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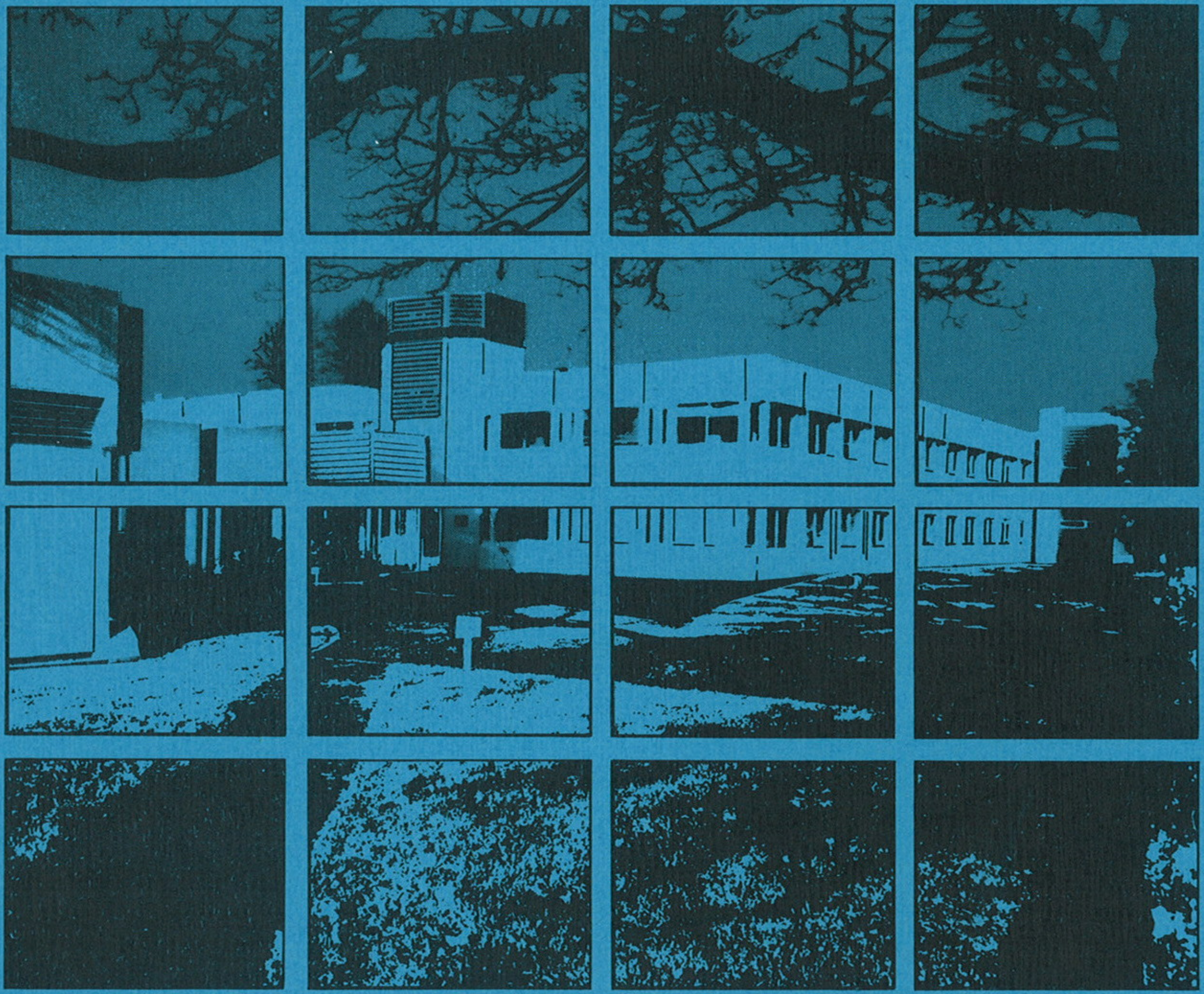
Measurement of moisture fluxes in unsaturated soil in Thetford Forest



Report No 66

INSTITUTE OF HYDROLOGY

MEASUREMENT OF MOISTURE FLUXES IN UNSATURATED SOIL IN THETFORD FOREST

by

J D COOPER

ABSTRACT

A report of contract research carried out for the Department of the Environment on experimental studies to improve methods of estimating recharge for homogeneous areas and to aid the understanding of the factors controlling the amount and timing of natural recharge to groundwater.

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SUMMARY

Natural recharge of aquifers is conventionally estimated either by computing the difference between measured rainfall and estimated evaporation, or by analysing river flows in the area of interest. The first of these methods is sensitive to large errors and uncertainties in the calculation of actual evaporation, particularly when applied to areas such as eastern England where annual evaporation may be only about 50-100 mm less than annual rainfall. The second method requires long runs of data, is subject to uncertainties concerning aquifer leakage and abstractions, has poor time resolution and does not readily distinguish between the effects of different crops, soils or geology.

Since drainage from the soil eventually appears as recharge to the aquifer the direct measurement of drainage is a promising alternative to the above methods. A composite technique has been used for the measurements described in this report. During the summer a 'zero flux plane' (ZFP) is identified, dividing upward water fluxes in the upper part of the profile from downward draining fluxes in the zone beneath. Water content changes above and below the ZFP depth represent evaporation and drainage, respectively. During winter, when a ZFP is not present, drainage is calculated from a simple profile water balance using a meteorological estimate of evaporation, together with measured rainfall and soil water content measurements. This method has been used to calculate the water balance for a forested site and a nearby clearing, both within Thetford Forest, for 34 months from January 1974 to December 1976. Additionally, the water balance of a second forest site for a period of one year has been computed using the same method.

The main findings were:

(1) At the main forest site good agreement was found between measured evaporation and a meteorological estimate derived by the method of Gash and Stewart (1977) for the spring and early summer periods. Subsequently, when soil moisture deficits exceeded about 60 mm, the measured evaporation rate became significantly lower than the Gash and Stewart estimate. The good agreement between these two sets of evaporation estimates in early summer supports the validity of the drainage measurements, for which no comparison with an independent estimate was possible.

(2) The evaporation and drainage of the second forest site, at Feltwell, was very similar to that of the main site despite marked differences in soil characteristics, tree species and water table depth, implying areal consistency of these quantities over the forest area.

(3) Evaporation from the forest was 49% greater than that from the grass in the clearing, and drainage was 44% less.

(4) The difference was found to be due mainly to the evaporation of intercepted water by the forest which accounted for 41% of forest evaporation.

(5) 43% of the total drainage beneath the forest and 19% beneath the clearing occurred during the period when a ZFP was observed, i.e. during spring and summer when there was a soil moisture deficit. This finding conflicts with the traditional concept of field capacity.

(6) Good agreement was found between results from replicate sets of instruments. The likely error in measured annual evaporation or drainage if only one set of instruments were used, was about 20 mm in both forest and clearing for all three years, despite wide differences in climatic conditions and drainage totals from year to year.

(7) The probable error in the annual evaporation or drainage measured by the method used is considerably less than that inherent in estimating evaporation using meteorological methods, which is of the order of 50 mm.

Frontispiece: Using the neutron probe to measure soil moisture content on the main site grid

1. INTRODUCTION

1.1 Aim of the Project

Approximately 35% of all public water supply in England and Wales comes from pumped groundwater (Smith 1972). Of this about 40% is accounted for by water from the Chalk aquifer which stretches in an arc from East Yorkshire across southern and eastern England to Dorset while much of the remainder is abstracted from the Bunter Sandstone deposits in the north and north-west Midlands. Areas within and close to these major aquifers are heavily dependent on groundwater; for instance, in southern and eastern England as a whole, groundwater accounts for about 50% of all public water supply.

As the demand for water grows it is becoming increasingly important to quantify and understand the components of the water balance of the aquifers which supply this water. The water balance may be written:

$$D = F + L + P + \Delta S \qquad (1.1)$$

where:

D = recharge by drainage from the soil

F = contribution to river flow and springs

L = seepage to other aquifers, the sea etc

P = water extracted by pumping

ΔS = change in storage of water in the aquifer.

This report concentrates on the first of these terms - drainage from the soil.

Conventionally this term is estimated either by taking the difference between rainfall and evaporation over an area or by attempting to estimate all other components in Equation 1.1 and solving for D. It is shown in the next Section that the first of these procedures leads to large uncertainties in the estimate of recharge, which may approach 100% of the estimate.

The latter method has been discussed by Buchan (1963) and used, for instance, by Wright (1974) to estimate the likely benefits from maintaining river flows over the Chalk outcrop in East Anglia by pumping groundwater. For many applications the method is attractive in that an integrated value for an aquifer unit as a whole is obtained. However, the number of areas where it is practicable is limited by the need to be able to estimate all terms on the right hand side of equation 1.1. It seems likely that in many cases uncertainties in the leakage term, L, and the actual amount of pumping, P, may be sufficiently large to make the method of little value (Buchan 1963). Moreover, the very fact that an integrated answer over the aquifer is obtained means that little or no information is obtained on the relative contributions

2. MEASUREMENT OF MOISTURE FLUXES IN UNSATURATED SOIL - THE ZERO FLUX PLANE METHOD

2.1 Aquifer Recharge from Measurements of Moisture Flux

The water balance of a soil profile, together with the crop growing on it, may be written:

$$P = I + T + e + D + \Delta M + Q \qquad (2.1)$$

where:

- P = precipitation
- I = water intercepted by the crop foliage and evaporated directly from it
- T = transpiration of water by the crop (equal to the quantity of water taken up by the roots)
- e = evaporation from the soil surface
- D = drainage from the profile
- ΔM = change in soil water storage
- Q = surface runoff.

It is assumed that all components except Q are one dimensional so that only the vertical direction need be considered. All components may be expressed as a depth of water over the ground surface i.e. as a volume per unit area. In particular the drainage, D, is an integrated water flux, ie a flow rate per unit area integrated over time. Ignoring any changes of water storage between the base of the soil profile and the water table, the drainage flux equals the rate of recharge water reaching the aquifer. Any storage changes will affect only the timing and not the total quantity of recharge water reaching the water table. Thus a knowledge of drainage flux from a profile is sufficient to compute the recharge to the aquifer at that point.

2.2 Measurement of Moisture Fluxes - the Zero Flux Plane Method

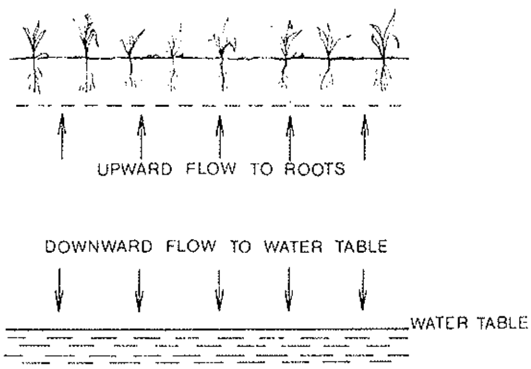


FIGURE 2.1

Water balance of soil profile under summer conditions

Figure 2.1 is a schematic diagram of a typical soil profile under summer conditions. Roots penetrate down to some depth, z_R, the limit of the root zone, and extract water from this zone creating low potentials within this part of the soil. If this potential becomes low enough then the upward (suction) forces will exceed the downward (gravity) force and the total potential gradient will be in a direction to induce water flow upwards into the root zone. If the water table is sufficiently deep drainage will still be occurring to it, so that in the lower part of the soil flow will be downwards. The potential profile will therefore look something like Figure 2.2a.

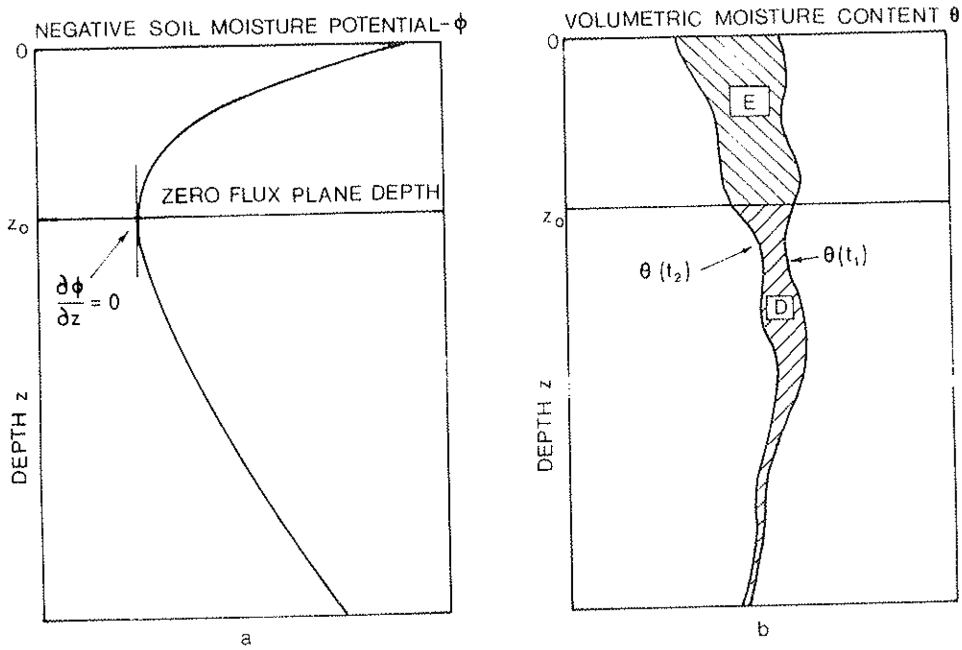


FIGURE 2.2 Potential and moisture content profiles under summer conditions illustrating the ZFP technique. Areas marked E and D are the amounts of evaporation and drainage between times t_1 and t_2.

