretical soil physics, to simulate water fluxes in these soils (e.g. De Laat, 1985). Much of that work has been conducted in the context of arable cropped soils and, because of inherent practical problems, there has been little field verification of the models.

In Britain a much smaller proportion of land is underlain by a shallow water table, but much of this is of high agricultural and/or ecological value. River channel changes for flood protection or navigational purposes may affect the water level in the river and hence the groundwater level in the adjacent flood plain. This in turn is likely to alter the water regime of the soil and hence the ecological balance of meadows.

This study has focussed on Yarnton Mead, an ancient hay meadow located to the north-west of Oxford, on the flood plain of the River Thames. The Mead is part of a site of Special Scientific Interest (SSSI) designated because of its flora, fauna and management history. The Institute was initially involved in the Yarnton area through a contract to produce a groundwater model to simulate the water table level modifications that could occur in Yarnton and adjacent meads, due to proposed de-watering associated with a nearby gravel extraction scheme. The gravel to be extracted is part of a formation which underlies much of the flood plain; it is covered by alluvium of variable depth, being 0.3 to 3.0 m over Yarnton Mead. The gravel is permeable and flow within it is essentially horizontal. Evidently without use of protection measures, pumping in the gravel workings could have significant effects upon soil water conditions in the Mead.

One immediate difficulty for the groundwater modellers was to establish how much discharge occurred from the shallow aquifer as a result of plant uptake, and how to represent this in the model. Soil water measurement sites were installed on the flood plain near Yarnton, including two on the Mead, specifically to obtain data to assist the groundwater modelling. However, it was also apparent that there was very little information available to use in making any assessment of the possible impact of water table level modifications on soil water conditions and vegetation at Yarnton Mead, or other sites. Hence the work described herein. Since 1987 the project has been partially funded by MAFF (River and Flood Protection). The level of MAFF funding increased substantially in 1990.

The gravel extraction scheme started in 1989 and could have an impact on Yarnton Mead in 1991 or 1992. The Institute is still retained to provide expertise on groundwater matters to the gravel contractors. The Nature Conservancy Council initiated a long term botanical monitoring programme on the Mead in 1988 (NCC, 1989). There has been collaboration between the project described here and these others, to mutual benefit.

2. Yarnton Mead

2.1 SETTING

Yarnton Mead, and Pixey Mead, which is adjacent, have been designated as an SSSI, for together they form one of the largest examples of flower rich neutral grasslands in lowland England. In addition they have a documented history which demonstrates that their management, of a hay cut and aftermath grazing, has remained unchanged for some 1000 years (NCC, 1989).

Yarnton Mead, which is about 40 ha in extent, is bounded by the Thames to the south and ditches along its western and much of its northern boundary (Fig. 1). The Mead surface is almost flat. Linear depressions of 0.2 to 0.3 m amplitude occur, and some are believed to be due to the presence of old stream channels which have since been infilled with alluvium. Aerial photography and remote sensing imagery suggest the presence of a system of braided channels trending north-east south-west across the Mead, which coincides with some of the depressions.

2.2 SEDIMENTOLOGY

The Mead is part of the broad Thames flood plain which is formed of Holocene clayey river alluvium overlying gravels which are interpreted as braided river deposits (Bryant, 1983). Radiocarbon dating evidence in the Upper Thames Valley suggests the alluvium to have been deposited during the Iron Age, or more recently, whilst the gravels are Pleistocene (Robinson and Lanbrick, 1984). These were deposited upon the impermeable Jurassic Oxford Clay. The gravels vary in depth from about 3 m to 6 m. The depth of alluvium is also variable, from less than 0.3 m to about 4 m. Borehole evidence, from the Mead itself and nearby, suggests a trend of decreasing alluvium depth from south-east to north-west. However hand augering in the vicinity of the soil water measurement sites has shown that over distances of less than 10 m, the alluvium depth can change from 0.5 m to 1.0 m. Evidently in some places there is much small scale variability in the alluvium depth.

The base of the alluvium is well defined. However, immediately below it, evidence from augering, soil pits and boreholes has shown that there is very often a layer 0.1 to 0.5 m deep of loamy sand, sand, or gravel with a loamy matrix. Probably some of the finer (loamy) material is alluvium which has been washed into the gravels. The sand has been identified as one of the many facies which form the gravel deposit (Dixon, pers. comm.).

Briggs *et al.* (1985) have suggested that the alluvium is an overbank deposit of a meandering stream. It is predominantly clay occasionally grading to silty clay texture. The clay is unconsolidated and exhibits marked shrinkage and cracking when it dries out, features which influence the soils developed upon it.

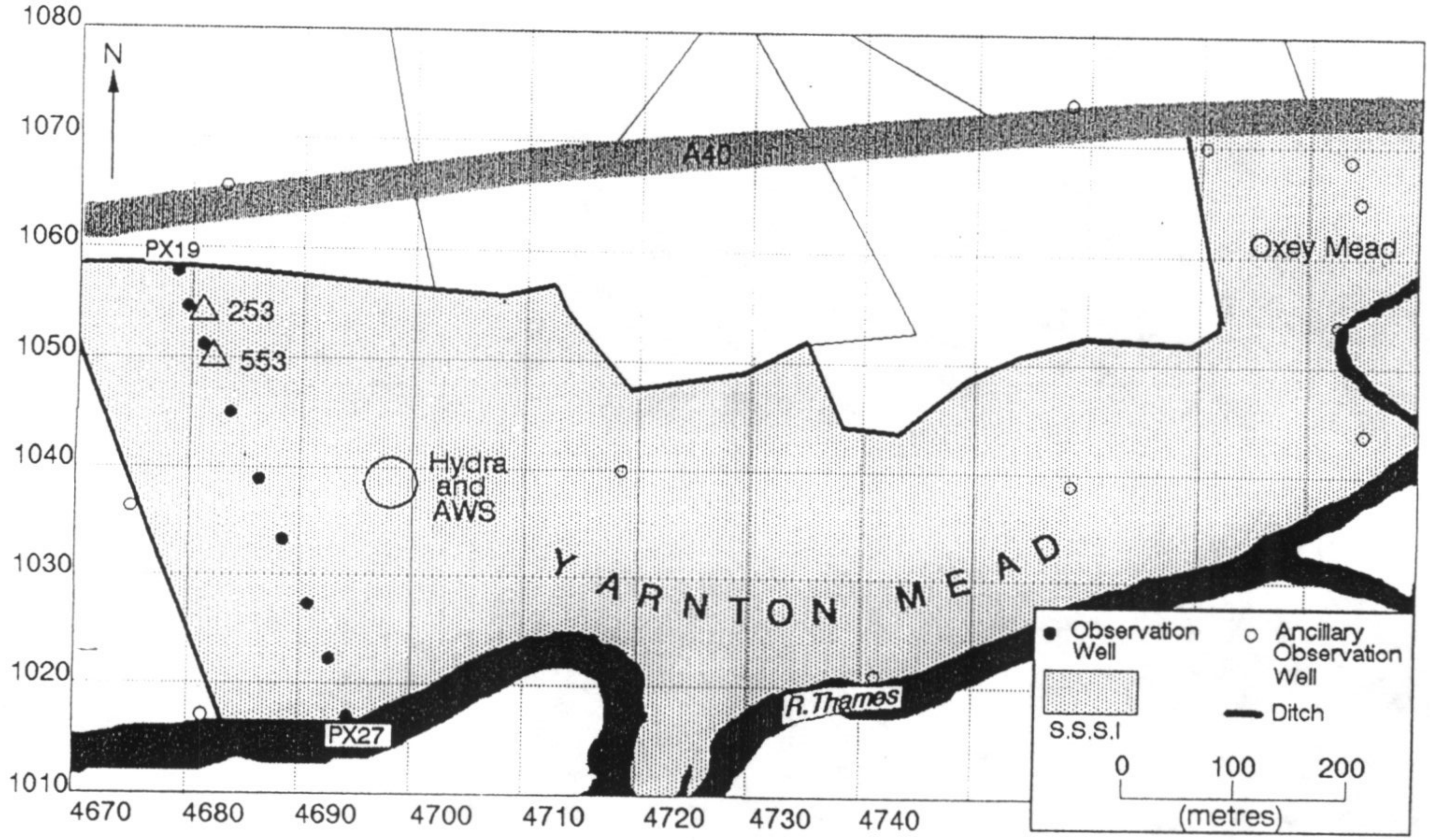


Figure 1 Yarnton Mead showing location of instrumentation

2.3 SOILS

The variable sedimentology and topography (and hence depth to water table) of Yarnton Mead give rise to several soil types. There has been no comprehensive survey of the Mead soils. However there have been several opportunities to observe the soils in the vicinity of the soil water measurement sites (Fig. 1) by hand augering survey, when cores were taken for root counts, and when pits were excavated to take cores for laboratory measurements. The soil profile descriptions are presented in Appendix A.

The soils about the sites belong to the Fladbury Series or variants of it. The Fladbury Series are pelo-vertic-alluvial gley soils developed in clayey alluvium (Jarvis *et al.,* 1979). It is only distinguishable from the more calcareous Thames Series by the absence of calcium carbonate above 0.4 m. Where the base of the alluvium is less than 0.8 m deep, the soils are akin to those of the Carswell Series described by Jarvis (1973). Two variants have been observed at Yarnton: the first is clayey over calcareous gravel and the second clayey over sand with gravel below.

The soil at site 253 is of the Fladbury Series, whilst at 553 it is a Carswell soil. Both have stoneless well structured clay surface horizons (A) merging to grey clay with strong mottles indicative of temporary anaerobic conditions. The boundary to the gravel/sand is usually sharp.

Above about 0.3 m the clay has a well developed granular or sub-angular blocky structure becoming coarser and prismatic with depth. Below, the structure weakens and the clay is massive. Its consistency is quite plastic if wet. On drying the massive clay shrinks and cracks into prismatic structures. The shrinkage of these montmorillonitic clays is considerable. In places during summer a polygonal pattern of cracks develops at the soil surface with some cracks of up to 20 mm wide and 100 mm deep.

The degree of mottling is variable. However, in several profiles, between about 0.3 and 0.6 m, a paler grey mottled horizon has been observed over a browner mottled horizon. This coloration could be a reflection of the parent material, but this explanation seems unlikely. It is interpreted as evidence that temporary perched water tables occur in some of these soils. Soil water potentials at another soil water measurement site, 153 (which was located near the middle of the Mead and operational from August 1984 to August 1987), occasionally indicated saturation at shallow depths, consistent with the presence of a perched water table. A profile pit adjacent to 153 also exhibited the coloration described above.

The presence of roots in the profile was noted when the soils were described; a few were commonly observed at about 0.6 m. The results of root counts made on soil cores are presented in Figure 2. Evidently some roots of certain species extend to, and below, the water table in an average summer. It is not known which species are so deep rooting. Also, there is no evidence to indicate whether the perennial species develop a new set of roots each year, or use the same ones year to year, and if the latter, when and to what extent they are responsible for the plants' water supply.

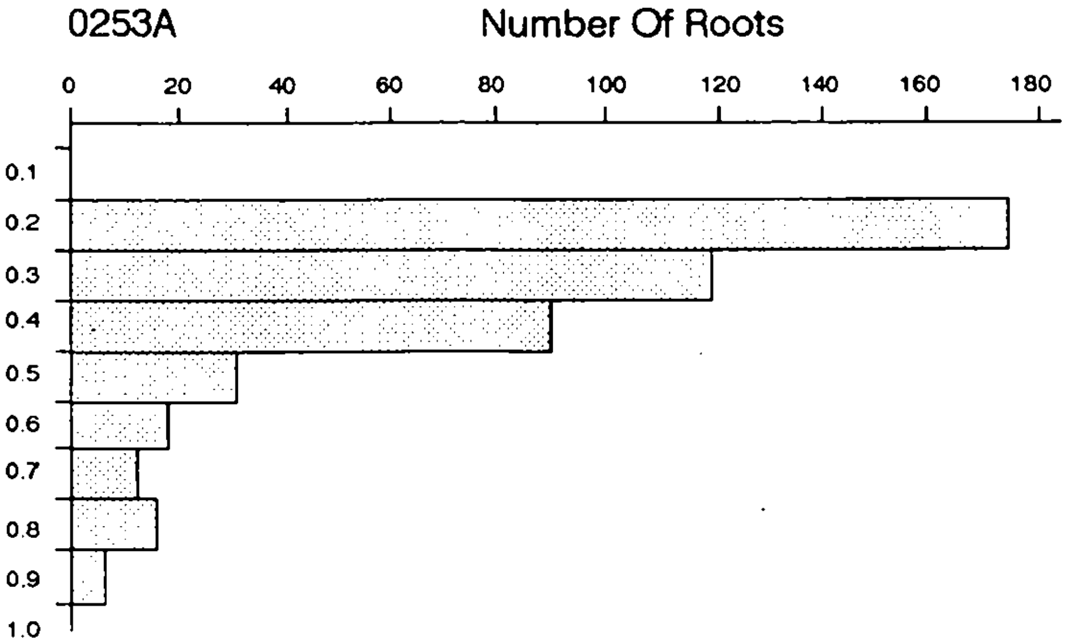


Figure 2 Results of root counts on 1 m soil cores

2.4 VEGETATION

Yarnton Mead can be described simply as a species rich hay meadow but across the Mead there is considerable diversity. The first botanical record for Yarnton was provided by Baker (1937) in a survey of Yarnton, Oxey and Pixey Meads. He noted 69 species in total. Baker emphasised the importance of three particular species to the character of the Meads :

- *Sanguisorba officinalis* (Great Burnet) which was abundant and often dominant in the drier parts but rare elsewhere

- *Chrysanthemum leucanthemum* (Moon Daisy) which was rare where the Burnet was dense but also only occurred in the dry areas;

- *Filipendula ulmasia* (Meadow Sweet) which was abundant in the wetter parts and depressions.

Baker's survey was part of a comparative study of hay meads and Port Meadow in Oxford, which has always been grazed by cattle and ponies. The different management gave rise to significant differences in the respective floras. It is noteworthy that until about 25 years ago, Yarnton Mead would always have been cattle grazed after the hay cut. However, for practical reasons, sheep have been brought to graze there in recent years and may have caused botanical changes.

In 1988 the the Nature Conservancy Council instigated a botanical monitoring project at Yarnton Mead (NCC, 1989). The first year's data have been described by McDonald and Hawker (1989) who report some 70 different species of vascular plants excluding grasses but including rushes and sedges. Several plant associations were recognised in addition to those distinguished by Baker (1937).

In the vicinity of the soil water measurement sites, and along the well transect (Fig. 1), three different plant communities, which correspond broadly to those described by Baker (1937), were noted in this study :

1. In the area around the soil water measurement sites *Sanguisorba* was very prevalent and extended to between wells PX22 and PX23.

2. The transect crosses three topographic depressions. These were characterised by the dominance of grasses and the presence, in the two northernmost, of *Carex acutiformis* (Lesser Pond Sedge), and in the southern one the presence of *Juncus* species (Rush) and *Phragmites* (Common Reed) also grows strongly along the river's edge.

3. Between these lower lying areas, the vegetation includes some *Sanguisorba* but it is not dominant. *Chrysanthemum leucanthemum* and many other herbs are also present.

3. Measurements

The field work at Yarnton was undertaken with the kind permission of the Yarnton Meadsmen and their agents, and with the approval of the NCC. The amount of instrumentation was kept to a minimum in order to limit damage to the habitat. Also, activities other than routine monitoring, were restricted in the weeks before the hay cut to prevent trampling of the hay crop. The detail of the methods referred to below is provided in Appendices B and C.

The focus of the soil water measurements since 1987 has been on the drier parts of the Mead, where the water table is deeper and so more extreme soil water conditions are likely to occur. Two soil water monitoring sites were installed in the northwest corner of the Mead where the alluvium is shallower. At one site, 253, the alluvium/gravel boundary is at about 1 m depth; at site 553 it is at 0.6 m depth. It was anticipated that when the water table fell into the underlying gravels, and the uppermost gravel drained, a hydraulic discontinuity could develop in the drained gravel, preventing upward movement of water from the groundwater. If that were to occur, the plants would be dependant upon the soil water held within the alluvium which might not be sufficient for their needs.

Much of the equipment at 253 was originally installed in the spring of 1985. It was supplemented in September 1987, at which time site 553 was established. Soil water content change was measured by the neutron probe method (Appendix B.1) and soil water potential by means of mercury manometer tensiometers and in 1990, gypsum resistance blocks in addition (Appendix B.2). A tipping bucket raingauge was located mid-way between the sites.

A transect of 9 wells numbered PX 19 to PX 27 was installed in September 1988, to monitor water table levels across the western end of the Mead (Appendix B.3). The transect is aligned north-south and passes through the soil water measurement sites, from the boundary ditch to the river. From September 1987, the Mead was usually visited weekly to conduct the various measurements and service instruments. During summer 1990 the frequency was increased to twice per week.

To obtain further information about the hydraulic properties of the Mead soil, laboratory measurements of unsaturated conductivity (Appendix B.5) and soil water retention properties (Gardner and Lumadjeng, 1988) were conducted on undisturbed soil cores.

Bulk actual evaporation rates were measured directly using a Hydra, an eddy-correlation system developed at the Institute of Hydrology (Shuttleworth *et al.*, 1988). The instrument and its use are described in the Institute leaflet included as Appendix C. The equipment provides daily real time data but experienced operation and data quality control is required to exclude errors introduced due for example, to the presence of moisture on the sensors. The large flat expanse of Yarnton Mead and its relatively homogeneous form of vegetation mean that there was no difficulty in satisfying the Hydra's requirements of an undisturbed upwind fetch of 200 m to 400 m or greater, for vegetation of this character (Gash, 1986). The instrument was located at the western end of the Mead such that there was an open fetch of 250 m or greater in all directions (Fig. 1).

An Automatic Weather Station (Strangeways, 1972) was installed adjacent to the Hydra. Both were operational from July to November in 1989, and from April onwards in 1990.

The variations in the actual evaporation measurements obtained in summer 1989 suggested that the quantity of vegetation present pre- and post the hay cut, might be an important controlling factor. Accordingly in 1990 the amount of vegetation present was monitored by making leaf area measurements on five occasions and determining the leaf area index (LAI) (Appendix B.4).

4. Results and discussion

4.1 WEATHER

4.1.1 Meteorological data

On-site meteorological data were available for the periods July to October 1989 inclusive, and March to December 1990 inclusive, when the Automatic Weather Station was on the Mead. At other times, daily rainfall measurements were available from the on-site tipping bucket gauge, and measurements from the Radcliffe Meteorological Station, maintained by the University of Oxford, were used to compute daily Penman potential evaporation values. When, for various reasons, there was no rainfall data from the Mead gauges, data from the Radcliffe Station were substituted. This was necessary on several occasions in 1987 but only very occasionally thereafter.

4.1.2 Rainfall

Figure 3 shows the monthly distribution of rainfall measured on the Mead over the four years 1987 to 1990; the annual totals were :

1987	643 mm*	*Data from Radcliffe Station, Oxford
1988	602 mm	
1989	541 mm	
1990	443 mm	

It is appropriate to consider these data in relation to measurements made at the Radcliffe Station because of the long data record there; the rainfall record begins in 1767 and other measurements began in 1881. The rainfall distribution at Yarnton was similar to that in the city, except for occasional localised storms, and the annual totals are within 8% of one another. In 1988 the catch at Yarnton was slightly greater; in other years the converse occurred. Table 1 shows the annual totals of rainfall, rain days (i.e. days when 0.2 mm or more fell) and bright sunshine hours, and the mean daily air temperature recorded in Oxford with differences from the long term mean values.

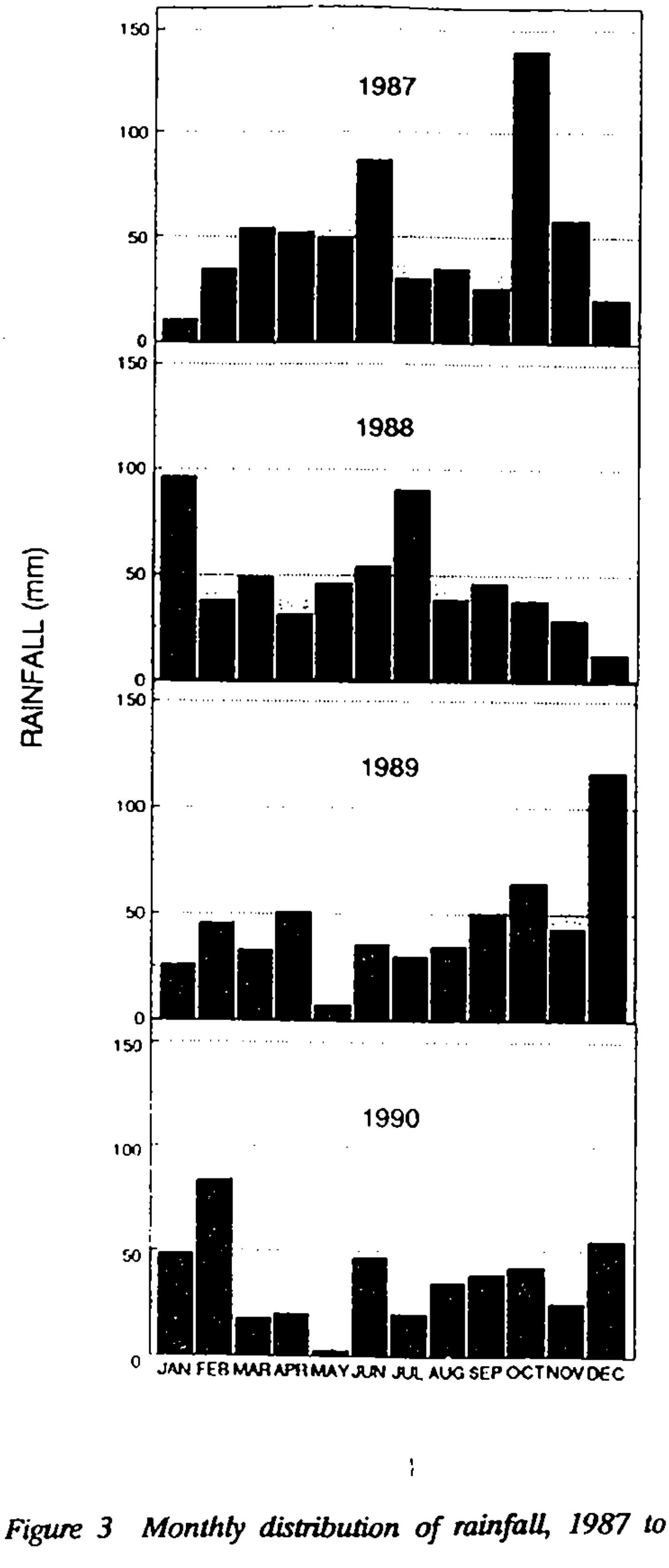


Figure 3 Monthly distribution of rainfall, 1987 to 1990

Table 7 Annual weather statistics from the Radcliffe Meteorological Station, Oxford (Burt and Ventner 1988, 1989; Burt and Nightingale 1990; Burt and Munro 1991)

	1987		1988		1989		1990	
	a	b	a	b	a	b	a	b
RAINFALL mm	593	-49	571	-71	598	-44	473	-169
RAIN DAYS $\geq$ 0.2 mm d^{-1}	167		162		138		135	
BRIGHT SUNSHINE HOURS	1373	-118	1402	-89	1868	+377	1876	+385
MEAN DAILY AIR TEMPERATURE °C	9.4	-0.1	9.9	+0.4	11.1	+1.6	11.1	+1.6

a = total
b = difference from long term average

In terms of annual rainfall, the three years 1987, 1988 and 1989, were similar and slightly drier than average. The difference between the number of rain days and sunshine hours recorded in 1989 and in the preceding years gives a better indication of the droughtiness of the summer and autumn of 1989; the number of rain days was reduced by about 15% and the number of sunshine hours increased by approximately 27%.

The rainfall total for 1989 would have been significantly lower than the long term mean but for wet weather in December which caused very extensive flooding at Yarnton; from 20th December much of the Mead was inundated for about 8 days. 1990 was the 12th driest year since records began at Oxford (Burt and Munro, 1991) although very wet weather in February caused further flooding which persisted for about 16 days.

4.1.3 Potential evaporation

The daily 0900 hour records of sunshine hours, maximum and minimum air temperature, relative humidity (derived from the wet bulb measurement) and wind run at 22 m height at the Radcliffe Station were used to compute daily estimates of potential evaporation. A computer program which adjusts the windrun to 2 m height and uses the original Penman equation (Penman 1948) was used for these calculations. These estimates were compared with those derived from the AWS data for July to October 1989 and April to December 1990 inclusive (Table 2). The AWS records hourly average air temperature and wet bulb depression, wind run at 2 m height, and net radiation. These measurements are used to compute daily Penman potential evaporation values (Roberts 1989). The data are thus considerably more refined than the Radcliffe daily measurements.

Table 2 Comparison of monthly totals of potential evaporation

	1989 AWS mm	1989 Radcliffe mm	1989 % Difference	1990 AWS mm	1990 Radcliffe mm	1990 % Difference
APRIL	-	-		71.4	77.4	8
MAY	-	-		104.1	107.2	3
JUNE	-	-		79.1	104.1	13
JULY	130.6	140.9	8	127.9	133.7	5
AUGUST	117.3	117.3	0	112.6	121.9	8
SEPTEMBER	64.9	69.4	7	72.7	69.7	-4
OCTOBER	37.9	38.3	1	43.3	40.2	-7
NOVEMBER	-	-		18.4	13.3	-28
DECEMBER	-	-		14.9	11.7	-21

The difference in summer 1989 was 5%, the AWS estimate being smaller. Over the 9 month period April to December 1990, the Radcliffe estimate was also found to be larger than that from the AWS, by 6%. In summer the difference was greater than in 1989 but this was balanced by higher evaporation estimates calculated for Yarnton from October onwards. Differences of this order were not unexpected given that two sites and different data inputs were being considered and so slightly different calculation procedures, were utilised. The Radcliffe data were therefore considered to be an acceptable substitute for the on-site measurements at Yarnton for those periods when these were not available.

Table 3 Annual potential evaporation estimates, and monthly mean of daily potential evaporation estimates, April - September, for 1987 - 1990. Data obtained using AWS estimate where possible. (MORECS estimate for grid square 149).

ANNUAL TOTAL PE mm	1987	1988	1989	1990
AWS and Radcliffe estimate	658a	674a	729	746
MORECS estimate	547	559	650	671

MONTHLY	APRIL	2.46	2.23	2.08	2.38
MEAN	MAY	3.05	3.09	3.93	3.36
DAILY	JUNE	3.26	3.31	4.37	2.73
PE	JULY	3.74	3.43	4.21	4.00
mm d^{-1}	AUGUST	3.08	3.28	3.78	3.63
	SEPTEMBER	2.18	2.09	2.16	2.42

a = all figures derived using Radcliffe data

Table 3 shows the annual totals of potential evaporation for each year. The estimated evaporative demand in 1989 and 1990 was 12 to 15% greater than in each of the preceding years. In June and July 1989, the potential evaporation averaged more than 4.0 mm d^{-1}, much greater than at the same time in either 1987 or 1988. In 1990, the lower mean daily rate of 2.7 mm d^{-1} in June arose because there were 12 rain days in that month.

4.2 WATER TABLE REGIME

Figure 4 shows the fluctuation in water table depth at the soil water measurement sites from early May 1987 until the end of 1990. The Figure shows the data measured at dipwells PX20 and PX21 (i.e. the two adjacent to the soil water measurement sites) after September 1988, when the wells were installed. The data for the earlier period were estimated from tensiometer soil water potential measurements at site 253. The tensiometer estimates of water table depth are subject to an error of about ±0.03 m.

The contrast between the spring and summer, i.e. May to August inclusive, water table depths of 1989 and 1990, compared with the earlier two years is apparent. In 1987 the water table fluctuated about 0.75 m in the spring, then fell to 0.9 m briefly in August, remained at about 0.85 m through September before rising steadily in October. During spring and summer 1988 the water table fluctuated about 0.7 m depth, although the very wet July caused it to rise to 0.55 m temporarily.

1989 and 1990 were similar in that in both years the water table fell progressively after flooding in January, to reach 1.05 m by the end of June. The level declined further in 1989 to reach a maximum depth of more than 1.1 m in August. In 1990, the water table stayed low for longer than in the previous year, though the maximum depth was less than in 1989.

The character of the intervening winters also differs. Whilst in winter 1987/88, and 1988/89 the water table rose only briefly above 0.4 m, in winter 1989/90, it remained above that level for more than two months.

The measurements from the dip well transect (Fig. 5) illustrate how the autumn rise of the water table and its fall in spring and summer is synchronous across the Mead. The elevation O.D. of the water table decreases away from the river. This is consistent with other evidence of recharge to the groundwater from the river and consequent flow away from it (Dixon *et al.*, 1990). The spring-summer change in elevation increases with distance from the river. However the below ground depth of the water table depends also on topography. It is clear from Figure 5 that the soil water measurement sites are located in one of the drier parts of the Mead.

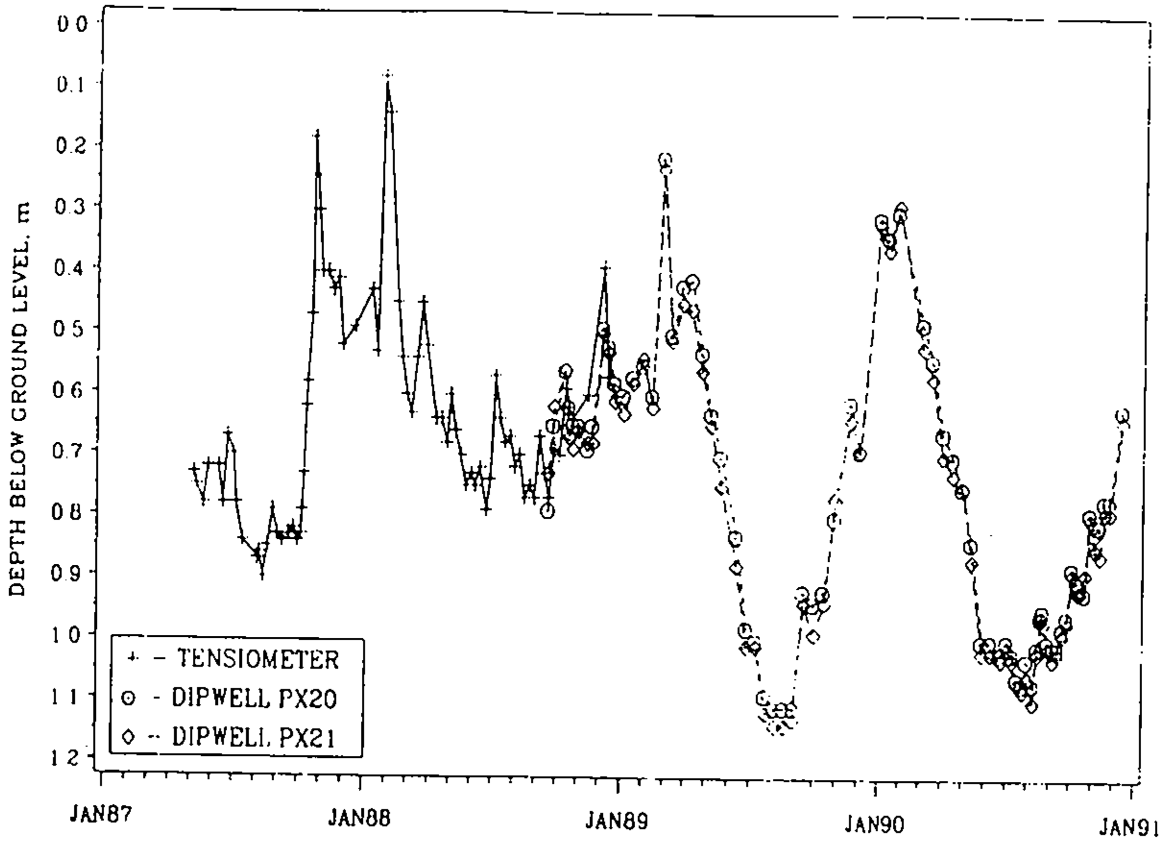


Figure 4 Water table depth at the soil water measurement sites

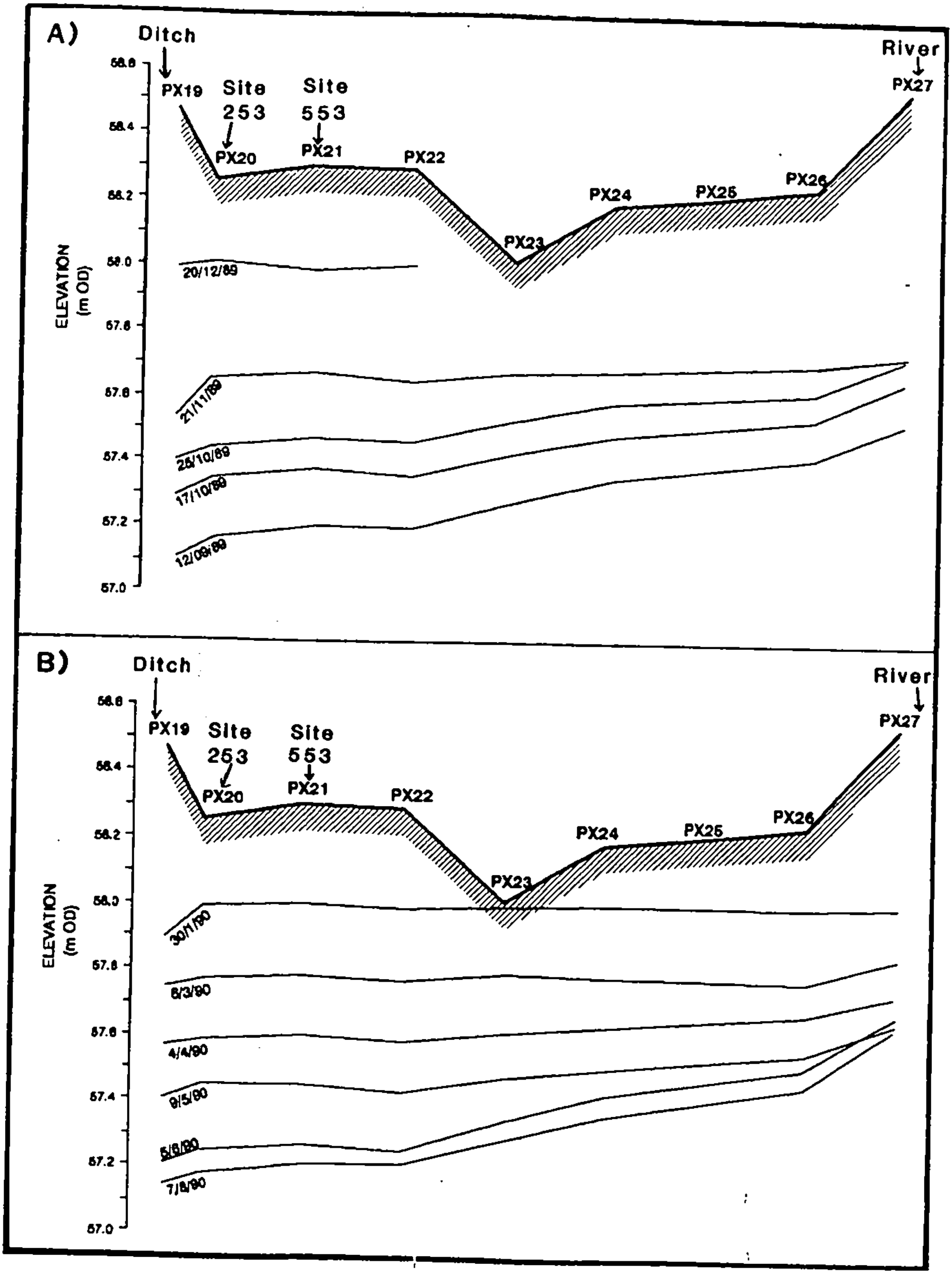


Figure 5 Water table depth measured along the well transect : a. in autumn 1989; b. in spring 1990

4.3 SOIL HYDRAULIC PROPERTIES

The field measured soil water content and tensiometer potential data have been combined in Figure 6 to show the water retention characteristics for the field soils at high potentials i.e. greater than - 800 cm. The spread in the data for any one site and depth may arise in part due to measurement error but is mainly a reflection of hysteresis: the data combine both measurements made as the soils dried out, and as they wetted up in 1990.

The figures illustrate the marked contrast between the alluvium and the underlying gravel. The volumetric water content of the gravel declines rapidly at pressure potentials of between 0 and -100 cm whereas in the alluvium water content changes much less over the range 0 - 800 cm.