The flux, v, defined as the volume of water per unit time passing through unit area, at any depth is given by Darcy's Law:

$$v = -K \frac{\partial \phi}{\partial z} \qquad (2.2)$$

where:

K = unsaturated hydraulic conductivity

ϕ = total moisture potential

z = depth.

Thus, knowing the unsaturated hydraulic conductivity and the potential gradient the flux may be determined. Moisture potentials may be measured using tensiometers so that $\frac{\partial \phi}{\partial z}$ is fairly easily determined, but the hydraulic conductivity presents more of a problem. Firstly, K may vary by a factor of 10^5 or so over the normal moisture content range of a typical soil (Hillel 1971, p105) and secondly there are large variations of K from place to place even in apparently homogeneous soils and over distances of a few metres (Nielsen *et al* 1973) at the same depth.

There is, however, an alternative to this which, for summer conditions, avoids the need to know values of hydraulic conductivity. This is the zero flux plane (ZFP) method.

Provided that there are no sources or sinks of water (i.e.interest is confined to the region below the root zone) moisture content changes are related to the moisture flux by the equation of continuity (Hillel 1971):

$$\frac{\partial \theta}{\partial t} = -\frac{\partial v}{\partial z} \tag{2.3}$$

where:

θ = volumetric moisture content

t = time.

Integrating Equation (2.3) between depths z_1 and z_2 yields:

$$\int_{z_1}^{z_2} \frac{\partial \theta}{\partial t}\, dz = v\,(z_1) - v\,(z_2). \tag{2.4}$$

Therefore, a knowledge of one of $v(z_1)$ or $v(z_2)$ and the rate of change of moisture content between the two depths enables the flux at the other depth to be calculated.

By examining Figure 2.2a it is clear that at the depth z_o the potential gradient is zero and, using Darcy's Law, Equation (2.2), the flux $v(z_o)$ is also zero.

Putting $z_o = z_1$ and $Z = z_2$ in Equation (2.4) gives:

$$v(Z) = -\int_{z_o}^{Z} \frac{\partial \theta}{\partial t}\, dz. \tag{2.5}$$

If the ZFP depth, z_o, does not change with time the accumulated flux, $F(Z)$, between times t_1 and t_2 is:

$$F(Z) = \int_{t_1}^{t_2} v(Z)\,dt = \int_{z_o}^{Z} |\theta(t_1) - \theta(t_2)|\,dz.$$

The situation in this case is shown in Figure 2.2b where the shaded areas represent the accumulated evaporation and drainage from the profile. All water depletion above the ZFP has gone to evaporation, whilst that below it is the amount of drainage.

Normally z_o does vary with time, however. The solution in this case is:

$$F(Z) = \int_{z_o(t_1)}^{Z} \theta(t_1)\,dz - \int_{z_o(t_2)}^{Z} \theta(t_2)\,dz - \int_{z_o(t_1)}^{z_o(t_2)} \theta(t(z_o))\,dz \qquad (2.6)$$

where:

$t(z_o)$ is the time at which the ZFP is at depth z_o.

2.3 Previous Uses of the ZFP Method

The method seems first to have been used by Richards *et al* (1956) to measure the moisture fluxes beneath a bare ground surface to derive hydraulic conductivity values for the soil. Richards *et al* used gravimetric sampling to measure the moisture content of their soil and mercury manometer tensiometers to define the potential profiles.

Following this de Boodt *et al* (1967) used the method for evaluating moisture fluxes and hydraulic conductivity under a growing crop, using a neutron probe for moisture content measurements and mercury manometer tensiometers for potentials. De Boodt *et al*, however, did not use the ZFP calculations to estimate evaporation from their crop, for which they relied on a lysimeter. The ZFP measurements were only made for depths below 0.3 m.

Giesel *et al* (1970) used the technique for a full water balance calculation of a soil profile beneath sugar beet for three months in summer. Once again they measured moisture potentials with mercury manometer tensiometers but used a gamma ray attenuation probe for measurements of moisture content which permitted readings close to the surface. From these measurements they calculated evaporation and drainage from their plot for a period of three months.

Daian and Vachaud (1971, 1972) used neutron probe measurements and an automatic scanning pressure transducer tensiometer to measure water fluxes during spring and autumn in a sandy profile. Royer and Vachaud (1974) extended these methods to calculate the water balance of a profile for ten months. Comparison with Thornthwaite's estimate of evaporation was good during spring and autumn when soil water content near the surface was high, but the measured evaporation fell to only a small proportion of the Thornthwaite estimate during the summer.

McGowan (1974) described a method, applicable to annual crops, for identifying a zero flux plane by observing the accelerated rate of water depletion at a particular horizon caused by the arrival of the root front. Comparisons with tensiometer-measured ZFPs and rooting depth measurements were good. McGowan used the method to calculate the soil water balance of a barley field for three months.

Arya *et al* (1975) used the ZFP method under a bare soil to determine the unsaturated hydraulic conductivity and pointed out that this allowed measurements of conductivity over a greater moisture range and in a shorter time than by using a method involving free drainage beneath a covered soil surface.

Cooper (1979) used the ZFP method to measure evaporation and drainage from a tea estate in Kenya to 5.7 m depth during a four-month dry spell. He found that transpiration by the tea occurred at a rate of 0.56 of the Penman EO estimate and was unaffected by soil moisture deficit. During the period the ZFP descended to 4.8 m depth.

It is notable that all of these investigations covered only short periods and that none contained an independent check on the results, although Royer and Vachaud (1974) and Cooper (1979) did compare their results with climatological evaporation estimates.

There is a clear need for data with which to check the reliability of the method and, to be useful in water resources applications, for measurements to cover extended periods. The experiment described in this report had the aim of satisfying both these needs.

3. SITE DESCRIPTIONS

3.1 General

This Chapter contains some general information about the Breckland area and Thetford Forest, followed by a brief account of the Institute's micrometeorological and plant physiology projects in the forest. Most of the measurements described in this report were made at the same site. There then follow detailed descriptions of the sites where measurements reported here were made.

Readers not wishing to spend too much time on the background and details of the soil and root distribution may gain sufficient knowledge to understand the rest of the report by reading the section on instrument location (p.19).

All sites described in this report were situated within the main block of Thetford Forest between Elveden and Mundford (see Figure 3.1). The forest is situated on the Norfolk-Suffolk border and occupies some 208 km^2, of the 1036 km^2 of Breckland. About half the forest area is within the central block.

The Breckland is an area characterised by sandy soils lying on Chalk in a gap in the Chalk escarpment in north-west Suffolk and south-west Norfolk. About three quarters of the area is arable land, with most of the rest being forest or heathland. 104 km^2 is used as a military training area, although much of this is also cultivated.

Corbett (1973) has written an excellent account of the soils of the forest area, which also contains much interesting background material on the history of the area, its geology, climate, land use and vegetation. To cover these topics in any detail would merely be to reproduce much of Corbett's monograph, so that only the most salient features will be described.

The forest was established in 1922 as part of the national campaign to become self-sufficient in timber following the first world war. The choice of site for the forest seems to have been a result of the agricultural depression of the 1920s and 1930s, which had a profound effect on marginal areas such as Breckland. Most of the planting took place between 1925 and 1936, so that the forest is still rather immature, in the sense that its age distribution is not yet static.

Scots pine (*Pinus sylvestris* L.) plantations account for 54% of the forest area, with Corsican pine (*Pinus nigra* var *maritima* (Ait) Melv.) the only other major species, occupying 24% of the area (figures for 1963 quoted by Corbett (1973)). In the future it is planned to replace almost all Scots pine by Corsican principally because the latter yields about twice the amount of timber (Backhouse 1972) and is more resistant to attack by insects and fungal agents. Corsican pine is, however, more difficult to establish. One of the sites (near Feltwell) for which data are reported was in a stand of Corsican pine, whilst the main site was beneath Scots pine.

The locations of the three sites used are indicated on Figures 3.1 and 3.2. The main forest site was the first for which data are available; some moisture content readings were taken from 1968. The clearing site had one neutron probe access tube installed in it in mid-1971, whilst measurements at the Feltwell site were taken only from early 1974. Each of the sites, and the instrumentation installed at them, are described in detail later in this chapter.

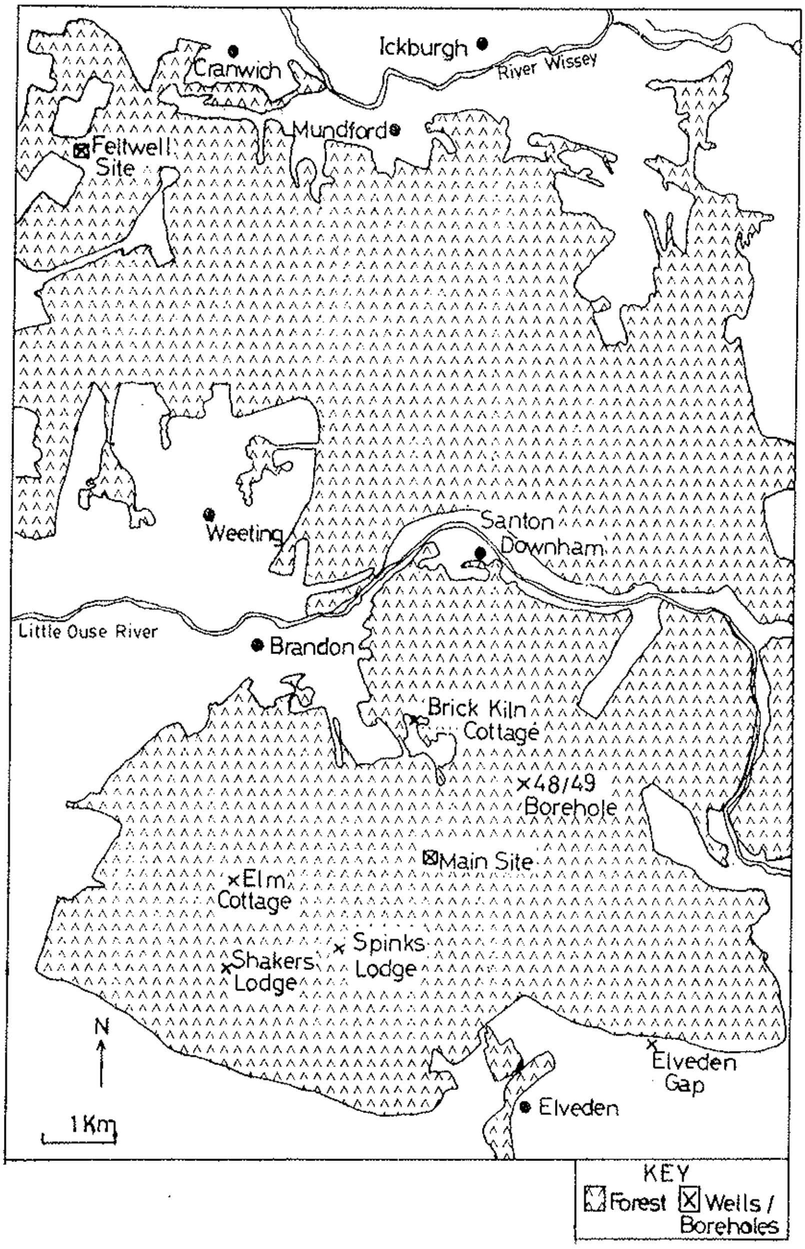


FIGURE 3.1 Main block of Thetford Forest showing locations of sites, wells and boreholes

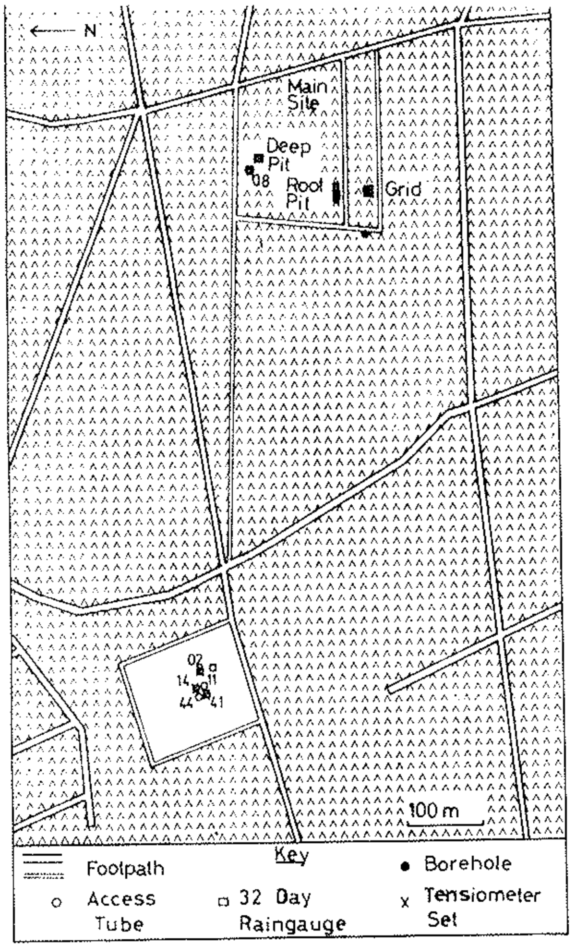


FIGURE 3.2

Plan of main forest and clearing sites

3.2 Climate

The Breckland area is amongst the driest parts of the UK, in terms of both annual rainfall and potential evaporation. They are similar in magnitude, rainfall being slightly larger. The balance between the two, giving the annual recharge, is thus very small and recharge estimates will be most sensitive to errors in determining rainfall and evaporation.