The results of the unsaturated conductivity measurements (Fig. 7) indicated that close to saturation, the conductivity of the gravels as represented by Core 253c, is in the region of 340 cm d^{-1} (Appendix B.5), an order of magnitude greater than that of the alluvium, 30 cm d^{-1}. It was only possible to obtain measurements over a very limited range of pressure potential, 0 to -25 cm water head. Within that range the conductivity of the gravel core fell rapidly with the falling pressure potential as the larger pores emptied, to values comparable with those of the alluvium examples. The form of the water retention curve indicates that the unsaturated conductivity of the gravel probably continues to decline more rapidly than that of the alluvium at lower pressure potentials.

4.4 SOIL WATER REGIME

4.4.1 Soil water content

The sequence of water content profiles measured as the sites wetted up in autumn 1987 (Fig. 8) demonstrates the effect of the position of the gravel/alluvium boundary upon soil water content as the water table moved from the gravel into the alluvium of site 553. Figure 9 shows the reverse situation as the water table fell in spring 1990. Data from the individual access tubes are presented to illustrate the range of measurements obtained within each site.

The sequence 30th September to 21st October 1987 includes the driest soil conditions that year, and almost the wettest when the water table rose to 0.17 m at the sites. (At that time measurements were made at 0.1 and 0.2 m then at 0.2 m intervals to the bottom of each access tube.) In terms of range of water content, both the sites behaved similarly at 0.1 and 0.2 m depth. However at the deeper alluvium site, 253, the change in volumetric water content was less than 0.025 at and below 0.4 m. At tube 0553, where the alluvium was shallowest, the saturated water content of the gravel at 0.6 m, immediately below the alluvium exceeded 0.6. This contrasts with a drained water content of about 0.3.

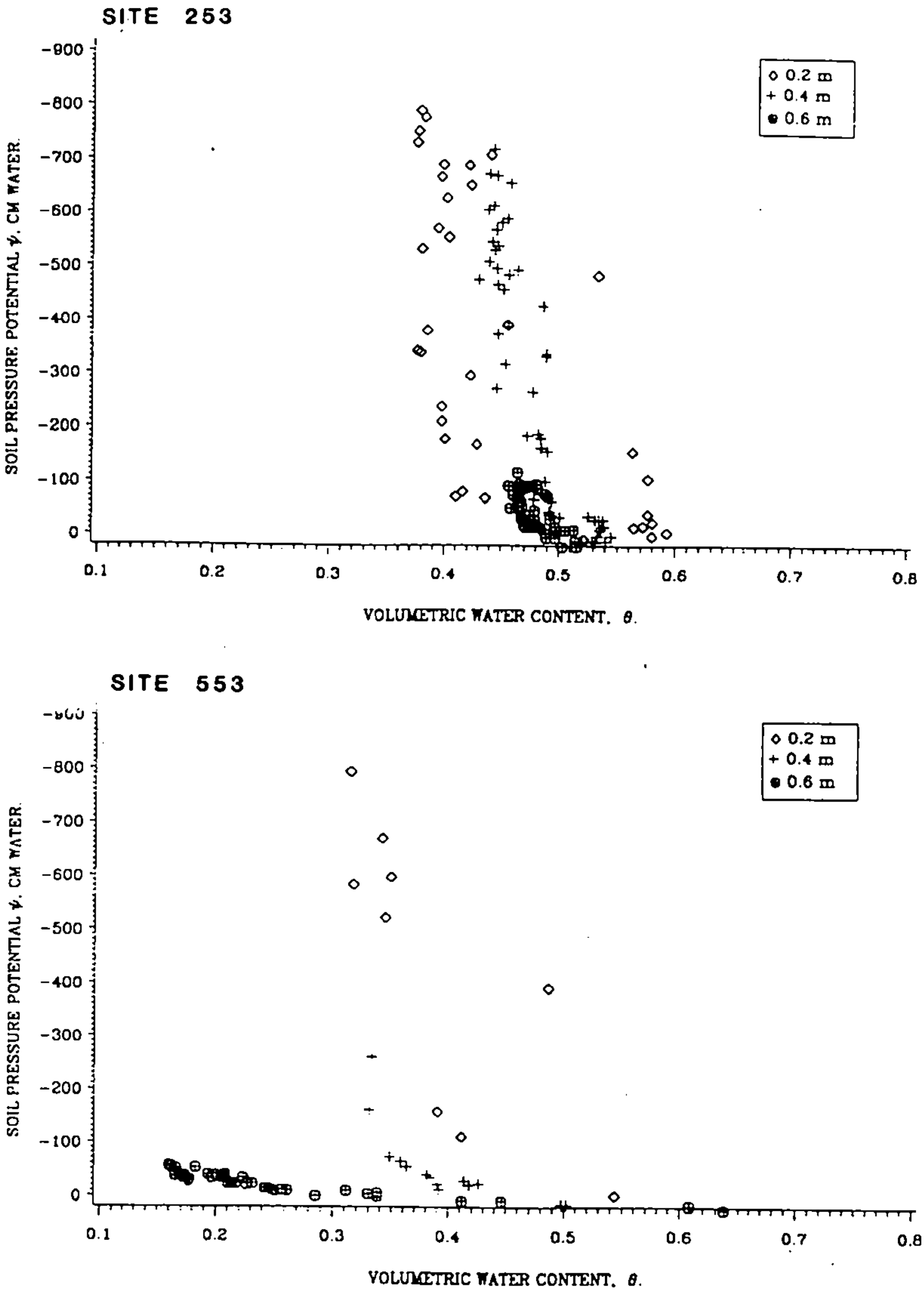


Figure 6 Field measurements of soil water retention at 0.2, 0.4 and 0.6 m for sites 253 and 553. Data for greater depths are not shown because the range of potential there was small

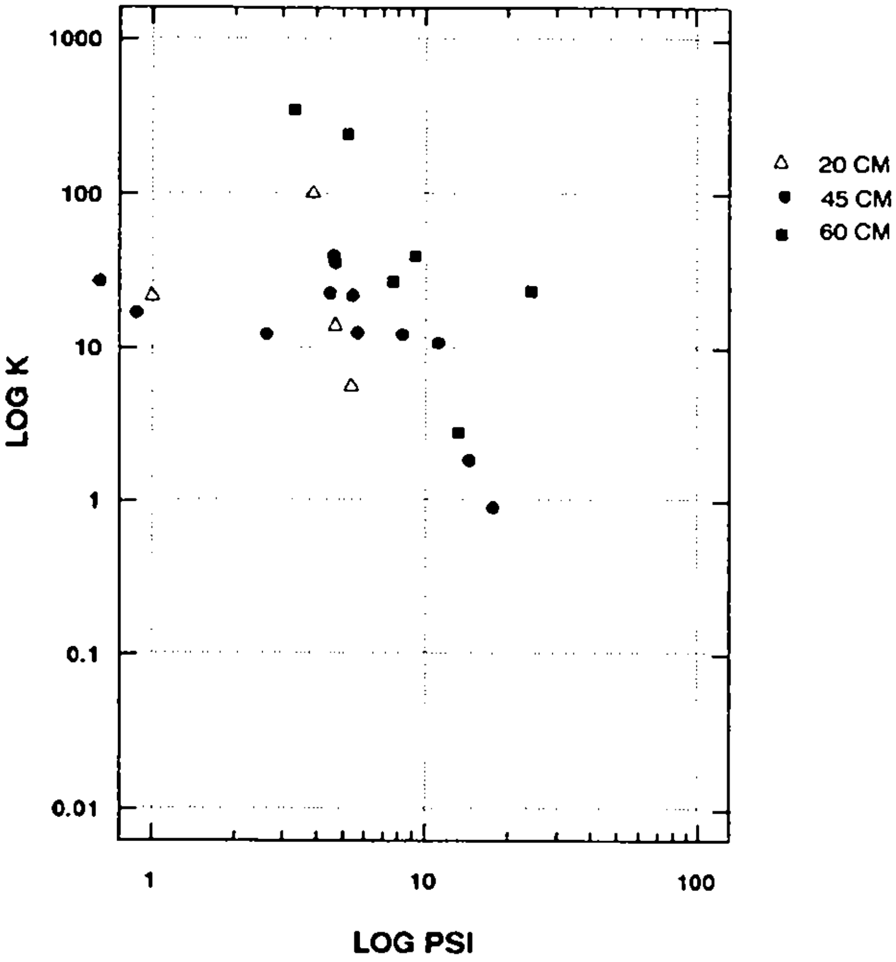


Figure 7 Unsaturated conductivity measured on undisturbed cores taken from adjacent to site 253

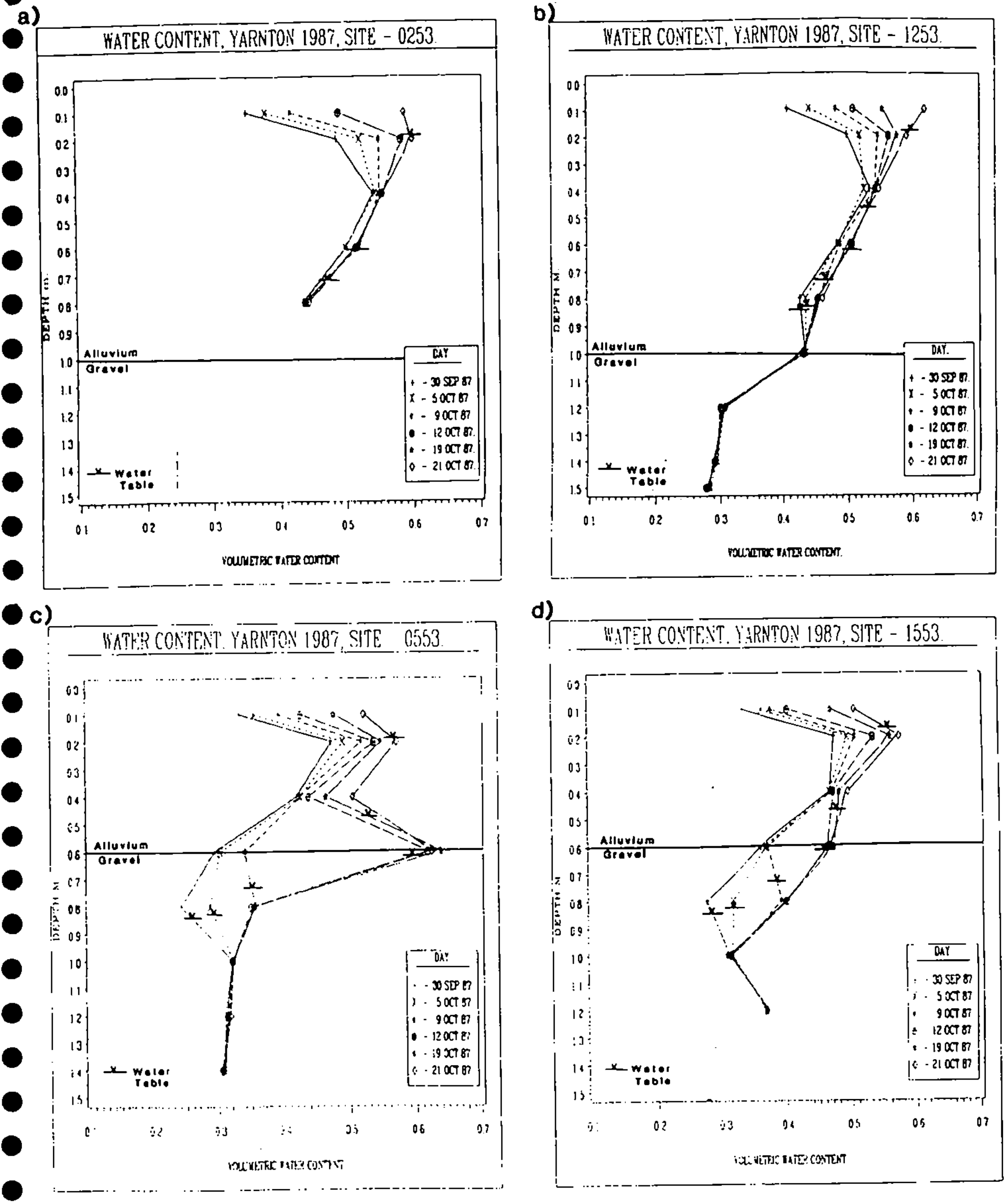


Figure 8 *Water content profiles measured between 30th September and 21st October 1987 at 253 (a and b) and 553 (c and d)*

The spring/summer water content profile sequence (Fig. 9) also illustrates the large change which occurs as the water table falls from the alluvium into the gravels at site 553. Another notable feature is that between 5th June and 14th August the water content of the 553 profiles decreased at all depths to a greater extent than at 253. Below 0.7 m the decrease reflects adjustment to the falling water table but in the upper part of the profile arises from plant abstraction.

The calibrations used to convert the neutron probe count rates to volumetric water contents are not site specific and so caution is required in using the data to obtain absolute water content values. However, with respect to water content change, the errors so introduced are probably very small (Bell, 1987). In homogeneous soil, the neutron probe responds to the water content of a sphere of soil around it, the size of which increases, from about 0.2 m diameter, with decreasing water content. Probe measurements are therefore influenced by the presence of boundaries in the soil, (including the water table) which may be some distance from the measurement point. The shape of the water content profiles in the figures will therefore be rather smoother than was actually the case in the field soil.

Time series of volumetric water content measurements from September 1987 to December 1990 (Fig. 10) show the changes that occurred at 0.6 m and above i.e. where most of the plant roots are located. The two sites behaved very similarly at 0.2 m depth during much of the first two years of measurement (Fig. 10a). In summer 1989 and 1990 it is apparent that the soil at 0.2 m depth at 553 was a little drier than at 253. The trend for 553 to be drier also occurred in summer 1988 but not to nearly such a great extent.

At 0.4 m depth, (Fig. 10b) differences in absolute water content are apparent between the sites at all times. However the changes at each site are synchronous and of a similar order. This picture contrasts with that at 0.6 m depth (Fig. 10c). At 253 the range of variation at 0.6 m, even in summers 1989 and 1990, was less than 0.1. At 553 the range and frequency of water content change was much greater at 0.6 m depth i.e. at the top of the gravel; the water content continued to decline after changes at this depth at 253 had almost ceased.

4.4.2 Soil water potential

Units of cm water head, rather than the S.I. unit of kPa are used in this discussion to express soil water potentials, for convenience. By definition the total hydraulic potential at the water table then numerically equals the depth of the water table in cm. The position of the water table can be determined from these figures by deducting the gravity potential component from the total hydraulic potential to obtain the pressure potential; the pressure potential equals zero at the water table.

Tensiometer measurements

Figure 11 shows sequences of potential profiles measured at both sites using tensiometers between 30th September 1987 and 21st October 1987 i.e.

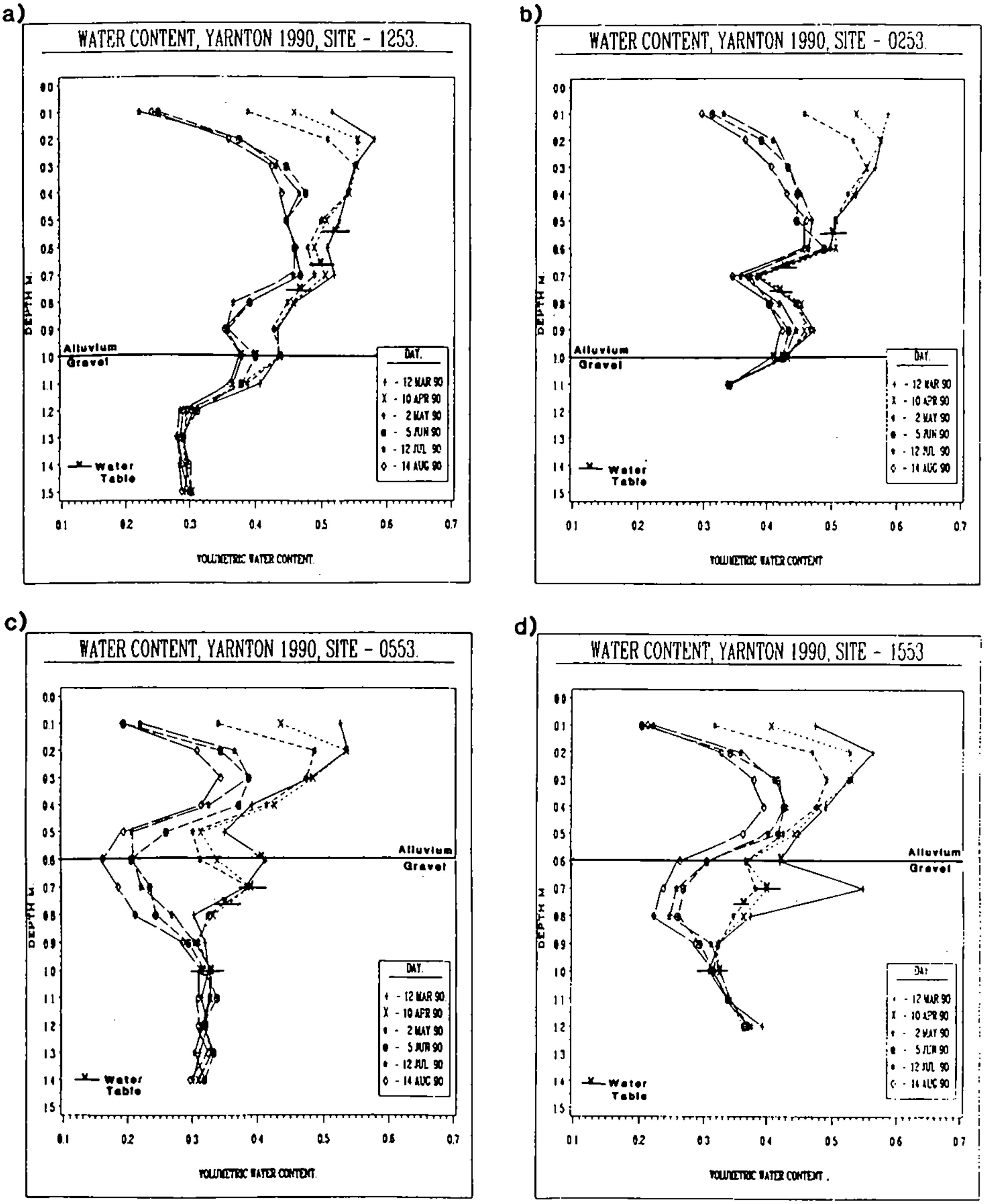


Figure 9 Water content profiles measured between 12th March and 14th August 1990 at 253 (a and b) and 553 (c and d)

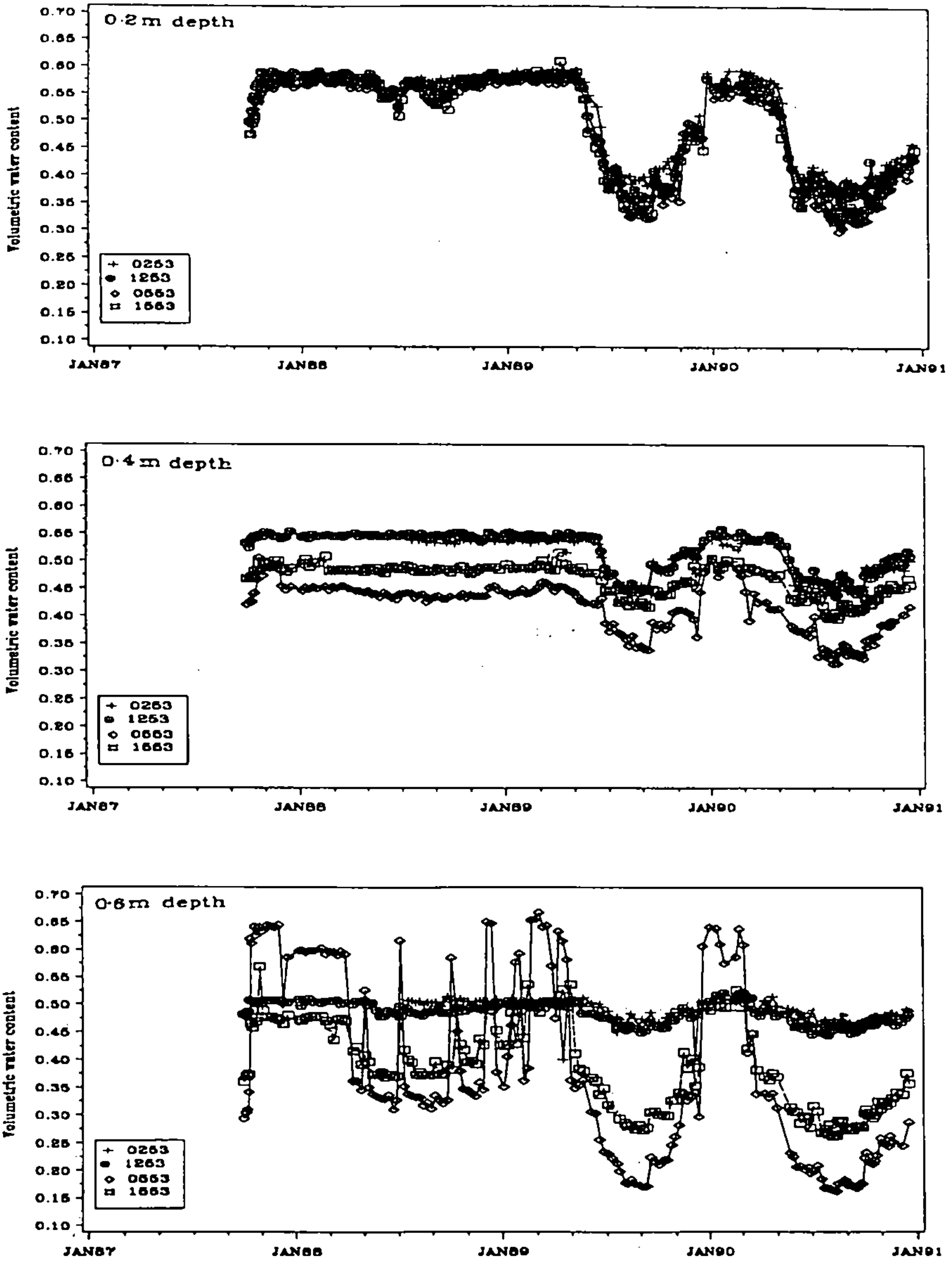


Figure 10 Time series of change in volumetric water content measured at 0.2, 0.4 and 0.6 m depth

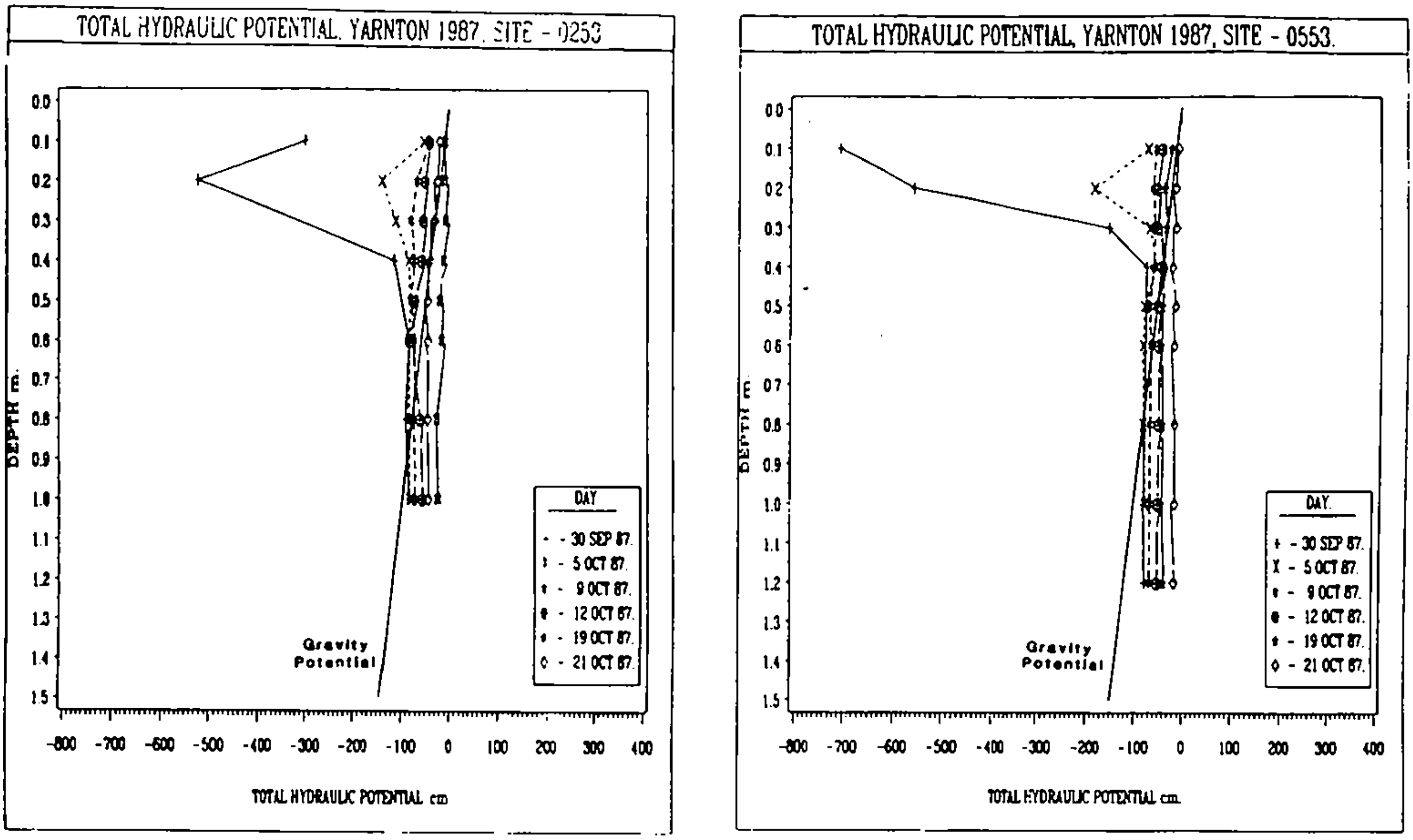


Figure 11 Soil water potential measured between 30th September and 21st October 1987

corresponding to the water content profiles presented in Figure 8. The data show that on September 30th, at the end of the dry period that year, total hydraulic potentials in the surface horizons remained within tensiometer range i.e. greater than -850 cm water head. At 0.6 m and below, the potential gradient was zero showing that the total potential at each depth was in equilibrium with the position of the water table.

There was an upward potential gradient at both sites from higher potentials close to the water table to lower potentials near the soil surface. There was therefore the possibility of an upward flow of water from the water table towards the plant roots - the rate of any such flux would depend upon the conductivity of the intervening soil, and the potential gradient.

The 10.6 mm of rain that fell between September 30th and October 5th caused an increase in potential as well as water content (Fig. 8). By October 9th at 253 the potentials in the surface layer had increased further and exceeded those below so that a downward potential gradient was introduced. This will have resulted in drainage through the profile to the water table. The potential profiles retained this form as further rainfall occurred, and the water table rose until 21st October when the soil was nearly saturated.

At 553 on October 9th there was a much smaller potential gradient, indicating that the profile had drained to come close to equilibrium with the water table. As the water table level rose between 9th and 21st October, potentials in the 553 profile adjusted rapidly to its new position despite additional rainfalls.

Figures 12 illustrates sequences of potential profiles as the Mead soils dried out through the spring and summer of 1990. In March at both sites, potentials at all depths, except 0.1 m at 553, were in equilibrium with the soil water table at 0.57 m. By April 10th, soil water extraction by plants had caused potentials at 0.2 m and above to decrease. There was also a decline in potentials below but probably due to the 0.11 m fall of the water table. A similar adjustment occurred between that date and 2nd May during which time the water table fell by a further 0.15 m to 0.82 m b.g.l. However plant abstraction of water caused potentials at 0.4 m and above to fall further in this zone. The uppermost tensiometers failed as potentials fell below -850 cm water head.

This pattern of declining potentials due to plant abstraction of water in the upper part of the profile, and to the falling water table level below, continued through the summer at both sites. However, the sequences of potential profiles (Fig. 12) were selected to illustrate the overall trend in the data and simplify the true situation by omitting occasions when rainfall wetted the upper part of the profile causing potentials to rise there. At 0.4 m the tensiometers operated intermittently. Above this depth they functioned occasionally after rainfall; this depended on the timing of tensiometer servicing after rainfall events. The intermittent nature of the data from these shallow depths makes it difficult to interpret sensibly beyond recognition of the fact that potentials there could fluctuate rapidly in response to rainfall and rise temporarily into tensiometer range.

The potentials at 0.5 m and below never fell below tensiometer range at either site. The time series in Figure 13 illustrates how at 0.5 m depth and

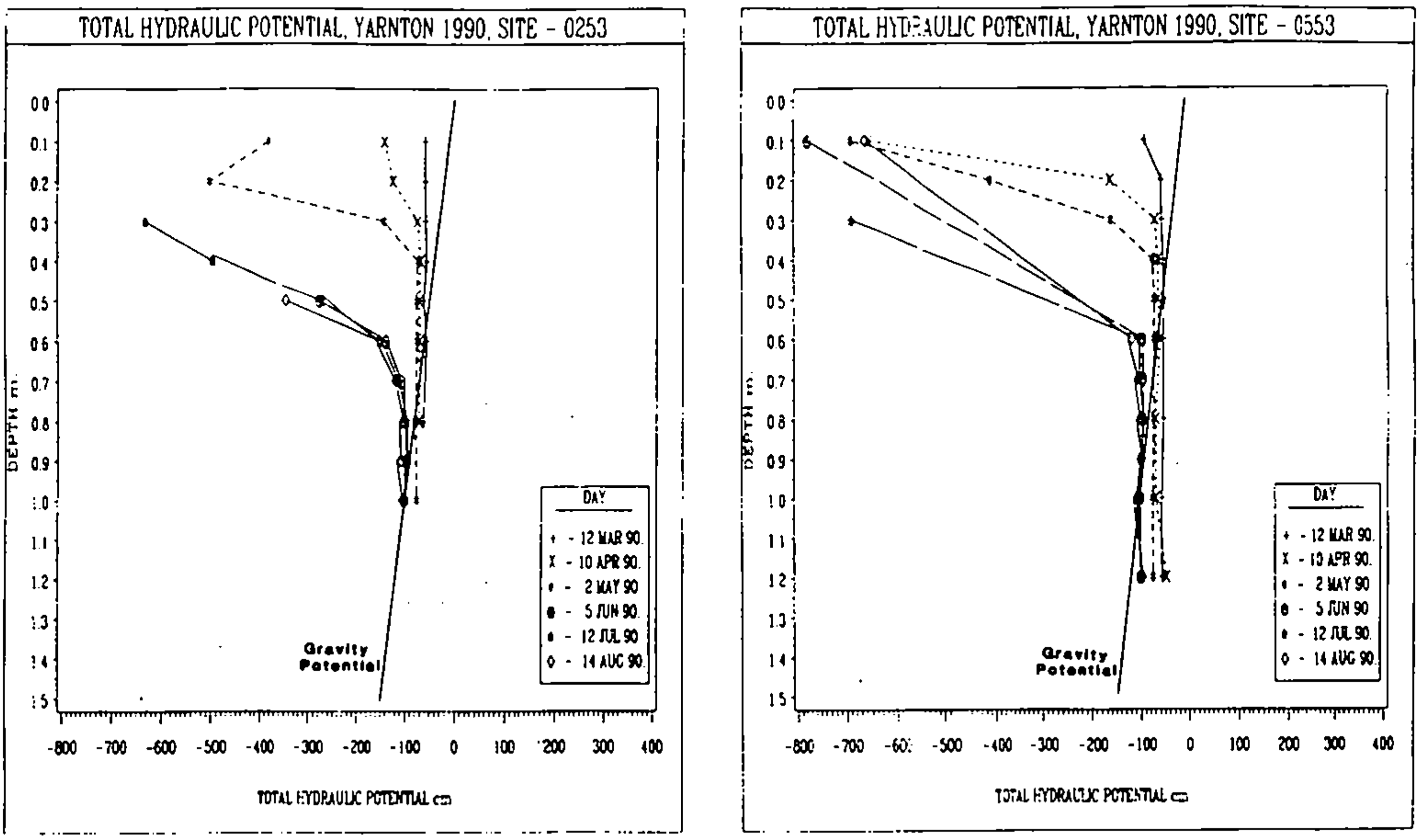


Figure 12 Soil water potential profiles measured between 12th March and 14th August 1990.

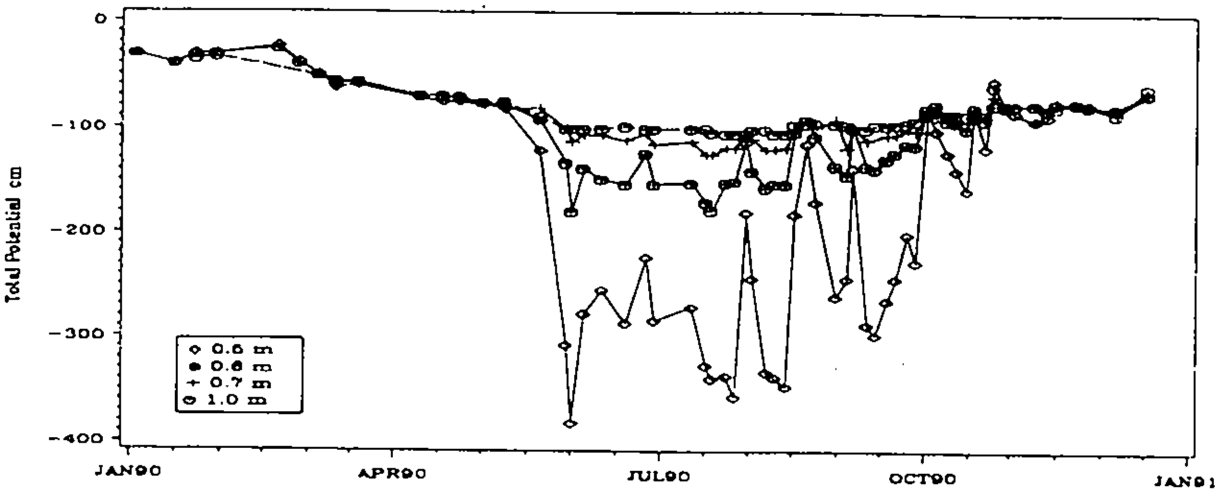


Figure 13 Time series of soil water potential measured at 0.5 m and below, at site 253

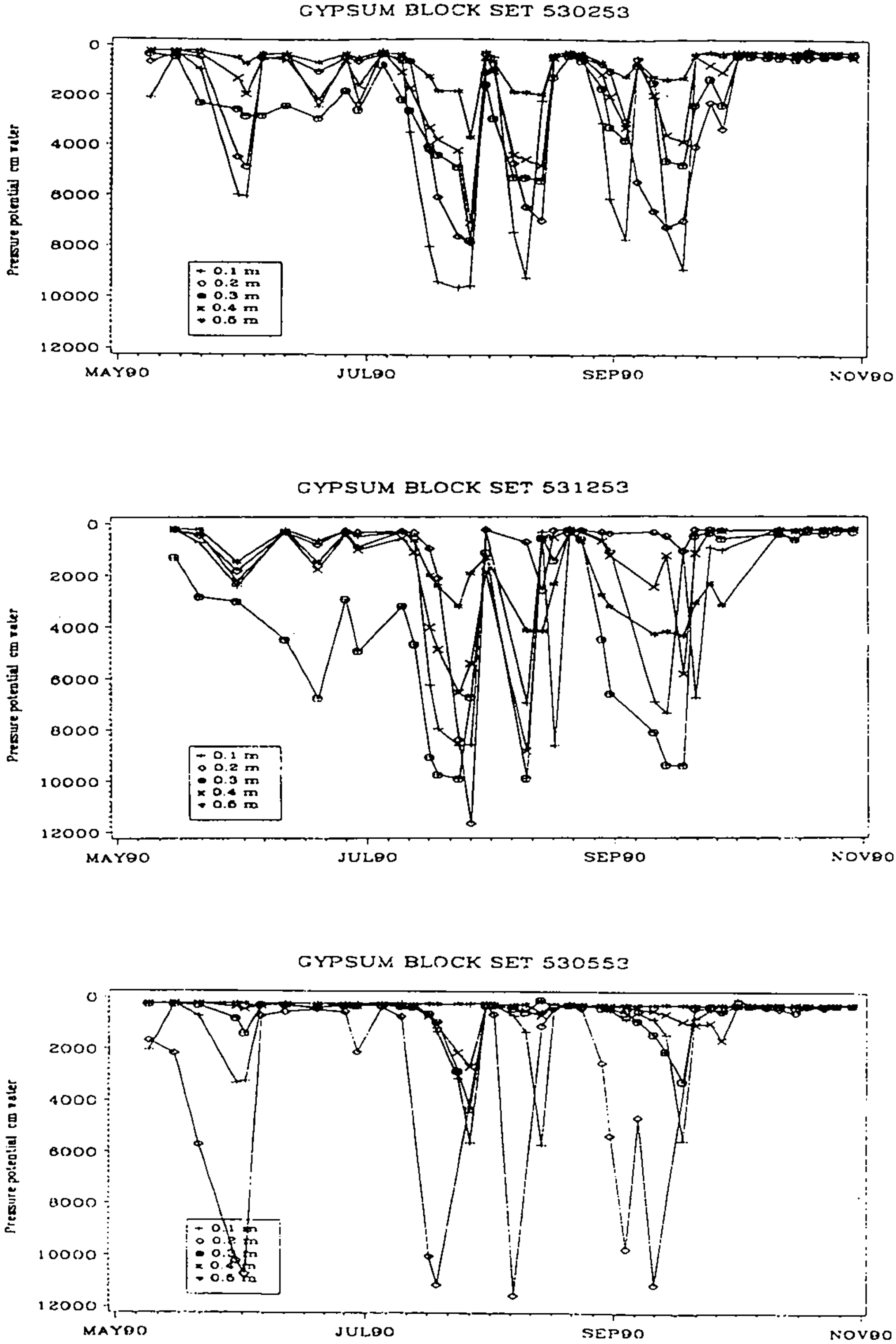


Figure 14 Time series of gypsum block measured potentials at 253 and 553

below, the position of the water table influenced the soil water potential at 253. The temporary increases in potential reflect soil wetting after rainfall. The pattern was similar for site 553 except that potentials above the water table remained higher at these depths, than at 253. Except after rainfall, the evidence always showed that there was a zone where potentials were in equilibrium with the water table, above which was an upward potential gradient from the water table and so the possibility of an upward flux of water towards the roots and soil surface.