Table 3.1 (adapted from Table 5 of Corbett, 1973) shows values of mean annual rainfall, potential evaporation, potential drainage, 'actual' evaporation (calculated by assuming a limit to water abstraction from the soil of 106.7 mm) and 'actual' drainage from the profile. These values were calculated from data taken at Mildenhall some 14 km SW of the main site. It should be noted that the latter method for calculating drainage gives a value some 5.6 times higher than that using potential evaporation with no restriction, illustrating once again the sensitivity of recharge (or drainage) estimates to the model parameters for the evaporation phase.

TABLE 3.1 Mean annual rainfall potential evaporation and drainage and 'actual' evaporation and drainage at Mildenhall (adapted from Table 5 of Corbett (1975))

	Rainfall	Potential evaporation*	Potential drainage	'Actual' † evaporation	'Actual' † drainage
	mm	mm	mm	mm	mm
January	48.3	1.3		1.3	47.0
February	35.8	10.2	15.5	10.2	25.7
March	31.8	33.0		33.0	
April	43.4	57.2		57.2	
May	41.1	86.4		86.4	
June	37.8	96.5		84.3	
July	61.5	95.3		61.5	
August	51.6	77.5		51.6	
September	51.1	50.8		50.8	
October	48.8	21.6		21.6	
November	52.1	5.1		5.1	
December	45.7	- 1.3		- 1.3	14.8
Year	548.9	533.4	15.5	461.7	87.5

* M.A.F.F. (1967)

† With soil water holding capacity of 106.7 mm (4.2 in.)

3.3 Main Forest Site

General and hydrometeorological and plant physiology experiments

This site was established in compartment number 122 of Downham Highlodge Warren, an area of about 15 ha of Scots pine planted in 1931. The latitude and longitude of the site are 52°25'N, 0°40'E and the National Grid reference is TL805835. The site is at an average altitude of about 50 m and slopes downwards at about 1° to the west.

The site lies within a gently rolling area of the forest, with a height variation of less than 30m over a considerable area. It is at least 4 km in any direction from the edge of the forest.

At the time of the experiments the trees had reached a height of about 16m. The only other vegetation of note is a copious covering of bracken (*Pteridium aquilinum* (L.) Kuhn) over the forest floor from May to about November each year. This reaches a height of up to 2m in places although a more typical height is about 1.2m.

A large and complex experiment to study the hydrometeorological behaviour of the forest was operated at this site for some years. Its presence was one of the important factors governing the choice of site for the present work, since a check on the results was, in principle at least, available. Details of the experiment have been published by Stewart and Thom (1973), McNeil and Shuttleworth (1975) and Gash and Stewart (1975). Apart from the hydrometeorological experiment, measurements of interception of rainfall by the forest canopy and the bracken (*Pteridium aquilinum* (L.) Kuhn) have been made, in the early years by Dr P C Robins of Imperial College Field Station, and latterly under the direction of J H C Gash of this Institute, under a contract to DOE.

Measurements of rainfall, throughfall and estimated forest transpiration (Gash and Stewart, 1977) made as part of the above project have been made available for use in the water balance calculations to be presented later in this report. In parallel with the evaporation measurements a study of the relevant plant physiological factors has been made by Dr P C Robins and Dr J M Roberts. These have concentrated on litter accumulation, root distribution, plant water potentials, stem size variation and stomatal resistances. Most of this work has been performed on the trees, including a study of the differences between Scots and Corsican pine on two adjacent sites close to the main one. A considerable amount of work has also been done on the bracken, however (Roberts, in prep).

Some of the most illuminating experiments concerned with the plant physiological aspects of the water balance have been carried out on trees severed from their roots under water, thus removing any resistance to flow imposed by the soil-root pathway (Roberts, 1977). These experiments have shown amongst other things that the root-soil part of the pathway contributes about half of the total plant resistance, excluding that due to the stomata. By removing the water source from these cut trees Roberts (1976a) has also shown that the total water stored in the trees which is available for transpiration is unlikely to exceed 3 mm in total.

Soil and root distribution

A detailed study of the distribution of soil and roots at the main forest site has been published by Roberts (1976b). This work has been amplified by the excavation of a large (24 m x 3 m) pit some 2.85 m deep to map soils and roots occurring at various depths. This latter work is described in detail in a supplement to this report by S A Boyle. Additionally, some work has been performed by J M Roberts and Mrs C F Pymar (unpublished) which throws light on the effective depth of root activity which is of direct relevance to this report. The main conclusions only of these three pieces of work will be summarised here.

(a) Soil

The soil at the site is classified (Corbett, 1973) as Worlington series. Considerable debate (see e.g. Perrin *et al.*, 1974; Corbett, 1973) concerning its origin persists and it is not clear whether the sand and/or the chalky drift was transported to the site by wind-blow or periglacial processes.

From the standpoint of the work described here the conventional soil classifications are of limited use and a straightforward description of the various horizons will be made. A schematic diagram of a typical vertical cross section through the soil is shown in Figure 3.3. A layer of litter varying from 50 mm to 100 mm in thickness, consisting of dead pine needles, bracken fronds and other plant debris covers the soil surface. At its base the litter is considerably decomposed and feels damp even during dry spells in the summer. Beneath this a grey A horizon consisting, apart from some organic matter, almost exclusively of sand particles grades into a sand E_b horizon at about 0.3 m depth. Once again the E_b horizon is almost exclusively sand and has a bright orange-brown colour. The depth of the lower boundary of this horizon varies markedly, with a fairly prevalent upper level of about 0.75 m which plunges steeply into deep pockets, about once every two metres and having a width at the top typically from 0.2m to 0.5m. The depth of the pockets normally does not exceed 1.7 m, but occasionally they may reach the upper boundary of the chalk at about 2.7m and even penetrate below this.

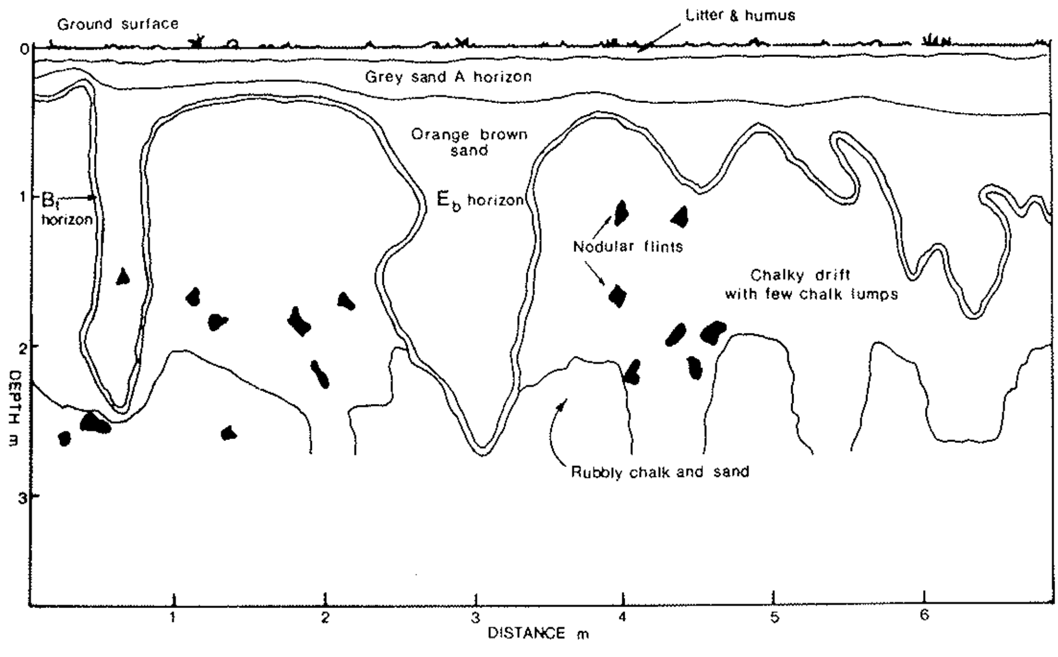


FIGURE 3.3 Cross-section through soil profile at main forest site observed in deep root pit

A thin layer of dark reddish-brown clay enriched (approximately 14%) sand forms a B_t horizon below the sand E_b horizon. This is typically 50 mm thick. It is usually a single band but occasionally splits into two or three thin ($\lesssim$ 5mm) layers within the E_b horizon. At the bottoms of the deep pockets both the thickness of the horizon and its clay content increase, as evidenced by a darker colour and stickier texture of the horizon. In the large pit two examples were observed of a B_t horizon extending down to and below the normal surface of the chalk. One of these was excavated and found to penetrate to about 4.5m below ground, or 1.8m into the chalk. The material of this horizon when it penetrated to the chalk was found to be very sticky and dark in colour, implying a very high proportion of clay, although no measurements of clay content are available.

Below the B_t horizon lies a C horizon of chalky drift - a mixture mainly of sand and finely ground chalk also containing lumps of chalk and many flints. This material is very heterogeneous with large variations of chalk content from place to place. Most (though not all) of the flints found in the profile are contained within the chalky drift with a marked increase in their frequency of occurrence and size towards the bottom of the horizon at about 2.7m. Generally speaking the chalky drift is mechanically very compact, presumably being partially cemented by the calcareous material. The material at the top of the horizon tended to be rather softer.

Lastly, below the chalky drift C horizon lies the Chalk. The surface of this lies at about 2.7m and is much more regular than the $E_b/B_t/C$ horizon interfaces, varying typically by only 0.2 m in depth. The upper metre of this chalk is weathered but it appears to be relatively undisturbed and 'blocky' below this. The presence of numerous nodular flints suggests it to be Upper Chalk, although the geological records of the area are unreliable. Insufficient investigation was made to establish the presence or absence of banding of the flints, although some very large examples were found. The average size of flints in the chalk is about 100mm which is rather larger than in the C horizon where 50mm or less is more typical.

(b) Roots

Roberts (1976b) has investigated the rooting distribution using, principally, vertical soil cores to 2m depth supplemented by observations from windows on the sides of a pit dug for the purpose and from monoliths taken from the upper metre of soil.

The principal conclusions from this work were:

(i) The total length of roots per unit volume of soil decreased sharply down the profile. This decrease was almost entirely due to a decrease of the fine (< 0.5mm dia) root fraction. Of the 12,600m of root beneath a square metre of soil surface, 64% occurred in the upper 0.15m, 80% in the upper 0.3m and 93% in the upper metre.

(ii) The density of roots generally fell with distance from the tree stems typically to about half at points equidistant between trees. The variation, again, is apparently accounted for purely by the fine (< 0.5mm) roots, which anyway are by far the most numerous.

(iii) Roots hardly penetrated into the chalky drift C horizon except in a few instances. However, the clay-rich B_t horizon was very heavily populated by roots with a high degree of branching.

(iv) The number of growing root tips decreased with depth in a similar, but faster, manner to that of total root length. The numbers of root tips reached a maximum in about June of each year.

(v) The total length of bracken roots per unit area of soil was about 10% of the length of pine roots, although they hardly penetrated deeper than 0.6m.

Apart from the deep observation pit described in the supplement these observations were complemented by examination of the root systems of felled and windblown trees which in many instances showed a very marked effect of the encounter between the growing root system and the chalky drift. Sizeable ($\gtrsim$ 10mm dia) roots often had a flattened appearance as they were forced to change direction abruptly at the interface with the chalky drift and in other cases the root system could be seen to have grown around a pocket of drift, almost completely enclosing it. In these instances much softer, sandy material was found to adhere to the roots. A minority of trees were found to have one or several large roots extending almost vertically downwards, which suggested that water could be extracted by these trees from greater depths, although these roots were usually badly damaged so that their lengths could not be estimated reliably. Roberts had found some evidence for deep roots and suggested that these were the cause of the higher root density close to trees.

The digging of the large observation pit broadly confirmed the above observations and provided a lot of extra information about the rooting patterns below 1m and the interaction between root density and soil. In particular it was found that:

(i) Whilst the B_t horizon was heavily exploited by roots these were concentrated particularly on the interface between the B_t and C horizons.

(ii) The upper layers of the C horizon did contain a substantial number of fine roots. For instance at 1 m depth there were an almost equal number of roots found in the B_t horizon as in the C horizon.

(iii) One large root followed a sand pocket and then the B_t horizon to a total depth of 4.5m, some 1.8m below the general level of the surface of the chalk. This demonstrates that some (though a very small proportion of) roots do reach great depths and may provide water from these regions.

Some work has been performed by J M Roberts and Mrs C F Pymar (unpublished observations) on the likely role of deep roots. During the summer of 1975 they severed the main lateral roots from two trees within the experimental site and monitored leaf water potentials and stomatal resistances. No significant difference in either of these quantities was found compared with those exhibited by neighbouring undisturbed trees even when all lateral roots had been severed. During the same period the surface layers of the soil around a group of trees was kept moist by irrigation and once again leaf water potentials and stomatal resistances monitored for these trees and for others not subjected to irrigation. No differences were detected until about early August when soil moisture deficits of the unirrigated areas reached about 60mm, after which the leaf water potentials for the irrigated trees became higher while their stomatal resistances were lower.

Location of instruments at main forest and clearing sites

Figure 3.2 shows the relative locations of the instruments employed during the course of the project. The majority of results from the main forest site have come from four instrument sets on the forest grid. Access tube number 08 and its associated tensiometer set sited some 50m away provided a further long run of data.

There were two clearings about 1 km from the forest site, one to the east (not shown in Figure 3.2) and one to the west. The former, which had been clear-felled in 1969, was used for rainfall measurements whilst in the latter soil moisture tensiometers and neutron probe access tubes were installed in addition to raingauges.

Access tube grid in forest

An access tube grid was installed between January and March 1971. There were, in all, 81 tubes in a 9 x 9 square array spaced at 4 ft (1.22 m) centres in each direction. The deepest depth at which readings were possible in all tubes using a neutron probe was 3.1m, although four tubes (A9, B9, C9 and I9) could be read deeper. These are identified on the plan of the grid, Figure 3.4 overleaf.

Wooden railway tracks, elevated about 1m above the ground surface, were erected prior to installation of the access tubes, so that almost all work could be performed without the necessity of standing on the ground. The use of these prevented damage to the soil surface and bracken understorey.

Tensiometers were installed inside a circle of diameter 0.4m at the centre of each of four squares defined by four access tubes. Using this arrangement all tensionmeters were at least 0.6m away from any particular access tube, which is sufficient to ensure that no disturbance was caused to the neutron probe readings in these tubes.

The choice of squares for tensiometer installation was made using the following considerations: the squares should not be right at the edge of the grid in case anomalies should need to be checked by reference

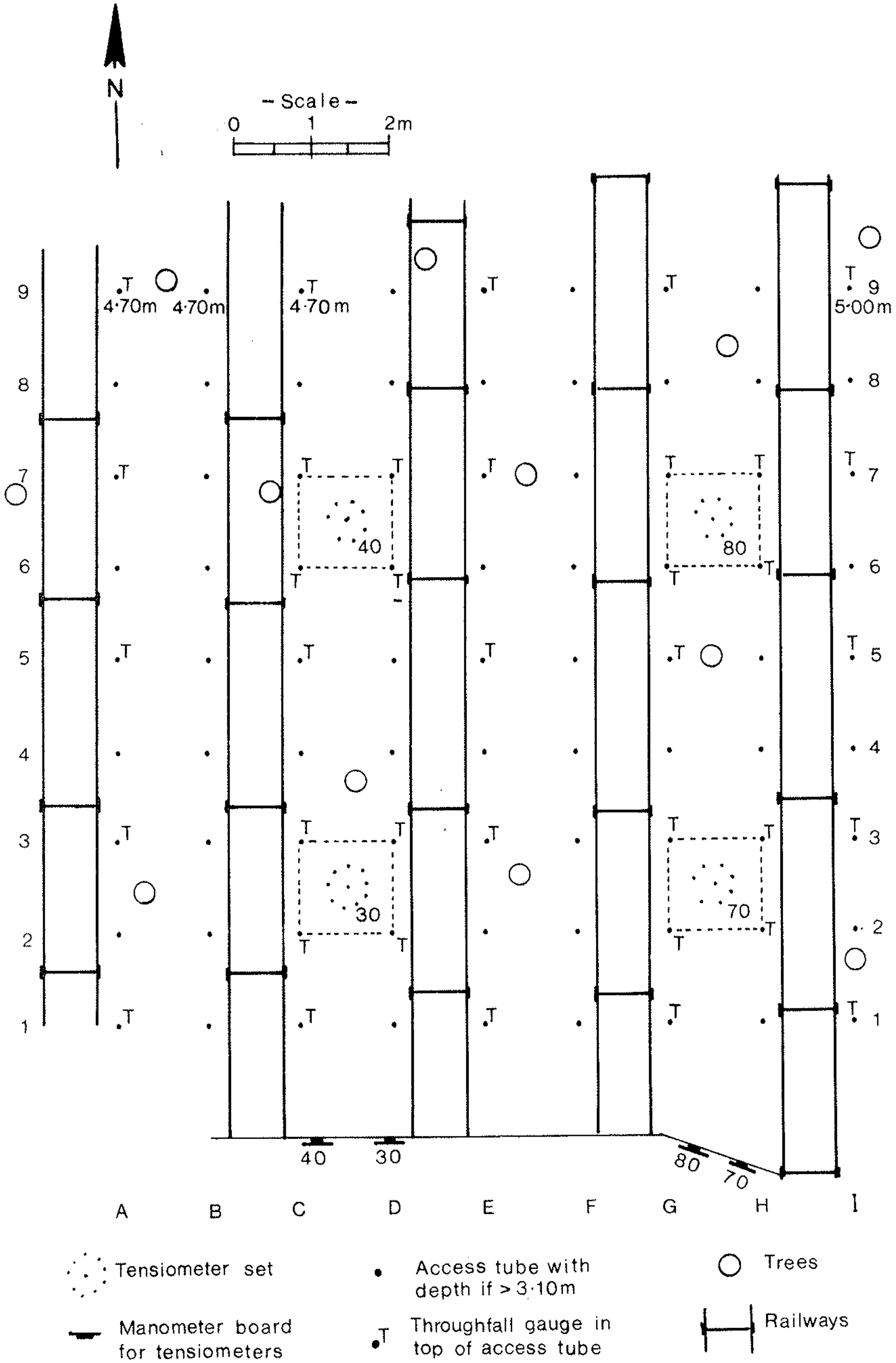


FIGURE 3.4 Thetford access tube grid

to the next nearest neighbour access tubes; the four sets should be in a square pattern to preserve the symmetry of the grid; they should, within the constraints imposed by other considerations, be as far apart as possible and the tensiometers should be located between two sets of railway tracks. This last requirement was made for two reasons: it was thought that it would be easier to install and service the tensiometers if they were placed between sets of tracks, and the tracks, although not of large cross-section (75mm x 50mm), could have sheltered the tensiometers if they had been too close to them. In practice it turned out that servicing of the tensiometers would have been easier if they had been installed between a pair of rails, although the second reason remains valid.

These considerations gave two possible choices for the squares and correlation analysis of the moisture contents measured in the relevant tubes was used to decide between them. A fairly clear-cut decision was possible based on the correlation coefficients of total profile moisture contents between the individual tubes and the mean of all 81 grid tubes. This was supported by an examination of similar correlations for the individual depths.

3.4 Clearing Site

A grass clearing situated some 1 km WNW of the main forest site was used to obtain data for comparison with those taken beneath the forest. Although relatively large (170m x 140m) its water balance could not be expected to be completely representative of an extensive area of grass because of the sheltering and also shading of the instrument sites in early morning and late evening by the trees around the edge. Nevertheless, the results are believed to give an indication of the differences in water balance between the two types of vegetation.

The grass was not cut in this clearing since the readings reported here were begun, although it had been mown two or three years prior to this. No systematic investigation of the soil profile was made in this clearing, though observations of the material removed whilst installing the instruments showed it to be very similar to that at the main forest site. A few cores were removed from the upper 0.6m of the profile for a rough determination of the root distribution. This showed that virtually all roots lay within the upper 0.2m.

The instruments at this site comprised one neutron probe access tube which could be read to 2.4m below ground, together with a set of twelve tensiometers installed at 0.2m depth intervals from 0.2m to 2.4m, (this set was coded O2), four neutron probe access tubes, forming the corners of a 3.6m square, readable to 3.0m and two sets of tensiometers around two of these tubes at the same depths as set O2.

A storage raingauge, which automatically channelled water into a different bottle every day for 32 days was installed in this clearing and used for rainfall records at the site until the end of 1974.

3.5 Feltwell Site

This site had been the location of a set of experiments carried out by D F Fourt of the Forestry Commission in 1963-66 using gypsum resistance blocks to 1.5m as indicators of soil moisture status. The opportunity to work on the same site, unfortunately not simultaneously, was therefore taken, particularly as the Forestry Commission results indicated a possibility of deep extraction of water by the trees from a water table some 10m or so beneath, a situation which conflicted with early results from the main site.

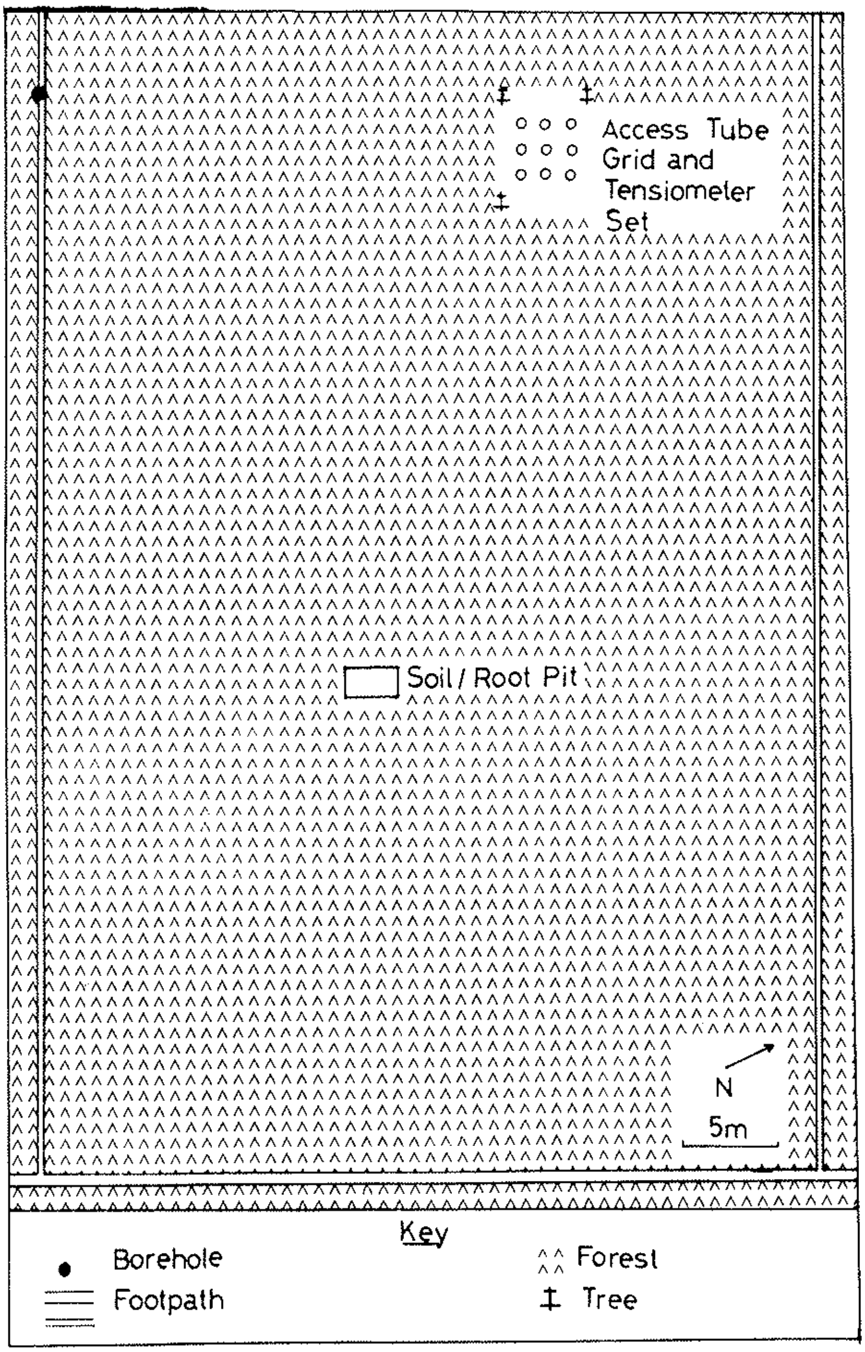


FIGURE 3.5

Plan of Feltwell Site

By contrast with the main site, the Feltwell site was planted with Corsican pine of height about 16m. There was no bracken understorey at this site, the ground surface instead being covered mainly by brambles and nettles.