The sequences of tensiometer-measured soil water potential profiles are characteristic of those obtained in 1989 as the soils wetted and dried. Throughout summer 1988 potentials remained much higher due to the frequent rainfalls and higher water table conditions. Even the uppermost tensiometers functioned almost all summer showing that potentials rarely fell below -850 cm in the surface soil.

Gypsum resistance block measurements

Figure 14 shows the gypsum resistance block hydraulic potential measurements in 1990 plotted as time series. There is an obvious contrast between the two sites; lower potentials were measured by both sets of equipment at 253 than by those at 553. It is also immediately apparent that rainfall events in the course of the summer caused wetting at all depths to 0.5 m, at both sites sufficient to raise potentials, as measured by the blocks, above -1000 cm.

In terms of absolute values of soil water potential, there is little correspondence between potential as measured by the blocks and the corresponding tensiometers, where there is an overlap in the data. For example, the tensiometers at 0.5 m functioned satisfactorily through the summer because potentials remained high yet the blocks in the arrays at 253 suggest potentials as low as -3000 cm developed at these depths, although the trends in the data are the same as in the tensiometer data. This finding casts some doubt on the accuracy of the absolute values of potential measured by the blocks. Accuracy of better than ±500 cm should not be expected in any case (Appendix B.2).

The difference between the two sites is considered to be real because the behaviour of both arrays of blocks at 253 is similar and corresponds to the evidence from the tensiometers that lower potentials occur at 253. With the exception of the blocks at 0.3 m in array 253 and at 0.2 m in array 553, the data from each of the three arrays has a coherent, synchronous pattern; potentials decrease at successive depths, with time, after rainfalls.

If the very low potentials measured at 0.2 m depth at 553 are regarded as anomalous, then the lowest measurements -9000 to -10000 cm water, occurred at site 253. The lowest potentials at 553 were less than -5000 cm water, but this was exceptional; for most of the summer the potentials at all depths exceeded -1000 cm water. In contrast, the data from 253 suggest that at 0.4 m depth, potentials fell below -1000 cm for periods of up to 3 weeks.

4.4.3 Soil water potentials experienced by plants

The soil water potential measurements have provided two types of information relevant to plant water use at Yarnton Mead. The first relates to the potentials that occur within the rooting depth of much of the vegetation and indicates the work required of the plants to abstract water from the soil. The second concerns the direction of water movement within the soil and the possibility of water supply to the plants from the groundwater.

The data clearly demonstrates that at both of these sites despite their different soils, in particularly dry years, the water table has a considerable influence on the soil profile. Even when the water table reached its lowest depth in 1989 and 1990, potentials in the unsaturated soil between it and 0.6 m depth remained close to the equipotential profile determined by the water table position. Consequently potentials at 0.5 m, and to some extent at 0.4 m remained high for much of the summer. i.e. above -1000 cm. It is only in the surface layer i.e. between 0 and 0.3 m depth that very low potentials occurred. The evidence indicates that low potentials generally did not persist for periods exceeding three weeks duration. Summer rainfall wetting the surface soil after a dry period caused the potentials to increase rapidly.

4.4.4 Direction of soil water flow

The soil water potential data has shown that after rainfall and in the absence of a high atmospheric evaporative demand, (eg. autumn 1987) the Mead soils tend to drain to a state which is in equilibrium with the depth of the water table. Site 553 responds more rapidly in this respect than 253.

In summer, plant abstraction of water from the surface horizon leads to the development of hydraulic potentials lower than that at the water table. On no occasion throughout the measuring period has a convincing persistent divergent zero flux plane been observed in the potential profile above the water table. Zero flux planes occur when plant abstraction at shallow depth introduces an upward potential gradient in the upper soil profile, whilst at the same time, drainage below results in a downward potential gradient in the lower profile. Between these two zones is a plane across which no water movement will occur, the zero flux plane or ZFP. ZFP's develop in most British soils over deeper water tables each summer. They may have occurred ephemerally at Yarnton to a greater extent than the data imply. However, because of the shallow depth of the water table and hence the high potential of the equipotential profile to which the soils drain, the unsaturated conductivity of the draining profile remains high and, therefore, drainage is rapid.

The absence of divergent ZFP's in these soils means that when they were not draining an upward flow of water from the water table could occur. The rate of any upward flux would depend upon both the gradient of total hydraulic potential, and the corresponding unsaturated conductivity. Between rainfalls, therefore, the form of the potential profile represents the balance of the evaporation flux out of the soil and the upward flux from the water table replacing water that has been evaporated. If the evaporative demand were "switched off" the upward flux would ultimately return the profile to the equilibrium condition.

The laboratory measurements of conductivity were made only at high potentials and the information is insufficient to calculate flux rates for the measured potential gradients. However, the water balance calculations have demonstrated that influxes of water from the groundwater body are important (Section 4.7).

4.5 CROP GROWTH

4.5.1 Crop Management

The usual agricultural management of the Mead is of a hay cut in early July followed by sheep grazing from late August until November or December. As Table 4 shows this pattern is not always followed. The hay yield in 1990 was poor, well below average. The delay in putting sheep on to the Mead in 1989 was not due to lack of herbage.

Table 4 Crop management and yield

YEAR	DATE HAY CUT	HAY YIELD Bales	DATE SHEEP INTRODUCED
1987	-	3180	-
1988	-	3528	-
1989	10th July	3544	10th October
1990	10th July	2250	28th August

4.5.2 Leaf Area Measurements

Table 5 summarises the results of the measurements of leaf area index (LAI) in 1990 (Appendix B.4). Prior to the first measurements on May 16th, it was noted that the vegetation began to show signs of renewed growth in mid April and through the following weeks, the foliage density increased considerably. Between 11 April and May 16th the crop height increased from about 0.1 m to 0.3 m The increase in LAI between 16th May and 26th June reflects a further change as the crop developed. Post-hay cut, the LAI reduced by 75% to 0.86 for the "whole" vegetation. Grazing after 28th August maintained the LAI at less than one into early October.

Field observation indicates that it is reasonable to assume that the LAI remains low through the winter months even after the sheep have been taken off the Mead. The LAI then increases when growth recommences in spring. The evidence suggests, however, that the LAI of the vegetation at Yarnton Mead is less than one for much of the year.

It is generally accepted that transpiration in most vegetation well supplied with water increases with leaf area to a LAI of about 3 (Rosenberg *et al.*, 1983, Ritchie and Johnson 1990). When shading of the ground is incomplete, radiant energy passes through the vegetation to be intercepted either by the plant litter or the soil surface. The availability of water in the litter or at the soil surface then determines the fate of this energy; some water may be evaporated contributing to the actual evaporation total. It is uncertain how appropriate such a model is to the situation of Yarnton of a very mixed sward combining annual and perennial species. However it is probable that for much of the year leaf area will be an important factor in determining how rapidly transpiration may take place and hence actual evaporation rates.

Table 5 Results of LAI Measurements.

DATE	NUMBER SAMPLES	MEAN FRESH WT SAMPLE g	LAI WHOLE SAMPLE	LAI GREEN MATERIAL	CROP HEIGHT ESTIMATE m
16.5.90	26	70.1	3.09	-	0.32
26.6.90	25	74.4	3.68	-	0.38
10.7.90 Mowing started					
17.7.90	7	17.2	0.86	0.52	0.05
28.8.90 Sheep arrived					
11.9.90	24	21.6	0.84	0.52	0.15
9.10.90	26	18.4	0.51	0.20	0.10

4.6 ACTUAL EVAPORATION

4.6.1 The data

The Hydra actual evaporation measurements recorded in 1989 and 1990 are shown in Figure 15. The same data are expressed as a fraction of the potential evaporation rate, as measured by the on-site automatic weather station, in Figures 16 and 17. Over the 112 day measurement period in 1989, reliable data was collected on 58 days. In 1990, 132 days of data were collected between April 4th and 28th September.

The run of data presented is not continuous for three reasons. Firstly, the Hydra does not operate when the sensors are wet due to rainfall or dew and secondly the Hydra cannot distinguish transpiration and evaporation of soil water from evaporation of dew or intercepted water. Where short gaps in the hourly data arise because the equipment is wet, it is reasonable to interpolate. In the first hours after dawn on a dewy morning, the data was set to zero to obtain a daily evaporation total. This is because the negative evaporation flux as the dew forms counterbalances the increased flux until it subsequently evaporates from the instrument and so does not affect the daily cumulative total. However, when the dew was persistent or there was more than a trace of rainfall, the data was excluded from this analysis because of the large component of intercepted water in the resulting daily evaporation figures. However, it was necessary to interpolate during those periods in order to make water balance calculations.

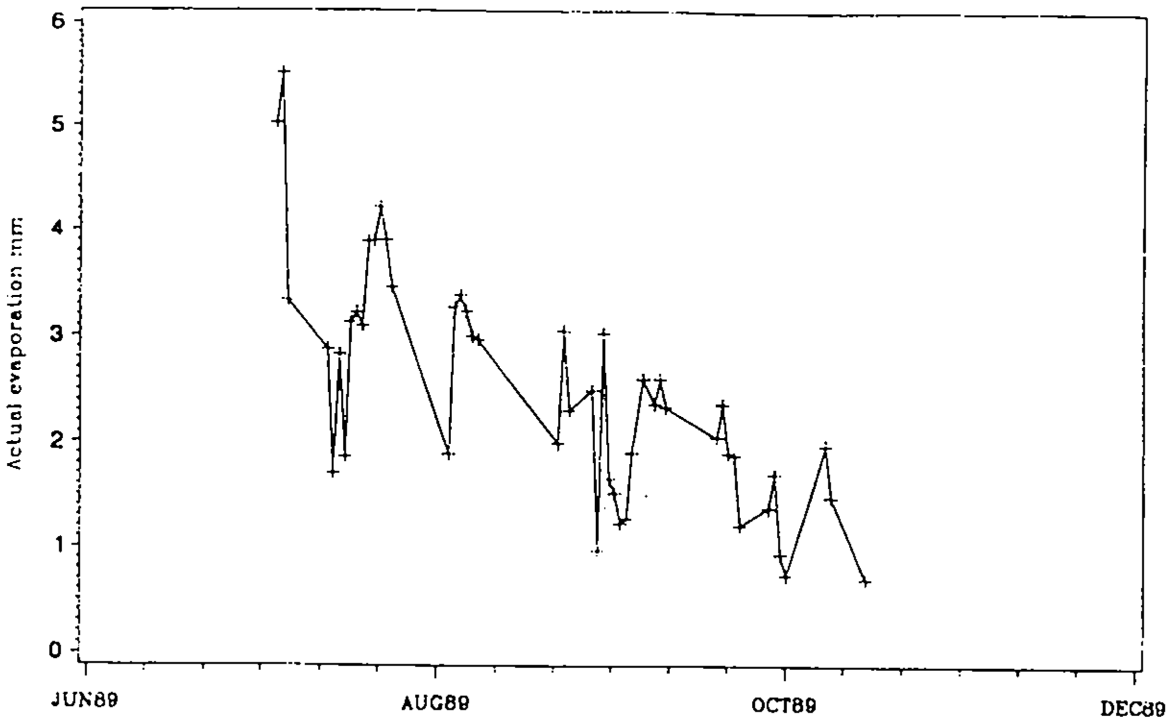
Finally, in 1990, the Mead site was used for testing new Hydra sensors on a second Hydra. Whilst for the great majority of the measurement period one Hydra was fully operational, data had to be discarded occasionally because of the unsatisfactory performance of new sensors during the testing schedule.

In terms of potential evaporation, 1989 and 1990 were similar. In summer, the daily potential evaporation rate occasionally exceeded 6 mm, maxima occurring in July each year. The greatest actual evaporation rates measured on dry days were 5.5 mm d^{-1} in 1989 and 3.9 mm d^{-1} in 1990. It is immediately apparent from Figures 16 and 17 that for most of the measurement period in each year the measured rate on dry days was significantly less than the potential evaporation rate. There is much variation in the data on a day to day basis but clear trends emerge.

4.6.2 Pre-harvest

The pre-harvest measurements made in spring 1990 (Fig. 16a), show clearly that the actual to potential evaporation ratio increased from less than 0.6 to 1, between April 4th, when measurements began, and early May. Then from mid-May the ratio decreased from 1, reaching about 0.75 in early July, before the harvest. The period when the evaporation ratio was increasing i.e. up until 8th May, will be considered initially. During this time the daily potential evaporation rate ranged from 1.7 to 4.4 mm d^{-1} and on dry days, the cumulative potential evaporation total was 93 mm compared with 64 mm actual evaporation.

The water-table fell steadily between the beginning of April and the beginning of May by about 0.15 m to reach 0.75 m bgl at the soil water measurement sites (Fig. 16c). In the upper part of the soil profile at the soil water measurement sites, hydraulic potentials measured by tensiometers fell rapidly (Fig. 16d). The rate of decrease accelerated in the last week of April corresponding with an acceleration in the rate of decrease of profile water content. However, although water content and potential were decreasing, it is apparent that up until early May there was water available at potentials greater than -800 cm in the upper part of the profile at both sites and it can be assumed that water was available at higher potentials in the soils of the depressions. The occurrence of actual evaporation rates of less than potential



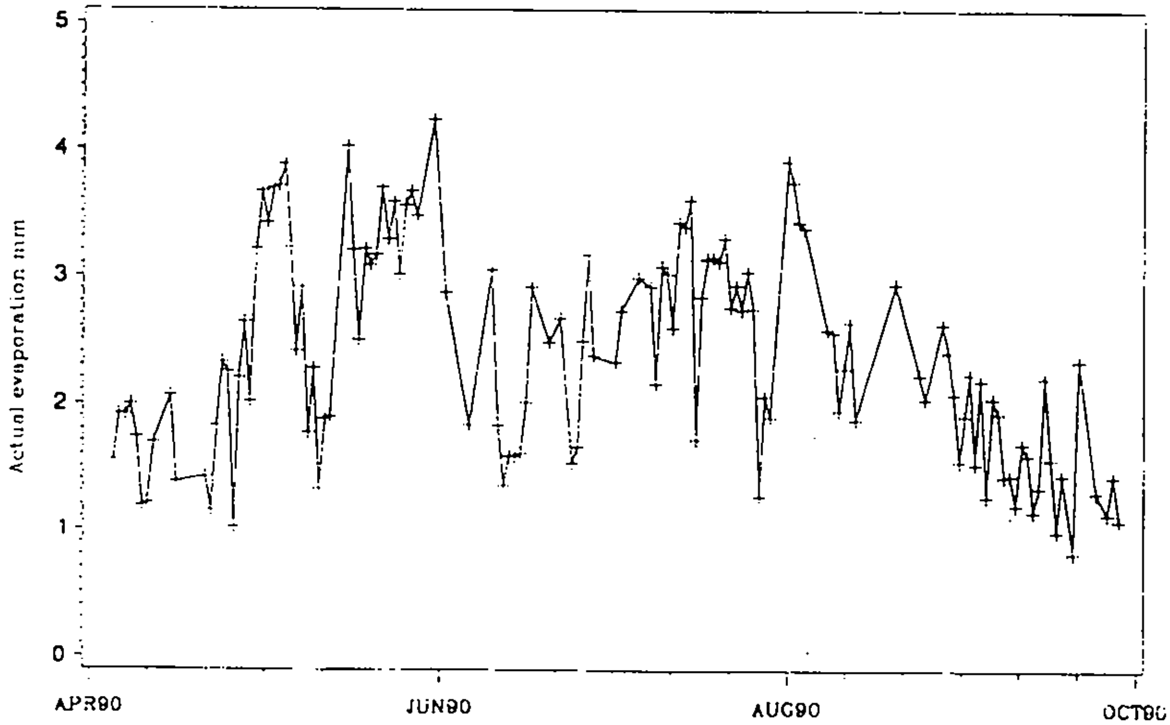


Figure 15 Time series of measured daily actual evaporation: a. 1989; b. 1990. Note, the data points have been joined to assist recognition of the trends in the data, although the time series are not continuous

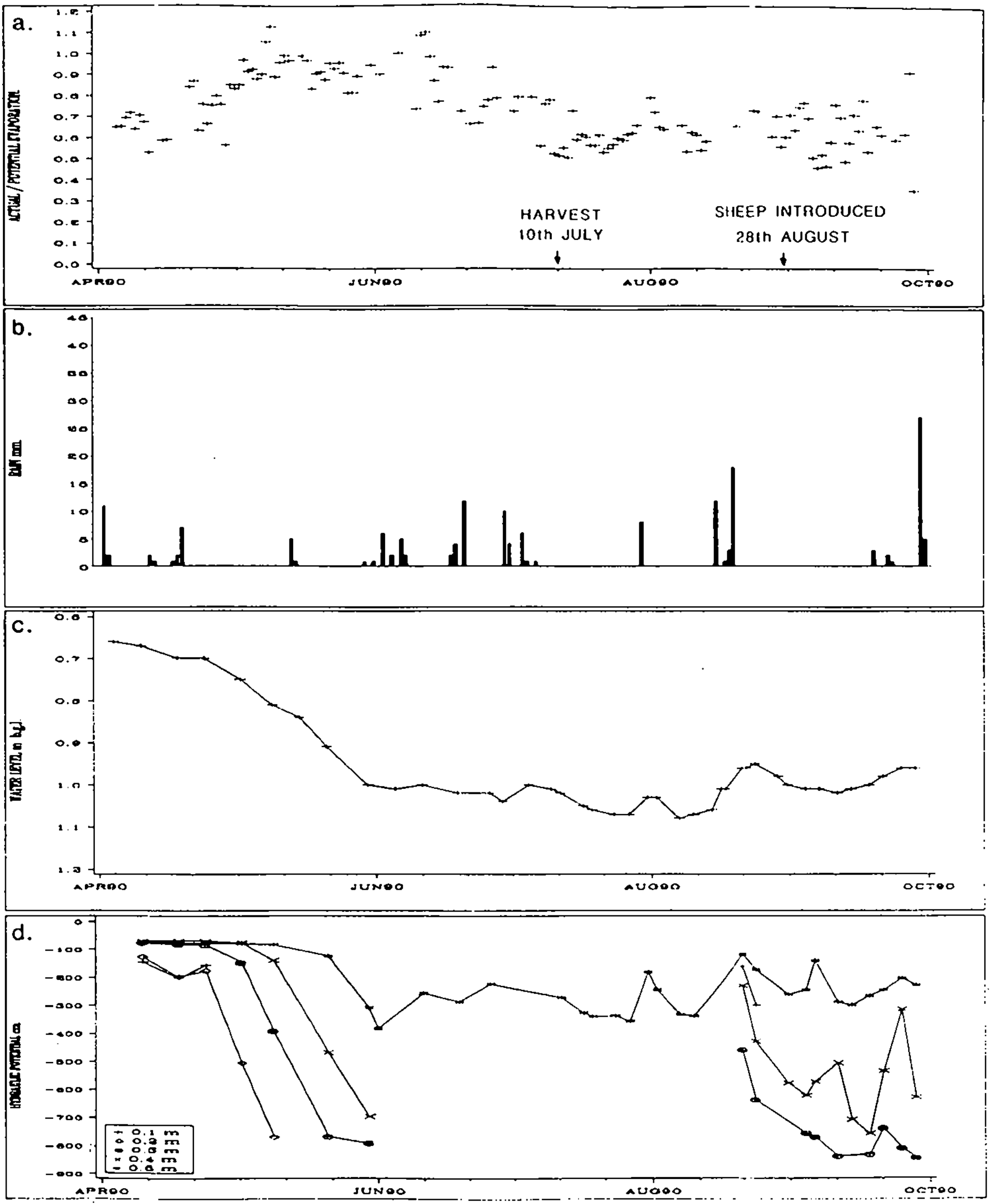


Figure 16 Time series for 1990 of a. ratio of actual to potential evaporation, b. rainfall, c. water table depth at PX21, d. soil water potential in upper 0.5 m at S53. Note, shallowest tensiometers operated intermittently in mid-summer but data not shown

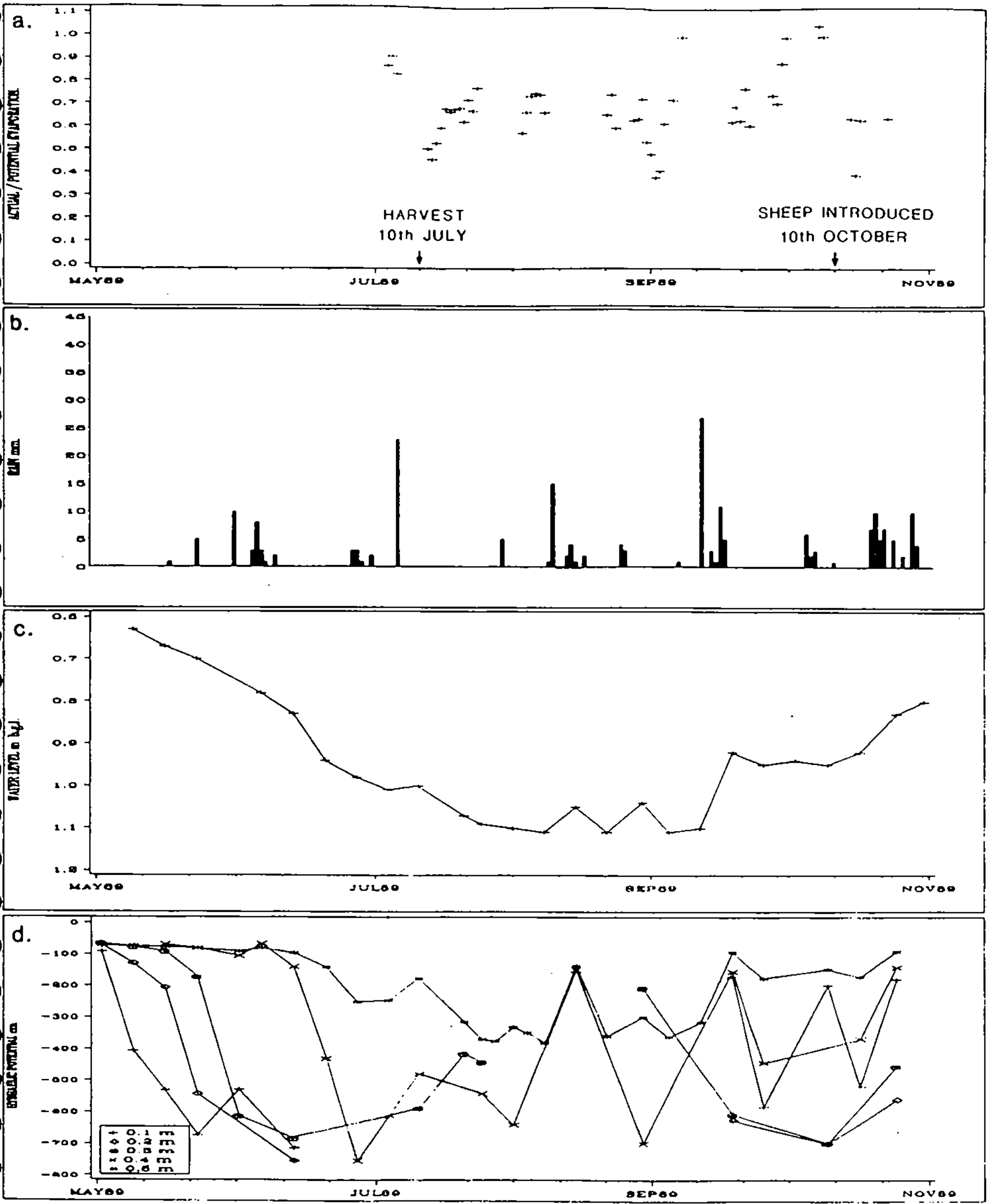


Figure 17 Time series for 1989 of a. ratio of actual to potential evaporation, b. rainfall, c. water table depth at PX21, d. soil water potential in upper 0.5 m at 553. Note, shallowest tensiometers operated intermittently in mid-summer but data not shown

between the beginning of April and early May is unlikely therefore to be a consequence of lack of soil water. The increasing evaporation ratio is the converse of what would be expected if soil water availability were the cause. It is possible that the soils were too wet and that the vegetation was under physiological stress due to anaerobic conditions in the lower part of the soil profile and so could not transpire optimally. A more probable explanation however, is that at the beginning of April there was insufficient vegetation canopy to intercept all the incident radiation and so transpire at the potential rate. The increase in the ratio of potential to actual evaporation is probably due in large part to the increase in leaf area as the crop developed.

The decline in the ratio of actual to potential evaporation over the eight week period mid-May to harvest coincides with a falling water table, and decreasing soil water content above it. The LAI of the vegetation was greater than 3 throughout and so leaf area can probably be discounted as a limiting factor. However, other changes within the vegetation such as the increasing average age of the foliage and the processes of flower and seed production might change its behaviour in terms of transpiration.

During the latter half of May, which was dry, the water level at the sites fell to reach more than 1.0 m depth after which it fluctuated by ±0.04 m. June was the wettest month of the spring and summer; 47.5 mm of rainfall fell, distributed fairly equally between the first and third weeks of the month. This was followed by 21.5 mm between the 30th June and 5th July. On dry days during the first week of June and through the second week, the ratio of transpiration to potential evaporation exceeded 0.9. Thereafter the ratio decreased further to then level out at about 0.75 between the rainfalls later that month and at the beginning of July. It is evident that the rainfall inputs were important in enhancing plant water use temporarily but the overall trend was for the evaporation ratio to decrease.

The gypsum block data indicate that potentials fluctuated during this period as the soil wetted and dried (Fig. 14). There is a three week gap in the soil water content record for May but the available data show that between the 2nd and the 25th the water content of the upper 0.6 m of the profile decreased by an average of 38 mm. Then, despite the June rain, there was a further decrease of 18 mm before the harvest. These results suggest that, at least in part, the decline in the evaporation ratio was due to decreasing soil water availability.

The Hydra was only operational for the three days immediately prior to the hay cut in 1989. The actual to potential evaporation ratio values then (Fig. 17a) are comparable with those at the same time in 1990.

4.6.3 Post Harvest

Immediately after the hay cut on 10th July 1989 the ratio of actual to potential evaporation fell to less than 0.6 (Fig. 17a). Over the following 12 days the ratio increased to nearly 0.8. Meanwhile the water table fell by 0.1 m at the soil water measurement sites, and slightly less nearer the river. There was then no clear trend in the data (the ratio varied between 0.5 and 0.8) until after 49 mm rainfall between the 12th and 17th September which caused the water table to rise by about 0.1 m. Between September 22nd and October 8th 1989, an almost dry period, the ratio increased to about 1. This increase in the actual evaporation rate relative to potential could have been a delayed response to the rise in the water table but the evidence is only circumstantial. At the same time the growth of the sward was unhindered by cutting or grazing and the consequent increase in leaf area may have resulted in the increase in the evaporation ratio.

The Hydra was only operational for four days after October 9th 1989. These few measurements suggest that the ratio had again decreased to less than 0.7. The timing corresponded with the commencement of sheep grazing on the Mead and it is possible that the consequent decrease in the leaf area was responsible.

In 1990, immediately after the hay-cut, which took place between the 10th and 12th July, the evaporation ratio fell to 0.52 but then fluctuated between 0.5 and 0.8 until the end of August (Fig. 16) as in 1989. The ratio tended to decline between rainfalls and then increase after rain. Thereafter there was greater variability in the evaporation ratio. The LAI remained relatively constant throughout this period. The water table rose by up to 0.1 m after rainfall in the middle of August but the level declined again in September which was dry until the last day.

4.6.4. Implications

The measurements of actual evaporation obtained for Yarnton Mead are significant from several perspectives. Until now it has been very difficult to obtain field measurements of evaporation from shallow water table soils. The Zero Flux Plane method, used where the unsaturated zone is deeper (Cooper, *et al.*, 1990), is not applicable because of the absence of zero flux planes. Much of the work on flow in shallow water table soils has been conducted using lysimeters with controlled water table levels.

Models of fluxes in shallow water table soils often assume that plant water use equals the smaller of either the potential evaporation rate, or the maximum steady flux which can be conducted from the water table at a given depth e.g. Youngs *et al.* (1990), de Laat (1985). These measurements will be used to test the performance of such models. However the data already demonstrate that crop growth stage is a factor because of the perennial vegetation.

Superficially, from the time of the hay cut one year to the commencement of development of the hay in April the following year, the vegetation at Yarnton Mead appears similar to the short grass turf described by Penman (1948). It was therefore expected that when the water supply was not limiting evaporation rates would be similar to the Penman potential evaporation estimate for short grass completely shading the ground. Clearly this was not the case in April 1990, or, it can be assumed, earlier in the year when the water table was high. Evidently the leaf area of the vegetation was significant but other factors may also have contributed to the plant response.

At times when the LAI was greater than 3 or was constant i.e. between mid-May and the harvest in 1990, and after the 1990 harvest, the data indicate that actual evaporation rates fluctuated with soil water conditions. Figure 18 shows the evaporation ratio for those days after harvest, when water level was measured, plotted against the water level. There is no clear relationship between water table depth and the ratio. The scatter is due in part to the response of the evaporation rate to rainfall additions to the upper soil profile.

4.7 SOIL WATER BALANCE

Water balances were prepared for the two sites using neutron probe measurements of soil water content change, on-site daily rainfall and the Hydra measurements of actual evaporation. All the Hydra data were used i.e. including data collected on days when there was dew or some rainfall and it was accordingly necessary to adjust the daily values. On days when there was a malfunction, or a lot of rainfall, an estimate of the actual evaporation rate was obtained by first interpolating the ratio of actual to potential evaporation. The interpolated value was then used to calculate the actual evaporation rate from the daily estimates of potential evaporation for the period concerned.

The water balances were calculated using the following equation :

$$D_i = \sum_i \left[R_i - E_i + \int_0^Z \theta(t_i)dZ - \int_0^Z \theta(t_{i-1})dZ\right]$$

Where D = drainage mm
R = rainfall mm
E = actual evaporation mm
θ = volumetric water content
Z = the smaller of z_i-1 and z_i where z is the vertical distance from the surface to 0.1 m above the water table.

The water balance was therefore calculated stepwise as in Figure 19 including only the unsaturated soil profile extending from 0.1 m above the water table. The 0.1 m layer above the saturated zone was excluded because neutron probe measurements within it are influenced strongly by the presence of the water table and any changes in its position. This approach meant that if there was a fall or rise of the water table between measuring occasions, the consequent change in water content of the lower part of the profile was not included in the water balance.

The water balance calculations provide a value for drainage from the unsaturated zone between neutron probe measurements. Positive drainage values represent the flux out through the base of this zone i.e. drainage to the water table. Negative drainage values indicate movement of water into the unsaturated via its base. This may occur as a result of a rise in the water table causing an increase in water content in the zone above. Alternatively, if the water table has remained stationary, or fallen during the period under consideration, the negative drainage value must arise either as a flow along a potential gradient from the water table to the plant roots, or as a

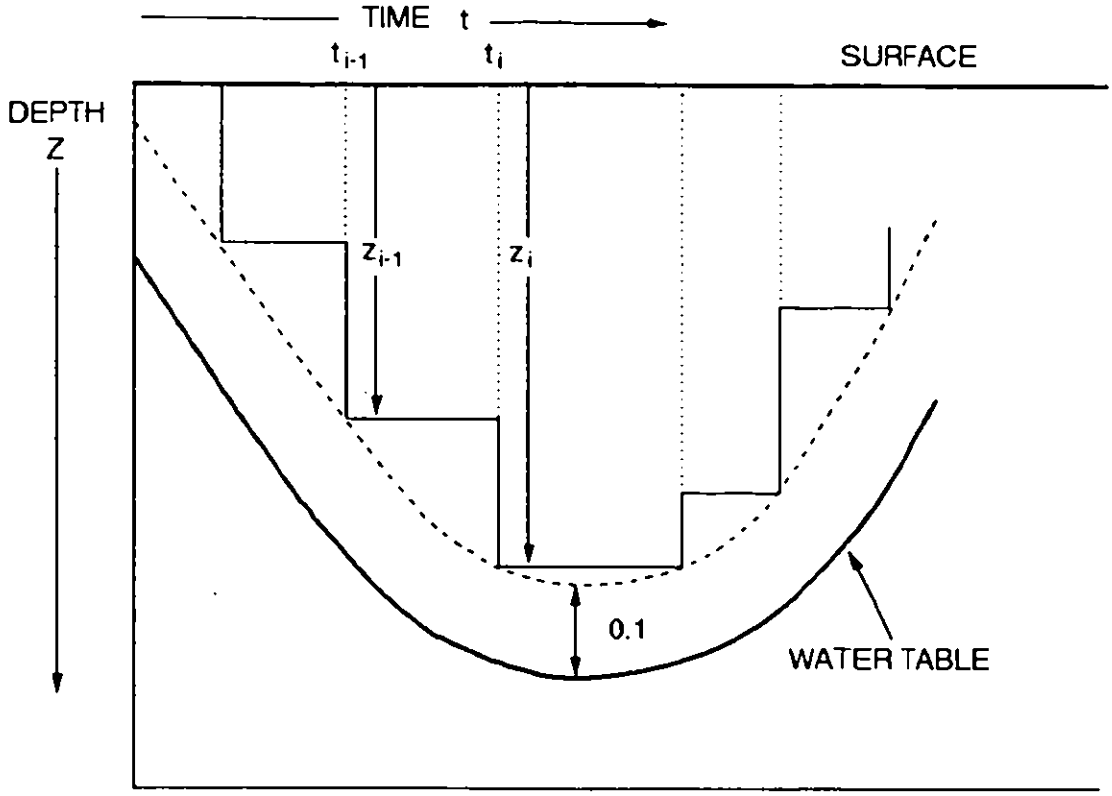


Figure 19 Diagram illustrating changing soil profile depth for which water balance was calculated

consequence of direct abstraction from the saturated zone by roots. It is not possible to distinguish one mode from the other.

The components of the soil water balance computed using the water content data from each access tube are shown in Figure 20 for the 99 day period 4th July to 11th October 1989 and in Figure 21 for the 185 day period 27th March to 28th September 1990. For ease of presentation profile drainage is referred to in terms of influx to the soil profile i.e. negative drainage calculated from the water balance has been treated as a positive influx value and vice versa.

The figures show that over the period considered in 1989 the cumulative total of net water influx to the profile was the same at each site: the mean value for each was 84 mm. Significant differences did occur in 1990 when the corresponding values were 253: 162 mm, and 553: 100 mm.

In 1989 the average rate of influx over the measurement period was 0.85 mm d^{-1} but over brief periods in July and August the calculated rate exceeded 2.5 mm d^{-1} at both sites.

Table 6 Summary of water balance results for 1990.

	WATER TABLE	INFLUX		RAIN	ACTUAL EVAPORATION
		253	553		
	m	mm	mm	mm	mm
27 Mar - 30 May	Descending 0.6 to 1.0	27	-31	34.5	147.6
30 May - 12 July	Fluctuating ±0.02 at 1.0	16	38	61.0	98.5
12 July - 28 Sept	Fluctuating ±0.07 at 1.02	120	93	51.0	168.4

In Table 6 the 1990 water balance results over three periods are presented. In spring (27th March to 30th May) drainage took place at 553 but at 253 there was a net influx. During that time the falling water table remained in the alluvium at 253 but was in the gravel at 553.