A small profile trench was dug by the Forestry Commission in the summer of 1973 which revealed a sandy topsoil of only about 0.30m depth lying over a chalky drift C horizon. This C horizon was markedly richer in chalk than at the main site and contained numerous chalk lumps. The interface with the chalk proper occurred at about 1.7m below ground. The soil is mapped as a complex of Methwold and Newmarket series (Corbett 1973).

Visual observation of roots in the profile trench and of trees blown down in the gale of 1/2 January 1976 showed them to be confined to the sandy soil with only minimal penetration into the drift, although the interface and hence the rooting depth were much shallower than at the main site.

Nine neutron probe access tubes capable of being read to 3.2m below ground were installed about 30m away from the profile pit in a 3 x 3 square array of 1.2m spacing. A single set of eleven tensiometers at depths from 0.2m in 0.3m increments to 3.2m was also installed in the same area as the access tubes. These instruments were installed in spring 1974 and a borehole of depth 19.9m was drilled some 25m from the access tubes in August 1975 for water level observations and for the installation of pressure transducer tensiometers (see Section 4.2). A single tensiometer of this kind was installed in early February 1976 at a depth of 7m below ground, followed in May 1976 by two others at 6m and 8m depth, although the 8m instrument failed to give reliable readings.

3.6 Wells and Boreholes

Right from the start of the project a series of groundwater level observations was begun. Initially this involved the location of existing wells within a radius of about 5 km of the main site, of which five were found.

Attempts to define the groundwater level contours from these observations left considerable scope for uncertainty. Further, the closest observation well to the main experimental site was about 1.3 km away. Two further boreholes were therefore drilled to well below the water table in the vicinity of the main site in August 1975 by the Institute of Geological Sciences. One of these was located within the experimental compartment and the other 1.9 km to the NE. An extra borehole was drilled at the Feltwell site at the same time. A water level recorder (R W Munro Ltd, model IH 103, modified to reduce friction) was stationed over the well at Shakers Lodge (TL 779819) from mid-1971 until February 1976. A continuous chart record of the level of this well is therefore available covering most of this period. The locations of all the wells and boreholes in the main forest area are shown on the map in Figure 3.1.

4. EXPERIMENTAL METHODS

4.1 Moisture Content Measurements

All moisture content measurements were made using a neutron probe. Until mid-1975 this was a Model 225 'Wallingford' soil moisture probe manufactured by D.A. Pitman Ltd and described by Bell (1969). After this a probe manufactured to Institute of Hydrology specifications by the Didcot Instrument Company was used. Because the source-detector geometry of the two designs is the same and the external shape of the two probes is very similar they may be used interchangeably. Hence no distinction will be drawn between the two models in the rest of this report. In all cases a ratescaler was used for counting the neutrons detected. This displays in digital form the mean count rate recorded over a preset 16 or 64 second integration time. Thus because the numbers of counts recorded over any time interval are expected to follow a Poisson distribution, the longer integration time gives twice the precision of the former (e.g. Bell 1976).

Emplacement of the 1.75" (44.5mm) diameter aluminium alloy access tubes followed generally the method outlined by Bell (1976), although the extreme stoniness of the soil meant that often a pilot hole could not be made using a soil auger; the guide tube and rammer system was used alone in these circumstances.

The calibration curve used for conversion of neutron probe readings to moisture content was:

$$\theta = 0.79 \frac{R}{R_w} - 0.024 \qquad (4.1)$$

where:

R = count rate recorded in soil

R_w = count rate recorded in a large drum of water.

This calibration was derived in a drum in the laboratory. It agrees well with calibrations carried out in the field by the method described by Bell (1976) and with that proposed by Couchat *et al.* (1975). A comparison between these latter two methods for the Thetford site, amongst others, has been published by Vachaud *et al.* (1977).

The relatively large number of access tubes read necessitated the use of 16 second integration times. Use of 64 second integration times would have meant roughly halving the number of access tubes which could have been read in the same time, thus gaining precision of the individual moisture contents but sampling the spatial variations rather poorly. Since the experiment was directed primarily at obtaining long-term moisture flux measurements it was considered more important to achieve a good spatial average.

The depth intervals were chosen to obtain a good sample of profile changes in the parts where they varied markedly with depth, that is near to the surface, rather than by statistical considerations. On the access tube grid in the forest depths read were normally 0.2, 0.35, 0.5, 0.8m, then in 0.3m increments to 2.9m and a last one at 3.1m. Tube 08 was read at depths of 0.2, 0.3, 0.4m, then at 0.2m intervals to 2.8m. The clearing tubes were read at the same depth intervals as tube 08 except that the lowest depth read in tube 02 was 2.4m and in the other four tubes 3.0m. Prior to June 1975 tube 02 had been read at depths of 0.2, 0.3, 0.45m then in 0.15m intervals to 2.4m. The Feltwell tubes were read at the same depths as the main forest grid tubes except that a reading at 3.2m depth was taken in all but two tubes instead of 3.1m.

From the individual measurements of moisture content v depth the amount of water in the profile has been calculated using trapezoidal integration. This assumes that moisture content can be interpolated linearly between reading depths and is the simplest form which can be used. For the surface layer the moisture content determined at 0.2m depth has been assumed to apply over the depth interval from the surface to 0.2m.

4.2 Moisture Potential Measurements

Mercury manometer tensiometers

All moisture potential measurements were made by tensiometers. For the water balance measurements conventional mercury manometer tensiometers were used (e.g. Richards 1949). Figure 4.1 is a diagram of the construction of these units. They were installed through 1.75" (44.5mm) dia aluminium alloy access tubing, sealed at the top with a rubber bung. The lower end of the tensiometer tube, carrying the porous ceramic cup, protruded 0.2m below the access tube into soil which had been sifted of stones and repacked. This procedure ensured good contact between the cup and soil, whilst making for ease of installation in the stony soil.

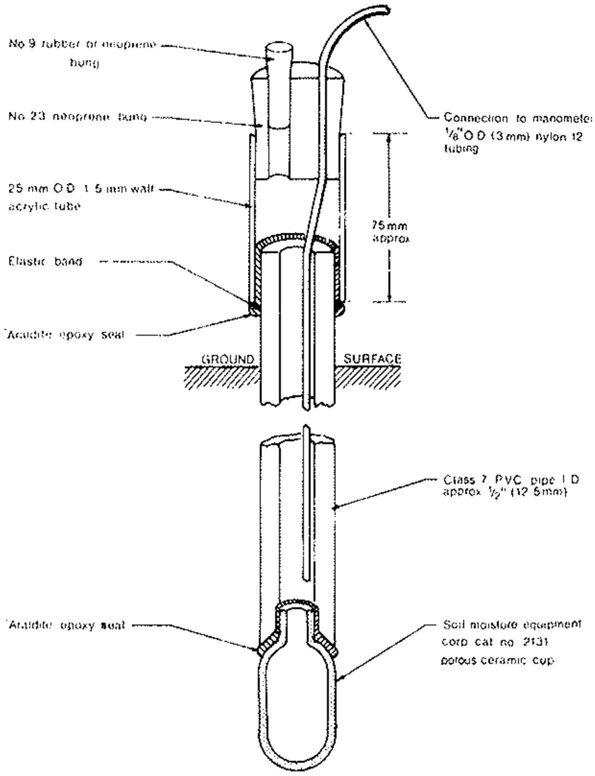
For ease of servicing from the elevated rails the tensiometers on the access tube grid and at set 08 at the main forest site were installed with about 1.5m of their stems protruding above ground. The tensiometers in the clearing and at Feltwell, however, were installed with only the acrylic tops protruding above ground to reduce disturbance of the readings by the heat of the sun.

The boards with scales and mercury reservoirs were mounted on 2" (50mm) angle iron stakes. These were placed as close as practicable to the tensiometers consistent with their not shading or sheltering them significantly. On the main access tube grid the boards were mounted at the access end of the elevated rails so that it was possible to read the tensiometers without going onto the rails. This entailed long (up to about 10m) runs of the nylon connecting tubing. However, no particular problems were encountered because of this.

To minimise disturbance of the mercury levels by expansion of the water in the tensiometers due to incident sunlight, readings were normally made early in the morning.

FIGURE 4.1

Construction of tensiometer



The presence of air in tensiometers causes only a small inaccuracy in static tensiometer readings, but because of the large compressibility of air its presence leads to a much longer response time than would be the case if there were no bubbles. A few small air bubbles were, therefore, tolerated but when large bubbles appeared in the acrylic tube the tensiometers were refilled, and the air flushed out of the nylon tube using a syringe (known as purging). Problems were not normally experienced for total potentials greater than - 600 cm H_2O, but below this both the incidence and effects of air bubbles became rapidly more serious.

Potential profiles and identification of zero flux plane depths

Examination of sequential profiles of total potential v depth has been used to identify zero flux plane depths. Owing to the large heterogeneity of the soil it has not been possible to measure potential gradients reliably over a sufficient depth interval to make direct solutions of Darcy's Law feasible. However it was possible to estimate zero flux plane depths sufficiently precisely to allow water balance estimates for the summer months to be made without reference to meteorological data other than rainfall information. To avoid the identification of apparently spurious ZFPs it has been found best to work with sequential profiles of total moisture potential so that the evolution of the ZFP can be seen. Examples of these are shown in the next chapter. To make a fairly objective and reproducible estimate of the ZFP depth the method, depicted graphically in Figure 4.2, has been used. The depth identified corresponds approximately to the point where $\partial\phi/\partial z = 0$ on a smooth curve drawn through the data points.

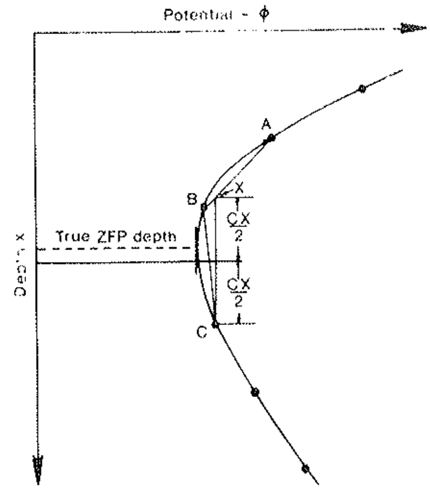


FIGURE 4.2

Illustration of method used to calculate depth of ZFP

Pressure transducer borehole tensiometers

The maximum depth to which conventional tensiometers may usefully be mounted is about 3m. This is because the absolute pressure P inside the tensiometer at a height, d above the tensiometer cup is given by:

$$P = A - \psi - d \qquad (4.2)$$

where A is atmospheric pressure and ψ is the soil moisture tension at the cup location. All terms are in units of water head.

For the tensiometer to work reliably the requirement that the absolute pressure at all points must be above zero (strictly speaking the saturation vapour pressure of water) must be fulfilled. With a tensiometer cup at 3m below ground and about 1.5m of the instrument above ground the lowest pressure in the system will be:

$$P_{min} = A - 4.5 - \psi \qquad mH_2O.$$

A is about 10m H_2O so that the maximum value of tension which can be registered is about 5.5m H_2O. For deeper installation depths this limit is reduced i.e. the range available for the matric potential component decreases linearly with depth.

One solution to the problem of making tensiometer measurements at depth is to avoid the long column of water to the surface by substituting for the mercury manometer an electrical pressure transducer, fitted directly to the tensiometer cup. It also provides an opportunity to record the output automatically. Strebel *et al.* (1973) have described such an instrument which they lowered successively into holes of different depths.