Through the wet month of June up until the hay harvest there was slightly greater use of groundwater at site 553 than at 253. Thereafter the reverse was the case. At both sites the rate of abstraction from the groundwater exceeded 1.2 mm d^{-1}.

If the data from 30th May 1990 onward are combined, similar totals arise. It is clear therefore that the main difference between the two sites in 1990 occurred when the water table was falling. The principal reason for this was

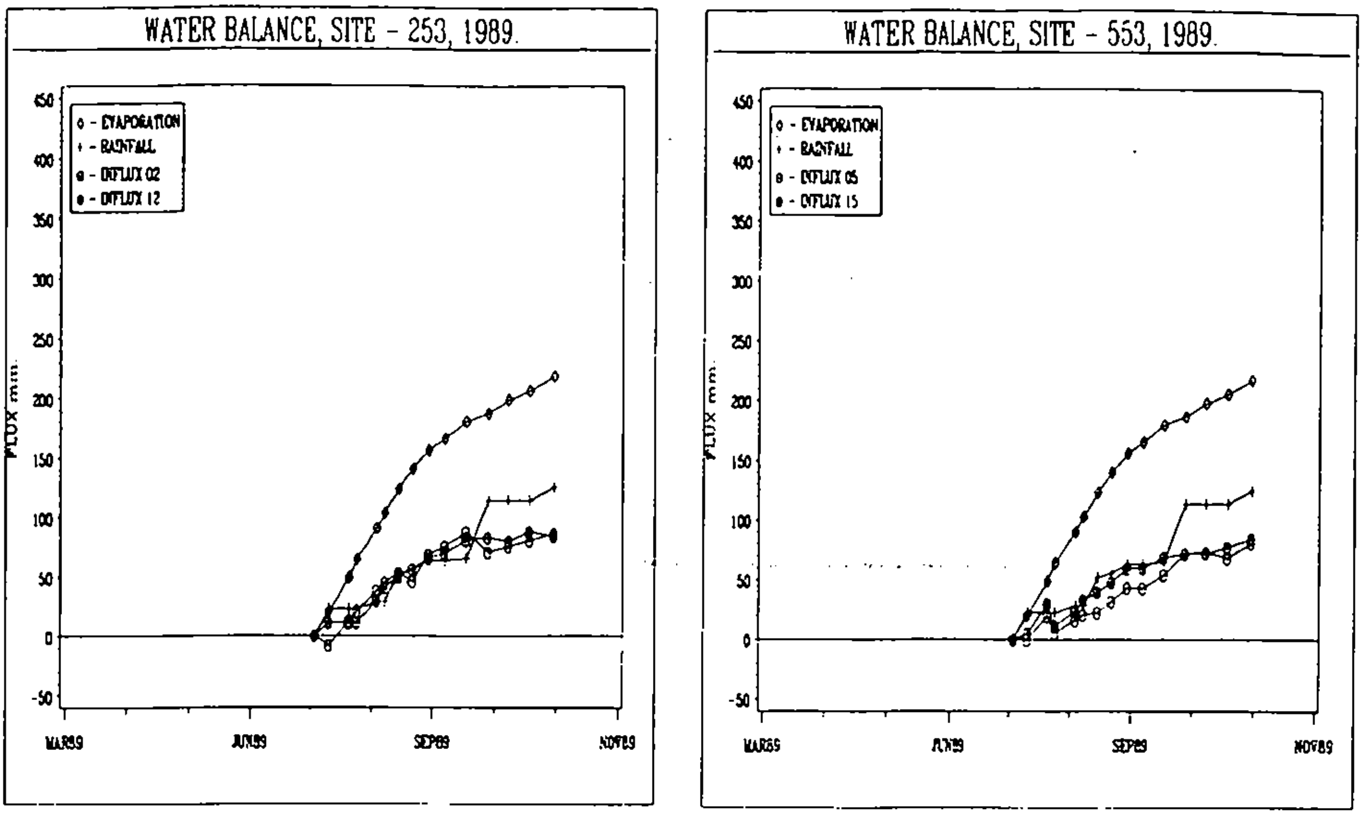


Figure 20 Cumulative values for the components of the 1989 water balance calculations

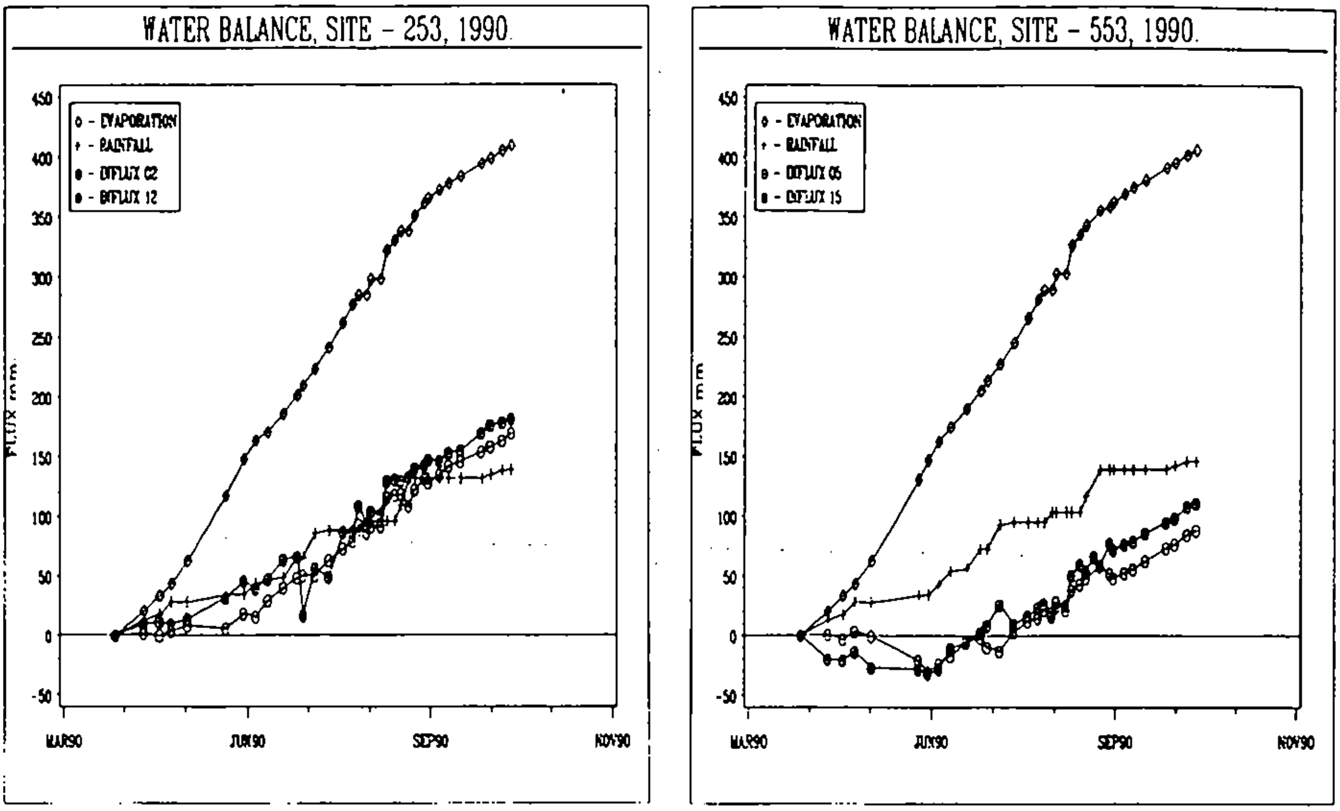


Figure 21 Cumulative values for the components of the 1990 water balance calculations

the large water content changes taking place in the gravel layer at 553. Some of the water removed from the gravel contributed to plant water usage; the excess drained.

Table 6 shows that from July 12th until the end of September, the groundwater influx was equivalent to 71% and 55% of the actual evaporation at 253 and 553 respectively. In 1989 the corresponding figures were 43% and 39% (i.e. for period 11th July to 26th September 1989). However, in that year there was little influx after 43 mm of rain in September. If the period 11 July to 12 September only is considered, influx rates were fairly similar each year:

	1989	1990
253	1.3 mm d^{-1}	1.6 mm d^{-1}
553	1.0 mm d^{-1}	1.1 mm d^{-1}

In preparing the water balances it has been assumed firstly that the bulk evaporation rate measured by the Hydra is representative of the two soil water measurement sites, and secondly that the actual evaporation rate at each was the same. Even if the first were not the case, the differences between the two sites would persist in the water balance calculations. It is not possible to evaluate how representative the Hydra values are likely to be for these sites. Towards the river and in the depressions the water table was shallower than at the sites but how significant that would be in terms of water balances is uncertain.

If evaporation from the two sites was not similar, due to the gravel layer at 553 restricting fluxes from the groundwater, then the difference between the two sites would be greater than these results suggest.

5. Conclusion

The soil water monitoring at Yarnton Mead has enabled the water regime to be quantified over contrasting years, 1987 and 1988 which were unexceptional in terms of rainfall, and 1989 and 1990, two particularly dry years. The measurements have shown that at the two sites which were located in one of the drier parts of the Mead, hydraulic continuity between the water table and the soil was maintained even when the water table reached its lowest point in 1989 and 1990. The water balance calculations for these two summers indicate (assuming that the Hydra evaporation measurements were representative of the two sites) that uptake from the groundwater accounted for more than 39% of the actual evaporation after harvest. Daily rates of uptake reached 2.5 mm d^{-1} over short periods.

The Hydra measurements have shown that actual evaporation rates are less than the Penman potential evaporation in spring, summer and early autumn. The state of the vegetation is evidently one controlling factor. Measurements of leaf area have demonstrated that the LAI is less than one for much of the summer and autumn, due to the summer hay cut and grazing thereafter, and almost certainly through the winter months when there is little growth. The implication is that evaporation may therefore be less than the potential demand for much of the year irrespective of soil water conditions. Early spring evaporation measurements, when soil water was non-limiting, showed that the ratio of actual to potential evaporation increased with time until early May. This was probably, at least in part, a reflection of the increasing leaf area of the crop.

At times when the leaf area of the vegetation was fairly constant it was apparent that the actual evaporation rate increased temporarily after rainfall. Straight forward relationships between, for example, water table depth and the actual evaporation rate were not forthcoming, emphasising that evaporation at Yarnton is controlled by several factors acting in combination; these will include the state of the crop, the water content of the upper profile and water table depth.

The study has provided a good basis for the evaluation of the suitability of models of fluxes in shallow unsaturated zones such as at this site. Measurements from other shallow water table sites are required to establish how applicable the results from Yarnton are to other situations.

Acknowledgements

The work at Yarnton Mead would not have proceeded without the support of the Yarnton Meadsmen, in particular the late Mr. E. Harris, Mr. D. Carter and Mr. P. Shurmer, or that of Keith Porter of the former Nature Conservancy Council.

The Hydra and AWS operation and data analysis to obtain daily totals was undertaken by David McNeil. Other practical assistence was provided at various times by Sam Boyle, Mike Stroud, Helen Follett, Jeremy Swanson, Jenny Franklin and Alexandre Fleury.

The Yarnton project has been discussed with several Institute colleagues, particularly J. David Cooper, John Roberts and Andy Dixon and this report benefitted from comments by J. David Cooper.

May I extend my thanks to all these people as well as to the Ministry of Agriculture Fisheries and Food who provided support funding. The active interest of Mr Roger Buckingham and Mr Eric Hunter as the Ministry's Liaison Officer and Environmental Advisor respectively has been appreciated.

Appendix A Soil descriptions

The following soil profile descriptions were obtained by auger survey in the vicinity of the soil water measurement sites. The survey was conducted by G. Colbourne in December 1989. The location of the survey points is indicated in Fig. A.1.

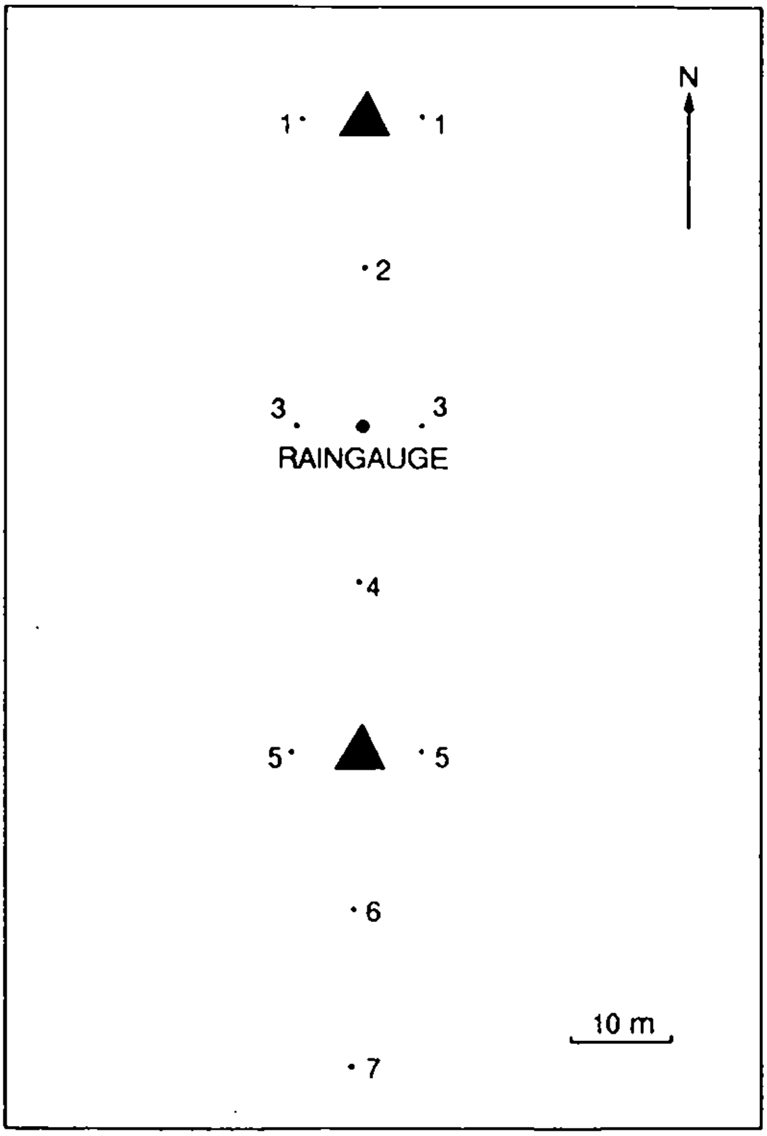


Figure A.1 Location of the auger survey points

1. WEST

Ah	0-15	cm	10YR3/2	Stoneless non-calcareous clay
Bg$_1$	15-30	cm	10YR5/2	Stoneless non-calcareous clay with common 7.5YR5/8 mottles
Bg$_2$	30-45	cm	10YR6/1	Stoneless non-calcareous clay with common 10YR5/8 mottles. Common roots
Bg$_3$	45-75	cm	10YR6/2	Calcareous clay with many 7.5YR5/6 mottles common (5-10%, est) small limestone fragments Few roots
Cg	75-110	cm	10YR6/4	Medium sandy loam with common 7.5YR5/6 and 10YR6/2 mottles. Stones as above. Very calcareous. No roots seen.
	110	cm		Gravel

1. EAST

As above but 1) 45-75 cm has no stones
2) No roots seen beyond 75 cm
3) 75-110 cm has greenish sand and sandy clay loam patches

2.

0.15	cm	10YR3/2	Stoneless non-calcareous clay
15-70	cm	10YR5/2	Non calcareous clay with many 7.5 YR5/6 mottles (calcareous below 50 cm). Common roots. Below 50 cm matrix colour grades to 6/4.
70-80	cm		Loamy gravel (hard to obtain sample)

3. WEST

0-15	cm	10YR3/2-3	Stoneless non-calcareous clay
15-30	cm	10YR5/3	Stoneless non-calcareous clay with few to common 7.5YR5/8 mottles
30-60	cm	10YR6/2	Stoneless clay with common to many 7.5YR5/8 mottles. Few roots.
60-80	cm		Sandy or loamy gravely (no sample obtained)

3. EAST

0-15	cm	10YR3/3	Stoneless non-calcareous clay
15-35	cm	10YR5/3	Stoneless non-calcareous clay with common 7.5YR5/6 mottles
35-70	cm	10YR6/3	Very slightly calcareous clay with common 7.5YR5/6 mottles. Few Ferri-manganiferous concentrations.
70	cm +		Gravel

4.

0-15	cm	10YR3/2-3	Stoneless non-calcareous clay
15-40	cm	10YR5/3	Stoneless non-calcareous clay with common 10YR5/8 mottles
40-65	cm	10YR6/3	Non-calcareous clay with many 10YR5/8 mottles. Few small limestone gravel fragments (also sandstone?)
65	cm +		Gravel

5. WEST

0-15	cm	10YR3/3	Stoneless non-calcareous clay
15-40	cm	10YR6/3	Stoneless non-calcareous clay with many 7.5YR5/6 mottles
40-75	cm	10YR6/4	Stoneless clay with many 7.5YR5/8 mottles. Common roots. Calcareousness not recorded. Few ferri-manganiferous concentrations.
75	cm +		Gravel.

5. EAST

0-15	cm	10YR3/3	Stoneless non-calcareous clay
15-35	cm	10YR5/3	Stoneless non-calcareous clay with common 7.5YR5/6 mottles.
35-55	cm	2.5YR6/4	Stoneless non-calcareous clay with common 7.5YR5/8 mottles. Common roots. Few ferri-manganiferous concentrations.
55-70	cm	10YR6/6	Medium sand with common ochreous mottles. Few small limestone gravel fragments. Calcareous.
70-90	cm		Sandy gravel but hard to obtain sample.

6.

0-15	cm	10YR3/3-2	Stoneless non-calcareous clay.
15-55	cm	2.5YR6/3	Stoneless clay with many 7.5YR5/6 mottles.
55-70	cm	10YR5/4	Clay with common 10YR5/8 mottles. Common small limestone fragments. Calcareousness not recorded.
70-100	cm		Yellowish brown, ochreous mottled medium sand (calcareous) with few to common small limestone fragments.
100-110	cm		Gravel - no sample obtained.

7.