As an alternative a tensiometer has been designed which can be inserted into an uncased observation borehole and left in place. The construction of the instrument is shown in Figure 4.3.

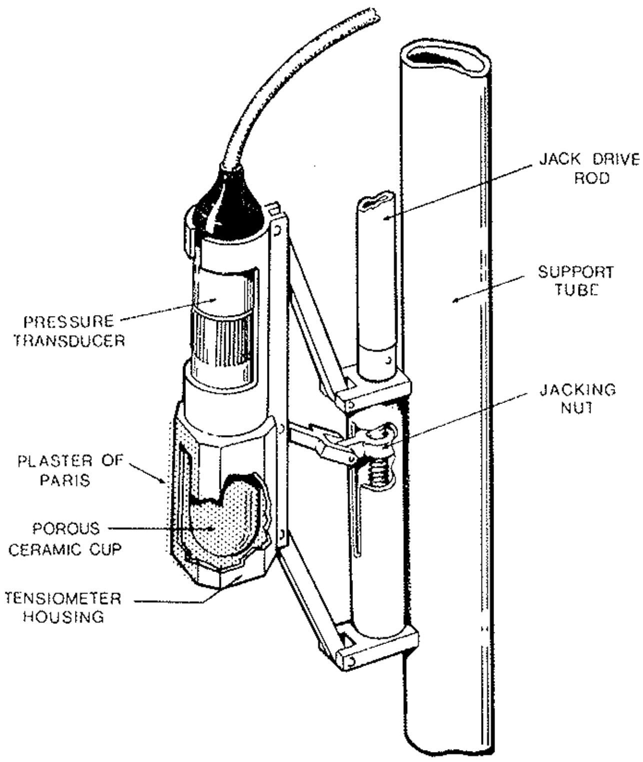


FIGURE 4.3

Construction of pressure transducer tensiometer for mounting in borehole

A pressure transducer is mounted onto a porous cup so that the whole forms a vacuum-tight assembly filled with de-aerated water. The porous cup is encased in a block of plaster of Paris which is pressed against the side of the borehole by a small screw jack. This establishes hydraulic continuity between the formation and the water within the porous cup and also serves to support the assembly. Several of these tensiometers may be installed on a single support tube within a borehole, which may be of any diameter above about 100mm. Each tensiometer has its own drive rod which is turned from the surface to operate the screw jack. The output from each transducer may be monitored from the surface by a portable digital voltmeter or a logging system.

At the Feltwell site one of these tensiometers was installed at 7m depth in February 1976, followed by two others at 6m and 8m depths in

May of that year. Readings were made approximately twice weekly using a portable digital voltmeter.

4.3 Protection of Ground Surface

Both installation work and frequent measurements of a neutron probe access tube carry the danger that the ground surface will be disturbed in such a way that near-surface water content measurements are not representative of the area as a whole. Two major effects are likely. Frequent trampling near the tube, or even quite light pressure from, for instance, the probe cable, may prevent vegetation emerging, thus preventing the soil in the vicinity of the probe from contributing to transpiration. Secondly, damage to the soil surface is likely to alter the infiltration characteristics of the soil. Normally one would expect compaction and therefore a lowered infiltration capacity, but the opposite effect may occur in some cases.

To reduce damage to the soil surface as much as possible the elevated railway system described earlier was erected prior to any installation work being performed on the access tube grid. All installation work was carried out during January to April when the bracken was dormant and on the few occasions when it was necessary for operators to stand on the ground, rather than on boards across the railways, large duck boards were used. All neutron probe readings of the grid access tubes were made from trolleys running along the railways. Tensiometers were serviced from boards laid across the railways and read from the manometer boards mounted at the perimeter of the grid.

For all other sites (main forest site 08, clearing and Feltwell) the areas occupied were smaller. Installation work was carried out using large duck boards. For readings a low 'Dexion' frame about 1.5m square and 0.4m high served to keep operators' feet away from the access tubes and tensiometers. In addition readings were always made from the same side of the frame. At Feltwell the frame was rather larger and the access tubes were read from boards laid across the frame and removed afterwards.

4.4 Rainfall and Throughfall Measurements

Prior to the establishment of a magnetic tape logging instrument for the interception project, rainfall was measured by a 32-day storage gauge in the clearing shown in Figure 3.2 and for some of the period to the beginning of 1975 by two Dines tilting syphon gauges with check gauges read daily in both clearings.

From the beginning of 1975 rainfall measurements were available from a 'Rimco' tipping bucket gauge in the clearing to the east of the main forest site and from two similar tipping bucket gauges above the forest canopy associated with the automatic weather station. These data showed good consistency with one another and with the other instruments so that the readings from the latter were discontinued. The data were recorded on magnetic tape and the readings were made available by JHC Gash of the Institute.

Soon after the establishment of the main access tube grid 25 throughfall gauges were installed on each alternate access tube in either direction. The construction of one is shown in Figure 4.4. They were normally read whenever the tubes on the grid were read. The calibration of these gauges was:

$$\text{Throughfall in mm} = \text{Amount collected in ml} \times 3.50 \qquad (4.3)$$

The number of throughfall gauges was increased to 37 in August 1975 with the addition of gauges to the tops of the twelve tubes of the sixteen read regularly which did not already have a gauge. Comparison between mean throughfall measured by these gauges and by separate measurements in throughfall troughs made by the Hydrometeorology section as part of their interception project showed very good agreement.

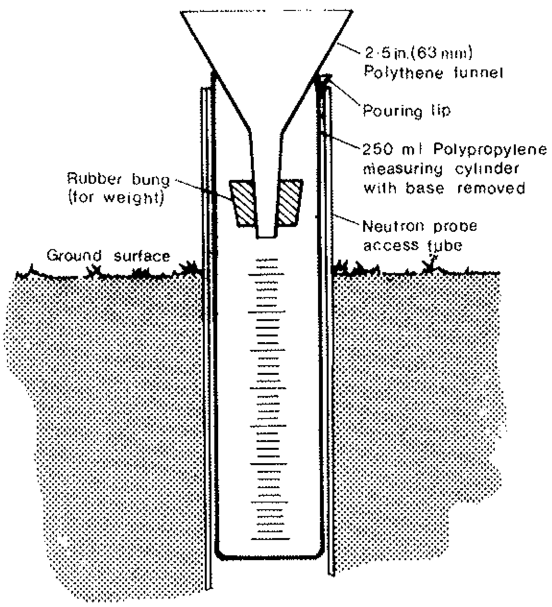


FIGURE 4.4

Throughfall gauge for installation on top of access tube

No account has been taken of stem flow which for the main site is a small component of the total water balance (about 2% of rainfall, Gash and Stewart, 1977), but may be very much larger elsewhere.

To derive interception estimates it was necessary to distribute the throughfall on a daily basis. For 1975 and 1976 the throughfall measurements from the troughs were normalised to the grid gauges for the period concerned (differences over short periods were up to about 15% between the two sets, though over a year they were insignificant) and then the grid throughfall distributed according to that recorded by the troughs. Prior to 1975 throughfall was distributed according to the daily rainfall.

No rainfall or throughfall data were collected at the Feltwell site, where the measurements at the main site were assumed to be applicable.

4.5 Calculation of Moisture Fluxes

There are two distinct situations to consider when calculating moisture fluxes from the data collected as described above. The first occurs during the late spring, summer and early autumn when a zero flux plane is present and the second during late autumn, winter and early spring when no ZFP can be identified and the profile is draining throughout its whole depth.

Periods when a ZFP is present

When a zero flux plane can be identified from the tensiometer data moisture fluxes are calculated according to Equation (2.6), modified to take account of the fact that no moisture content information is available between neutron probe readings.

If $\theta(z,t)$ is the moisture content at depth z and time t and $z_o(t)$ is the ZFP depth at time t it is assumed that the mean moisture content:

$$\bar{\theta}(z) = \tfrac{1}{2}(\theta(z,t_1) + \theta(z,t_2)) \tag{4.4}$$

is a good estimate of the moisture content between the two reading times.

The term $\int_{z_o(t_1)}^{z_o(t_2)} \theta(t(z_o))\,dz$ in Equation (2.6) is approximated

by:

$$\int_{z_o(t_1)}^{z_o(t_2)} \theta(t(z_o))\,dz \approx \int_{z_o(t_1)}^{z_o(t_2)} \bar{\theta}(z)\,dz. \tag{4.5}$$

Linear interpolation is used to estimate $\theta(z)$ if z is not a reading depth and integration is performed by the trapezoidal method.

Periods when no ZFP is present

For periods when no ZFP has been found within the profile it would be desirable for full self-consistency to make use of direct solutions of Darcy's Law. As mentioned in Section 4.2 however, it was not found possible to define moisture potential gradients with sufficient accuracy so that this technique could not be used at this site.

It is clear from Section 2.2 and in particular Equation (2.4) that if the moisture flux at any depth is known, the flux at any other depth in the profile can be calculated from a knowledge of the moisture content changes between the two depths. An estimated flux at the soil surface (given by rainfall - evaporation) was therefore used for the winter period and drainage estimates calculated from these and the measured moisture content changes. For the forest sites the model used by Gash and Stewart (1977) has been assumed whilst Penman estimates of evaporation (ET) were used for the clearing.

4.6 Borehole and Well Level Readings

The depths of the wells and boreholes were read normally once per fortnight with an 'Ott' electric contact gauge. The levels of the tops of all wells and boreholes were measured from the nearest Ordnance Survey benchmark using a surveyor's level, so that the groundwater level above ordnance datum could be calculated for all measurements.

One well, Shakers Lodge, (see Figure 3.1) had a 'Munro' IH 103 water level recorder stationed over it until February 1976. Charts on this were changed once per month.

5. EXPERIMENTAL RESULTS

5.1 Moisture Contents

The variations of moisture content in typical selected tubes in both clearing and forest for 1974 to 1976 are shown in Figures 5.1 to 5.6. Grid 'tubes' 30, 40, 70 and 80 each represent the mean of four tubes surrounding each of the four tensiometer sets identified by the same number. At each depth the reference moisture content datum has been calculated as the mean over a winter period, excluding readings taken less than 2 days after rain. It is expected therefore to correspond approximately to classical concepts of field capacity, although in these circumstances the datum is not expected to be exactly reproducible from year to year as it represents an equilibrium between winter input and drainage rates.

Some moisture content profiles are also shown in Figures 5.1 to 5.6. It is apparent that moisture content variations at any given depth take place about radically different mean values, illustrating the usefulness of defining a specific datum for each measurement depth in each tube.

5.2 Moisture Potentials

Moisture potential variations are illustrated in Figures 5.7 to 5.13, in a similar manner to those of moisture content,for some typical tensiometer sets. Total potential at each depth is plotted with reference to the basal datum line (solid) whilst the matric potential component is represented by the departure from the broken line. Moreover, although potential is generally a negative quantity, the graphs have been plotted with more negative values on what is conventionally the positive side of the axes. Thus high values of the line refer to low values of potential.

Some moisture potential profiles at different times through the year measured by the same sets of tensiometers are shown in Figures 5.14 and 5.15. These illustrate the need for examining sequential profiles to identify what appear to be real ZFPs and to reject spurious features. Zero flux plane depths are marked on these figures by horizontal lines.

5.3 Zero Flux Plane Depths

Zero flux plane depth variations for all tensiometer sets in each year are shown in Figures 5.16 to 5.20. In 1974 only one set of tensiometers (O2) was installed in the clearing and the variation of its ZFP depth with time is included in Figure 5.16. For the other two years the forest and clearing ZFP depths are shown separately and the Feltwell data are included for 1975 in Figure 5.17.

5.4 Site Water Balances

The cumulative water balances derived for the mean of the four sets of forest grid instruments and one set of instruments in the grass clearing (O2) for each year, together with the Feltwell site water balance for

1975, are shown in Figures 5.21 to 5.27. These have been derived by the methods outlined in Section 4.5. For periods when no ZFP has been observed in the profile the actual evaporation has been assumed to be equal to a theoretical estimate based on climatic observations. For the forest this is an estimate of transpiration plus actual measurements of interception collected as described in Section 4.4. This is referred to in the figures as "Penman-Monteith ET". The transpiration estimate is based on Automatic Weather Station data using the Penman-Monteith equation with an assumed surface resistance function and is described by Gash and Stewart (1977). For the clearing the winter evaporation is assumed to be equal to the Penman ET estimate calculated from data taken at the nearby Forestry Commission meteorological site, Santon Downham. During 1974 no Penman-Monteith estimates of evaporation are available and the assumption has been made that no transpiration occurred before and after the ZFP was observed, so that total evaporation equals the measured interception for these periods. It has also been assumed that both the Penman-Monteith estimate of evaporation and rainfall at the Feltwell site are the same as at the main site. The validity of these assumptions and the effects of possible errors are discussed in the next chapter.

The relationships between different climatic factors: rainfall, net rainfall beneath the forest canopy (throughfall), interception by the forest canopy, Penman EO, Penman ET and Penman-Monteith ET (not 1974) are shown in Figures 5.28 to 5.30. Comparative estimates of evaporation for each forest site and each clearing site for all three years are presented in Figures 5.31 to 5.35, while the corresponding drainage comparisons appear in Figures 5.36 to 5.40.

In all of Figures 5.21, 5.23, 5.26 and 5.31 to 5.40 the ZFP periods indicated are typical for the site and do not correspond to the ZFP periods for each instrument set. The individual ZFP periods may be obtained by referring to Figures 5.16 to 5.20. On the water balance graphs (Figures 5.21 to 5.40) all climatic information (rainfall, evaporation estimates) has been plotted daily but a symbol is shown only for every fifth day. A symbol has been plotted for each day that data was collected for the measured water balance components.

5.5 Water Table Observations

The water level observations in each well and borehole are shown in Figures 5.41 to 5.43. Gaps in the records are due to the well drying up. These data have been combined into water table level contours as shown in Figure 5.44.

5.6 Pressure Transducer Tensiometer Readings

The moisture tensions observed at depths of 6m and 7m for the period 5.2.76 to 3.12.76 are shown in Figure 5.45 along with the water table level in the same borehole. Unfortunately the tensiometer at 8m depth failed to produce reliable results. Since, however, the moisture tension at the water table is, by definition, zero, potential profiles for the entire unsaturated profile could be constructed by interpolation between the tensiometer readings and water table levels. Several of these are shown in Figure 5.46.

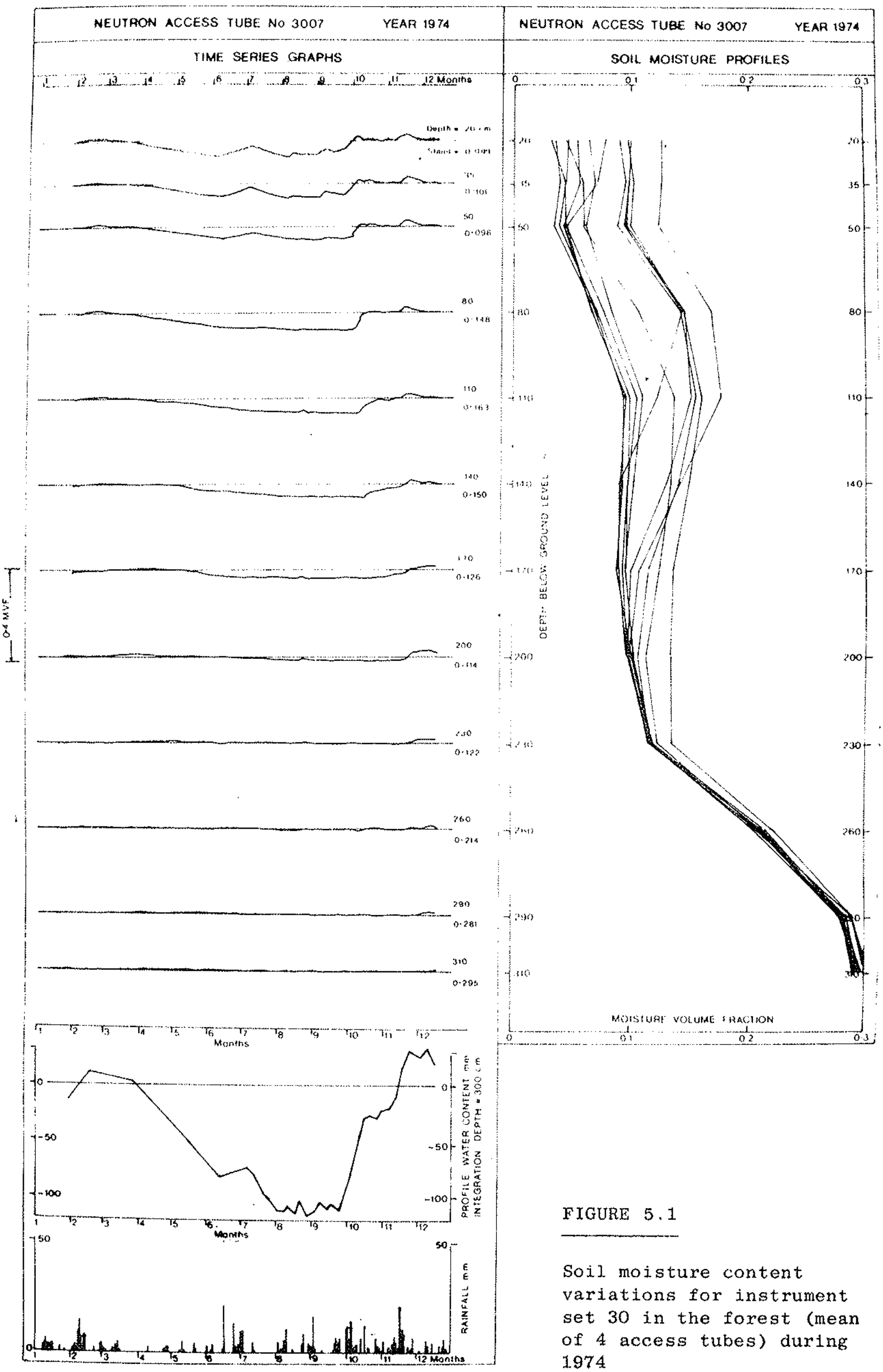


FIGURE 5.1

Soil moisture content variations for instrument set 30 in the forest (mean of 4 access tubes) during 1974

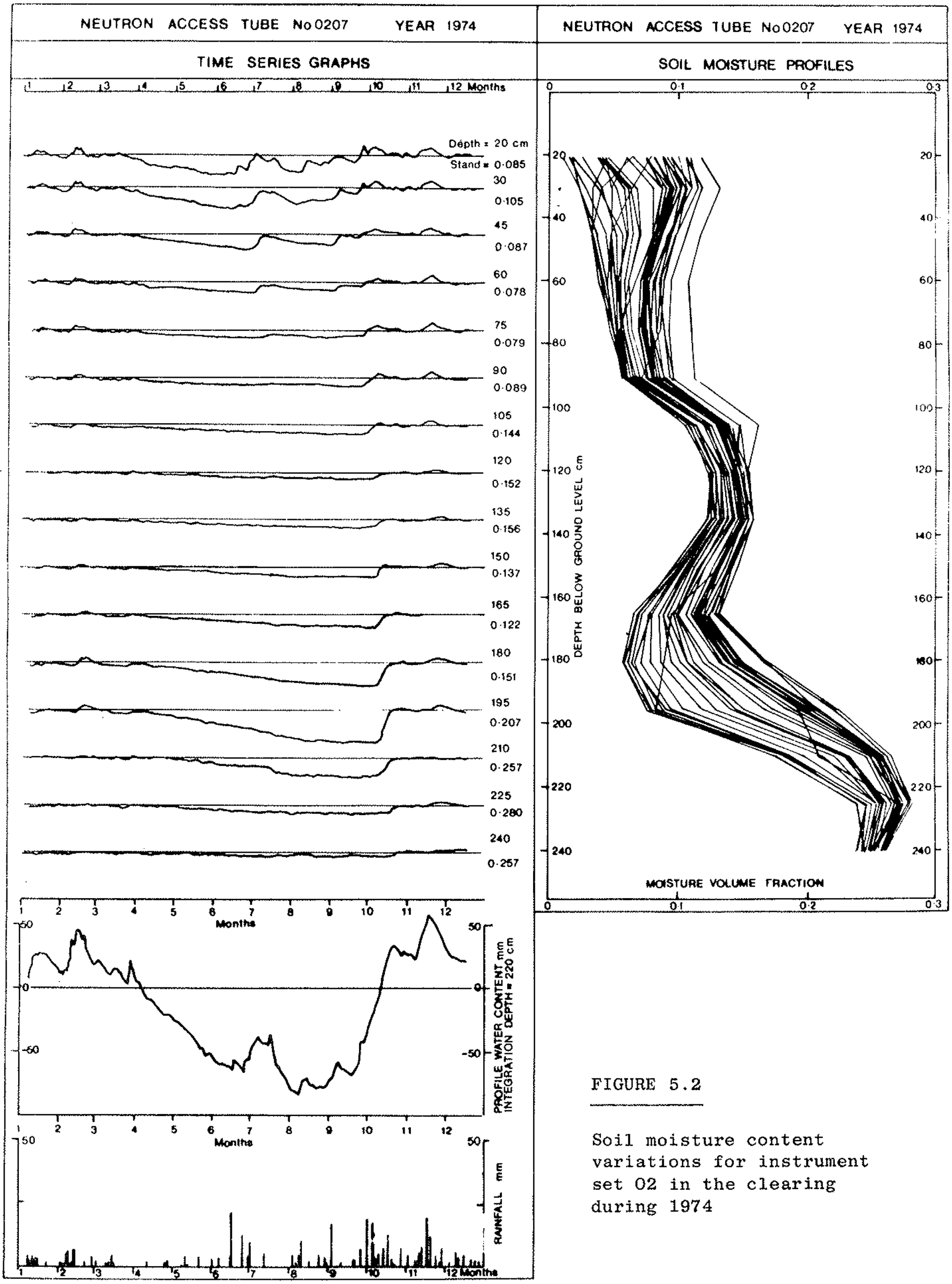


FIGURE 5.2

Soil moisture content variations for instrument set 02 in the clearing during 1974

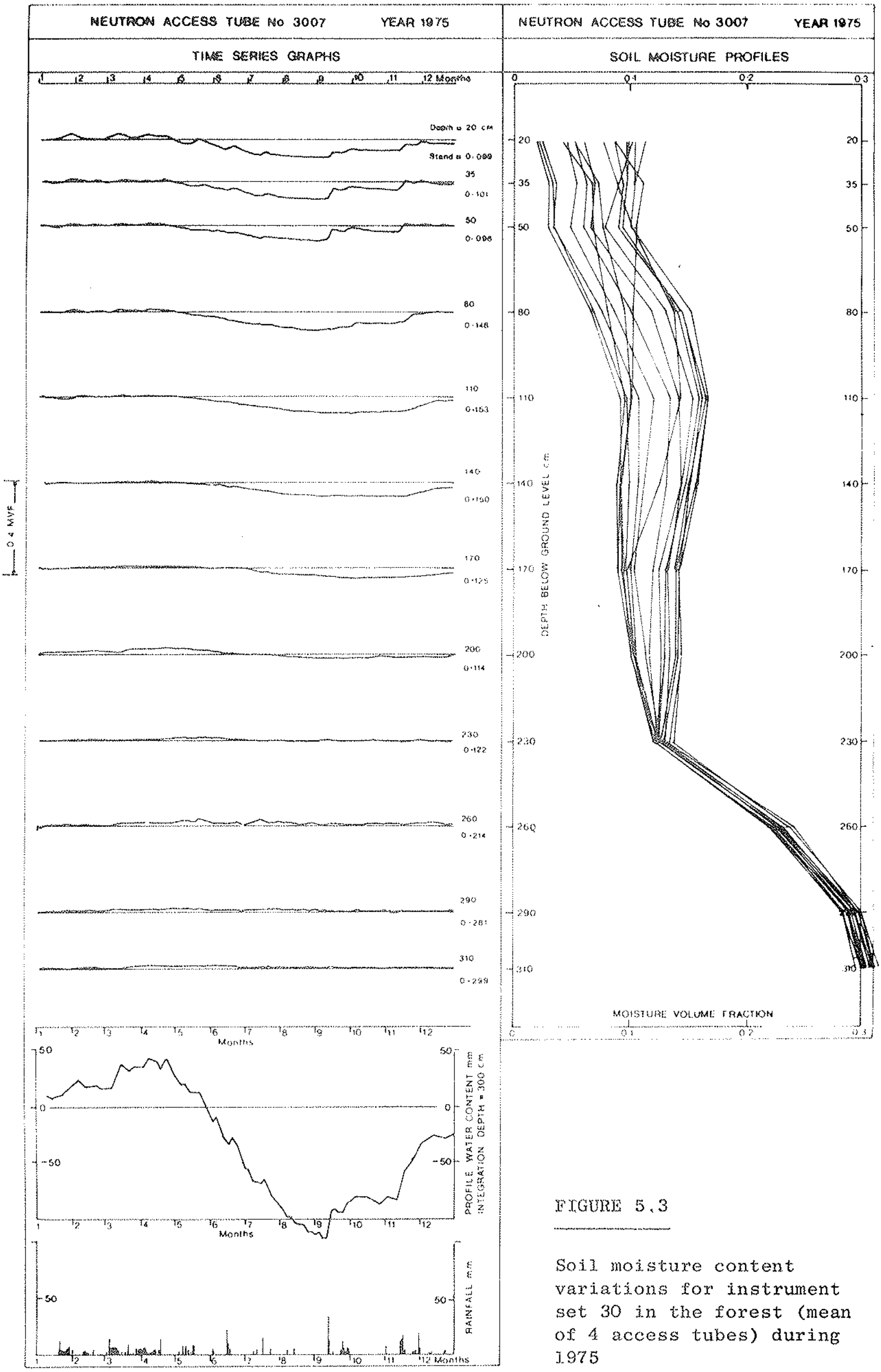


FIGURE 5.3

Soil moisture content variations for instrument set 30 in the forest (mean of 4 access tubes) during 1975