0-15	cm	10YR3/2	Stoneless non-calcareous clay
15-50	cm	10YR5/3	Stoneless non-calcareous clay with many 7.5YR5/6 mottles.
50-70	cm	10YR6/2	Stoneless non-calcareous clay with 5YR5/6 mottles. Common roots. Few ferri-manganiferous concentrations.
70-90	cm		Yellowish brown clay (calcareous) with abundant (30% est). Small limestone gravel fragments.
90	cm +		Gravel.

Appendix B Methodology

B.1 SOIL WATER CONTENT

Soil water content change was measured by neutron probe (Bell, 1987) in a pair of aluminium access tubes installed at each site. Installation of the tubes was difficult because of the presence of saturated sand and gravel in the lower half of each profile. A method was developed whereby a steel guide tube, inserted inside the open ended access tube, was used to ream out a hole into which the access tube could be sunk immediately, preventing collapse of the sand and gravel. Subsequently the access tube was pumped out and a plug of a rubber bung and bentonite inserted to as near the bottom as possible. The neutron counts were made at 0.1 and 0.2 m and then at 0.2 m intervals to the base of each tube until January 1989. Thereafter counts were made at 0.1 m intervals commencing at 0.1 m below ground level in each tube. The deepest measurement in each tube was as follows:

Site	Tube	Depth
253	0253	1.1 m
	1253	1.5 m
553	0553	1.4 m
	1553	1.2 m

The weekly sets of neutron counts were converted to volumetric water content, θ, using:

$$\theta = \frac{R}{R_w} m + c$$

where R = neutron count rate at a given depth

R_w = the long term mean water count rate of the neutron probe used and m and c are calibration constraints.

The two standard IH calibrations for loam and sand were used (Bell, 1987) to represent the alluvium, and sand/gravel below, respectively. The loam calibration was preferred to that for clay, because the alluvium is not a consolidated clay such as the Oxford Clay bedrock. Although site specific calibrations would be preferable, use of the standard ones is acceptable as it is water content changes, rather than absolute water contents, that are of interest (Gardner *et al.*, 1990).

B.2 SOIL WATER POTENTIAL

Tensiometers

Mercury manometer tensiometer arrays were installed to record soil water potential initially at 0.1 m intervals to 0.6 m depth, and at 0.2 m intervals below that. In 1989 additional tensiometers were installed below 0.6 m so that measurements could be made at 0.1 m intervals throughout the profiles. The deepest tensiometer in each array was :

Site	Array	Depth
253	1	1.0 m
	2	0.9 m
553	1	1.2 m

Tensiometers are unable to measure soil water potentials of less than about -850 cm water head, and are unreliable under frosty conditions. The latter complications rarely occurred during the mild winters of 1987, 1988 and 1989. Until summer 1989, the limited range of the tensiometers was not a problem. In both summer 1989 and 1990, data was lost because water potential at the upper tensiometer positions fell below their range.

Gypsum resistance blocks

Soil water potentials of less than -400 cm water head may be measured using gypsum resistance blocks. The electrical resistance measured between the two electrodes in a gypsum block depends upon the water content of the block. When a saturated block is placed in soil, water will move from the block into the soil until its pressure potential is in equilibrium with the surroundings. Subsequently water will move into the block if soil pressure potential increases. Thus the measured resistance of the block is a function of soil water pressure potential. However the relationship is hysteretic; different calibrations are obtained under drying and wetting conditions. The accuracy of gypsum blocks is therefore restricted, probably no better than ± 500 cm water. They are suitable for measuring soil water status for plant growth but the uncertainties are too great to use them to measure potential gradients (Campbell and Gee, 1986).

At the beginning of May 1990, three arrays of gypsum resistance blocks were installed at 553 and two at 253, and these were monitored until the end of October 1990. The depths of the blocks in each array were the same : 0.1, 0.2, 0.3, 0.4 and 0.5 m below the ground surface. The gypsum resistance blocks had all been calibrated previously following the desorption procedure described by Wellings *et al.* (1985).

The measured resistance of a gypsum block is temperature dependent; the resistance decreases as temperature rises. The relationship has the form

$$r_c = \text{alog}_{10} [\log_{10} r_s + \beta (T_s - T_c)]$$

where r_c = block resistance corrected to calibration temperature
r_s = field measure block resistance
T_s = field soil temperature, °C
T_c = calibration temperature (23°C ± 0.5 in the Institute laboratory)
β = a constant

Wellings *et al.* (1985) obtained a value for β of $0.0123°C^{-1}$ in the course of a study at IH. Others have obtained values ranging from $0.03°C^{-1}$ (Campbell and Gee, 1986) to 0.002 (Aitchison *et al.* 1951).

In this study, soil temperatures measured under grass in the grounds of IH were used to correct the block resistance measurements using $\beta = 0.0123°C^{-1}$. The soil temperatures were measured daily at 9 am using soil thermometers installed at 0.1, 0.2, 0.3 and 0.5 m depth. A measurement corresponding to 0.4 m depth was obtained by taking the mean of the measurements made above and below.

It is reasonable to assume that soil temperatures at IH are representative of those at Yarnton since the two locations have fairly similar soils and weather conditions. Differences are only likely to arise where the soil at one location is much wetter than the other as a consequence of localised rainfall. At 0.5 m depth, and perhaps 0.4 m, the Yarnton soils may be wetter, and so slightly cooler than at IH, because the water table is shallower at Yarnton. The soil water potential results obtained for these depths may therefore be more negative than was actually the case in the field. However, a difference of 2°C would cause a change of only 60 and 200 cm water head to potentials of -2500 and -7000 cm water respectively. Given the limited accuracy of gypsum resistance blocks for measuring soil water potential, potential errors of this order are not considered serious.

B.3 WATER TABLE DEPTH

A 426 m transect of 9 wells known as PX 19, 20, 21, 22, 23, 24, 25, 26 and 27, was installed, in September 1988, to monitor water table levels across the western end of the Mead. The transect is aligned north-south and passes through the soil water measurement sites, from the boundary ditch to the river. A well was sunk within 5 m of each of the sites; the others are at 58 m intervals along the transect. They were surveyed in to Ordnance Datum. At each well, a screen length of 0.6 m was open within the gravel. All were developed, using compressed air, after installation.

B.4 LEAF AREA INDEX

Leaf area index (LAI) is defined as the ratio of leaf area to unit ground area and provides a measure of the extent of the transpiring surfaces of a crop. The method of measurement used in this study was to take samples in the field, bulk them together and then measure the surface area of a known percentage of the material using a leaf area meter.

Field sampling

Plant surface area measurement by the method described requires destructive sampling of the vegetation under consideration. Depending on the character of the vegetation, all the plant material from an area of between 0.5 and 1 m^2 or more should be collected to obtain a representative measurement.

Access to the Mead was restricted, prior to the hay cut, to the pathways that were necessary to reach the instruments there. This, and the need to minimise the amount of plant material removed, meant that it was not possible to use a sampling strategy that incorporated the whole of the area within a 200 m radius of the Hydra. Instead samples were taken along the line of the well transect (Fig 1)

In practice, samples were taken at regular intervals along the transect by cutting to ground level all the vegetation in a 0.25 x 0.25 m square located by throwing a quadrat from the transect. 26 samples were usually collected thus. In total, an area of 1.63 m^2 was sampled on each occasion.

Measurement procedure

Each sample was weighed on return to the laboratory and then mixed with the others. The area of 5% by weight of each was measured and this procedure was repeated to ensure that the sub-sampling was representative. It should be noted that measurements were made on "whole" samples, not only leaves. After the hay cut, 10% by weight sub samples were used - and in addition, the proportions of green material was determined so that the LAI of the photosynthesising vegetation could be obtained.

B.5 UNSATURATED HYDRAULIC CONDUCTIVITY

Unsaturated hydraulic conductivities at high matric potentials (0 to -25 cm) were determined on undisturbed soil cores 0.2 m in diameter by 0.2 m long, using a method based on the core/crust method for saturated and unsaturated hydraulic conductivity measurement (Carter, 1988). It is referred to as the SSLRC (Soil Survey and Land Resource Centre) method.

Field sampling

The crust method for unsaturated conductivity measurement was originally developed as a field method (Bouma and Denning, 1972; Bouma *et al.*, 1971). It has been modified for routine laboratory use at STIBOKA in the

Netherlands. But for some minor details, the SSLRC method is the same as that used at STIBOKA.

In early August 1987 eight cores were taken from a pit excavated adjacent to site 253, at the depths indicated in Table B1. At the location chosen to site the pit the base of the alluvium was at about 0.6 m depth and it was possible to attempt to sample the underlying sand/gravel material. In fact only 2 complete cores were obtained from this layer successfully and subsequently one of these collapsed in the laboratory.

Table B1 ***Depth and position of undisturbed cores taken from adjacent to 0253 for hydraulic conductivity determinations. * Indicates measurements were conducted successfully on core indicated.***

	1	2	3
A	15 - 35	35 - 56*	59 - 79
B	15 - 35	35 - 55*	Core not obtained
C	13 - 33*	37 - 57*	79 - 79*

The codes A, B and C indicate three positions at the surface below which 0.2 m diameter cores were excavated from three depths. 0.2 m diameter drainage pipe cut to size with a sharpened end was used to collect and retain the cores throughout the experiments.

Laboratory method

The cores were returned to the laboratory where the base of each was trimmed and nylon netting was attached over the base to prevent the core collapsing when moved, prior to wetting by placing the cores on foam in about 5 cm depth of water.

The principle of the core/crust method for measuring unsaturated conductivity is that a steady flux is imposed on a soil core by means of ponding water over a sand/cement crust on the core surface. The soil matric potential(s) corresponding to the flux is measured by means of tensiometers(s) inserted into the side. A series of crusts of differing permeability are employed to obtain several flux rates. Prior to use of a crust, the saturated conductivity of the core is measured by ponding water directly on to the surface of the core.

The main difference between the method employed here (Franklin, 1988; Fleury, 1988 and Swanson, 1990) and that of SSLRC (Carter, 1988) was use of two 6 mm diameter tensiometers inserted at two depths in the core, instead of a single 24mm iameter tensiometer. With soil water potential measurements from two depths the potential gradient within the core corresponding to the measured flux can be calculated and so unsaturated conductivity, K_{unsat} can be estimated using Darcy's law :

$$Q = K_{unsat} \frac{d\psi}{dz}$$

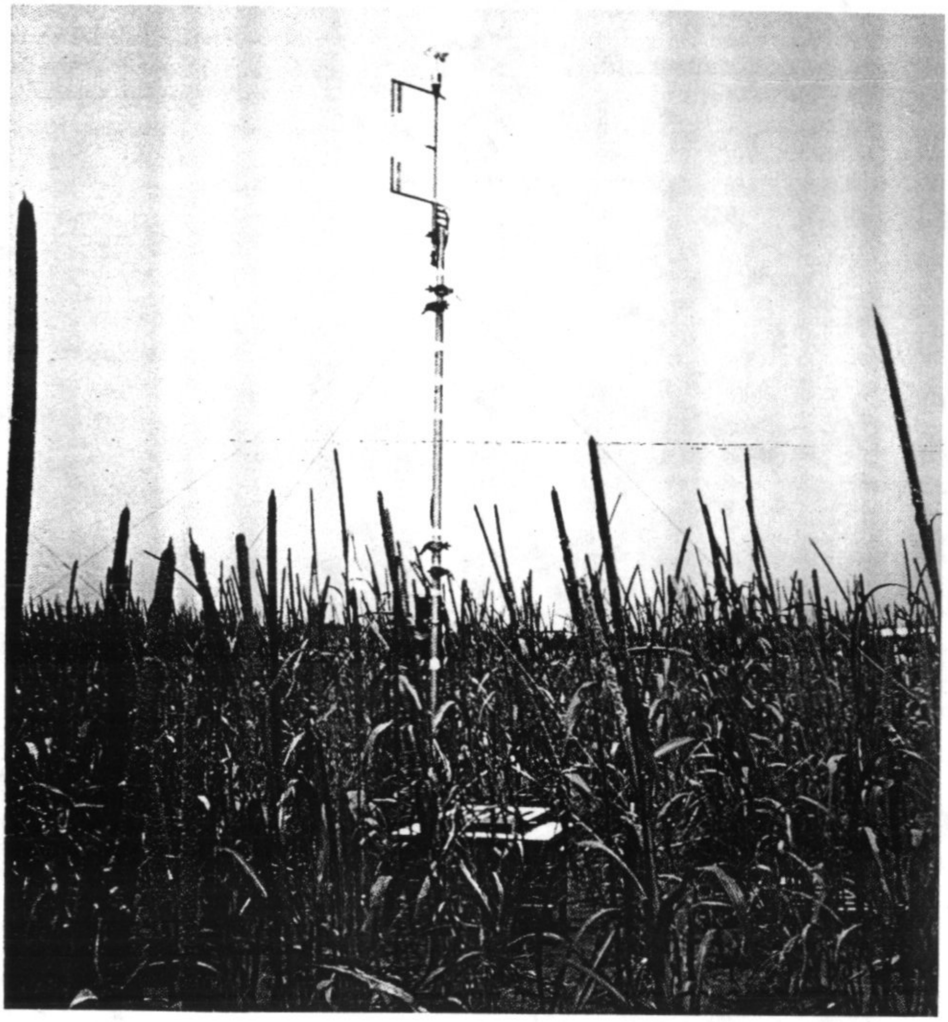
where Q = flux,
ψ = total hydraulic potential
and z = depth

When only one tensiometer is employed it is necessary to assume that the potential gradient is unity, i.e. $Q = K_{unsat}$. In trials with the method it was found that the potential gradient often was not unity and misleading K_{unsat} values were derived unless the measured potential gradient was allowed for in the calculation (Fleury, 1988). The matric potential, ψ_m, corresponding to each K_{unsat} determination was calculated as the mean of those recorded by the two tensiometers.

Appendix C

Direct measurement of evaporation using the Hydra

Evaporation estimation techniques can on a yearly time scale, be reasonably accurate for short vegetation plentifully supplied with water. On a shorter time scale, or for vegetation, where evaporation is less than potential, satisfactory results can only be obtained by modifying the estimation techniques. Confidence in these modifications is only justified by the use of direct evaporation measurements. Methods of measuring natural evaporation have been available for some time, but the effort and cost involved in collecting and analysing the data have restricted their use to a few research studies. The Hydra, an instrument developed at the Institute of Hydrology, now makes the routine measurement of actual evaporation a practical possibility.



Advantages of the Hydra.
The Hydra is a compact portable instrument incorporating a digital microprocessor to analyse the measurements as they are being made. The ability to run under battery power at remote sites makes the Hydra very attractive for both hydrological and agricultural applications. A prototype version has been used successfully in Britain for measurements over heather and forest and also as part of a hydrological study of the Amazon rain forest in Brazil. The Mark 2 version has proved itself in agricultural studies in the extreme environment of the Sahel. It has also contributed ground truth measurements to international experiments in France (HAPEX) and U. S. A. (FIFE), designed to improve global climate models by calibrating remote sensing data.

Consultancy service.
Measurements of evaporation made using the Hydra are now being offered by Institute of Hydrology technical and scientific staff. They can provide the expertise in the selection of suitable applications, the necessary experience to install and operate the instrument and interpret the results.

HYDRA Specification.

To provide a direct measurement of evaporation, sensible heat flux and momentum flux by the eddy-correlation method

Constituents.

1. An aerodynamic framework comprising – an ultra sonic anemometer, an infra-red hygrometer, a thermocouple thermometer, and a fast response cup anemometer. These measure fluctuations in vertical windspeed, humidity, temperature and horizontal windspeed respectively. This multi-sensor head is mounted perpendicular to, and usually two to three metres above the surface of interest

2. Below this a relative humidity sensor permits ambient absolute humidity to be calculated which is required for the calibration of the hygrometer. Available energy is also monitored by a net radiometer and soil heat flux plates, which allows a daily energy budget check to be done on the Hydra's performance.

3. A module containing the sensor electronics, microcomputer and a removable solid state data store.

The whole system is designed such that it is protected from electrical storms by a contunuous Faraday cage

Operation.

The microprocessor interrogates the sensors at a frequency of 10Hz, producing variances, crosscorrelations and raw outputs which it averages and logs on a 48k byte by 4 bit solid state store. This will hold four week's data. This is removed during a site visit and the data subsequently unloaded onto a floppy disk after applying calibrations and corrections using a microcomputer

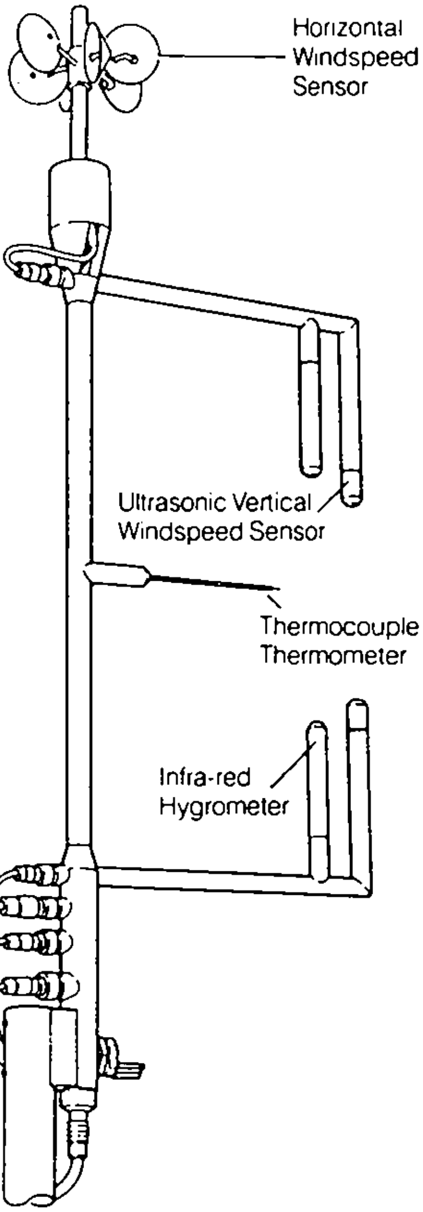
Power Requirements.

300 milliamps at 12 volts. Depending on the situation this is usually maintained by car batteries charged with solar panels.

Accuracy and Limitations.

As with all micrometeorological measurements, the Hydra requires an undisturbed upwind fetch of uniform vegetation typically of 200 to 400 metres. Errors due to frequency limitations of sensors, drift, atmospheric stability and in extracting fluctuations from background changes in the variables, are corrected for in the software.
With experienced installation, operation and quality control, the daily cumulative sum of the evaporation and sensible heat fluxes is normally within 5% of the measured available energy. Sensible measurements are not available during and immediately after significant rainfall when there is water on the sensors

The Mk2 HYDRA Sensor Head



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