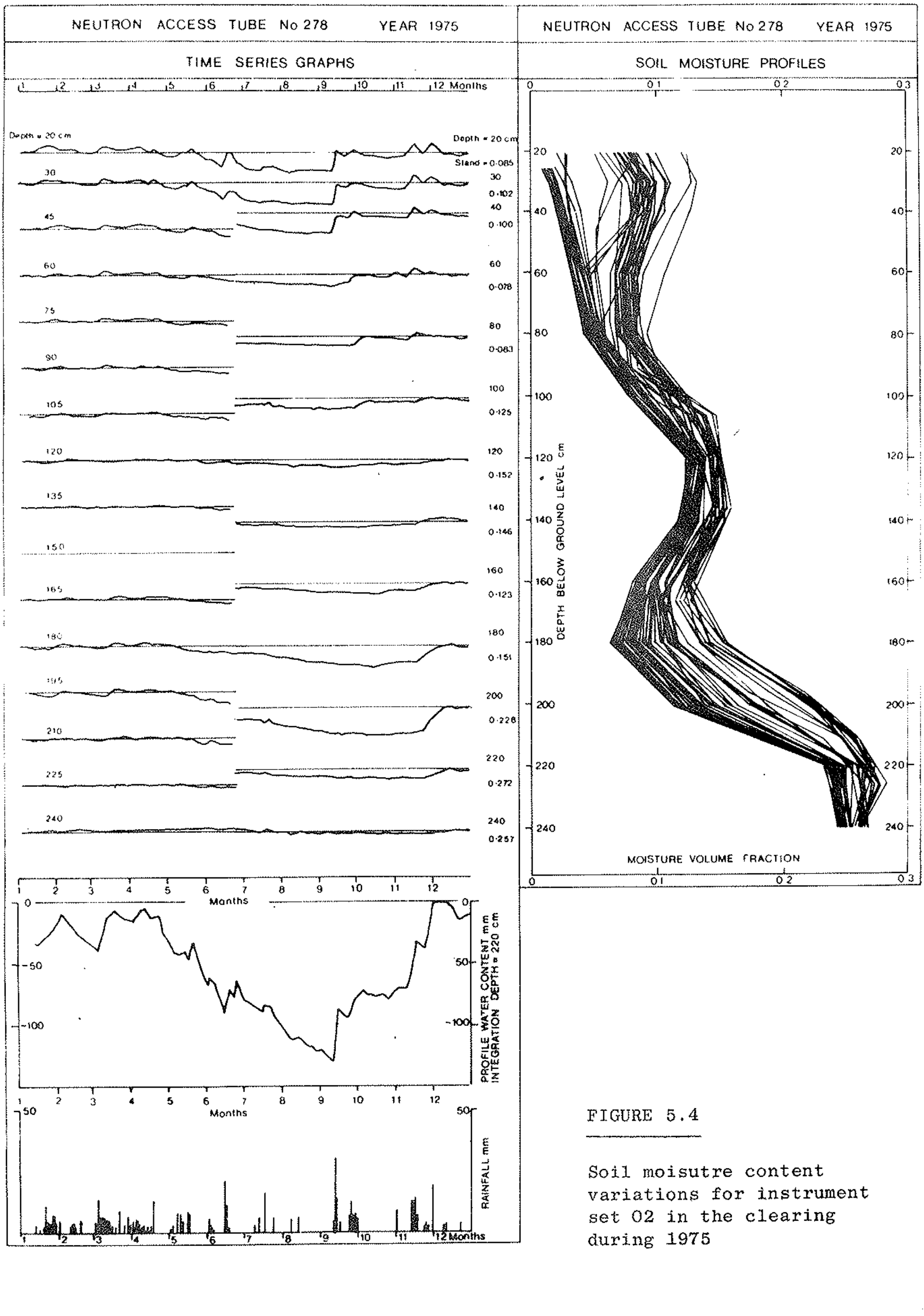


FIGURE 5.4

Soil moisutre content variations for instrument set 02 in the clearing during 1975

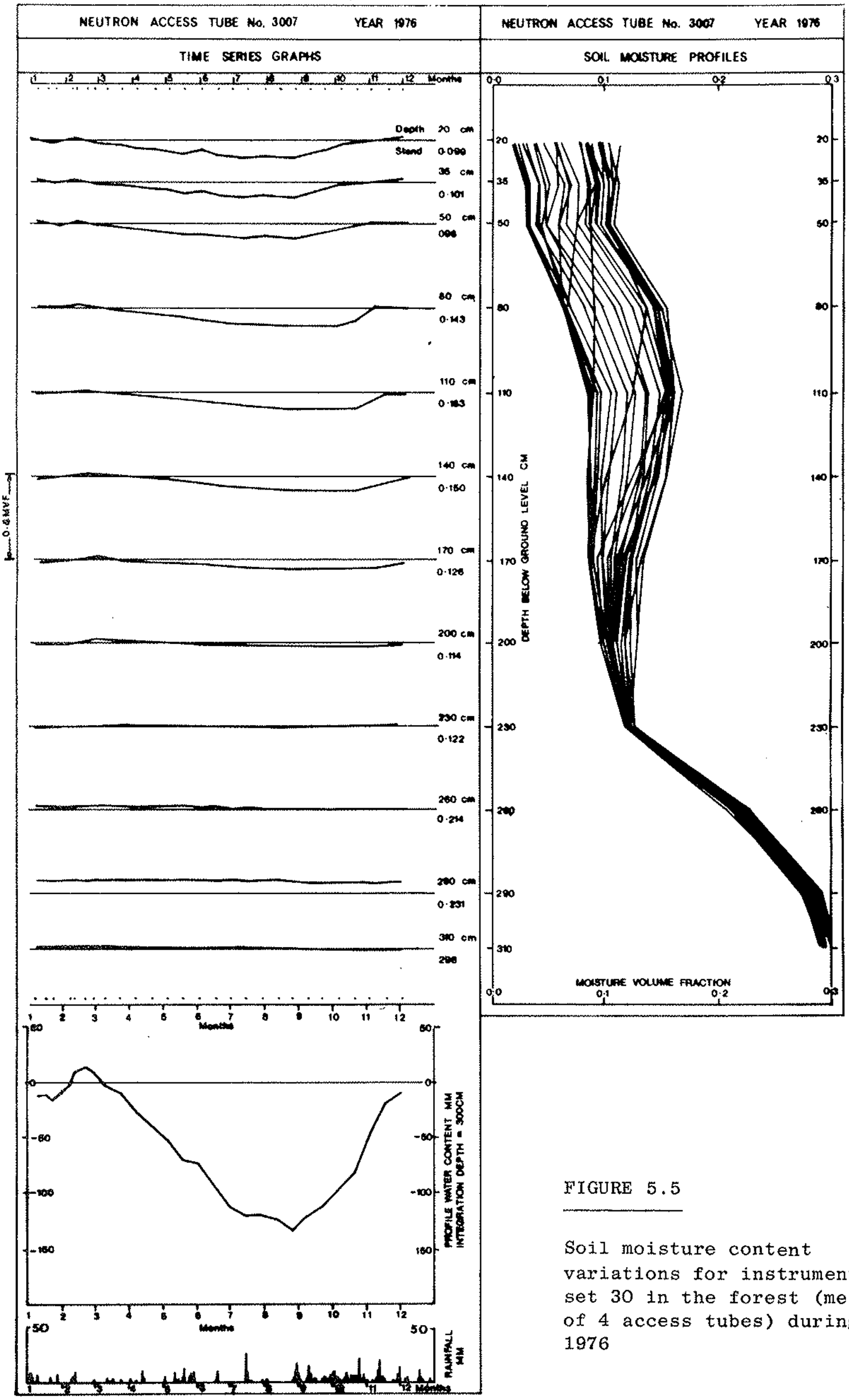


FIGURE 5.5

Soil moisture content variations for instrument set 30 in the forest (mean of 4 access tubes) during 1976

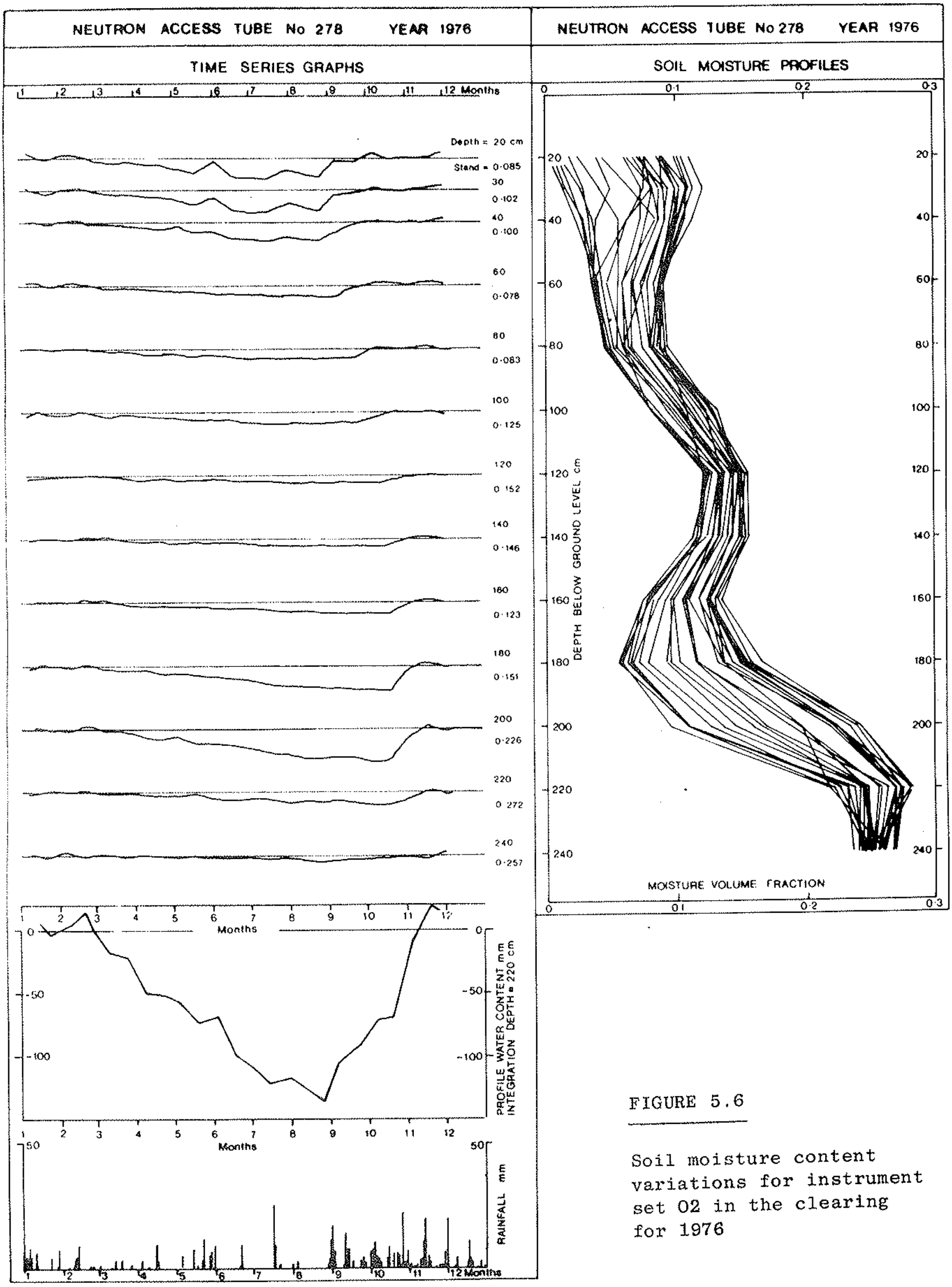


FIGURE 5.6

Soil moisture content variations for instrument set 02 in the clearing for 1976

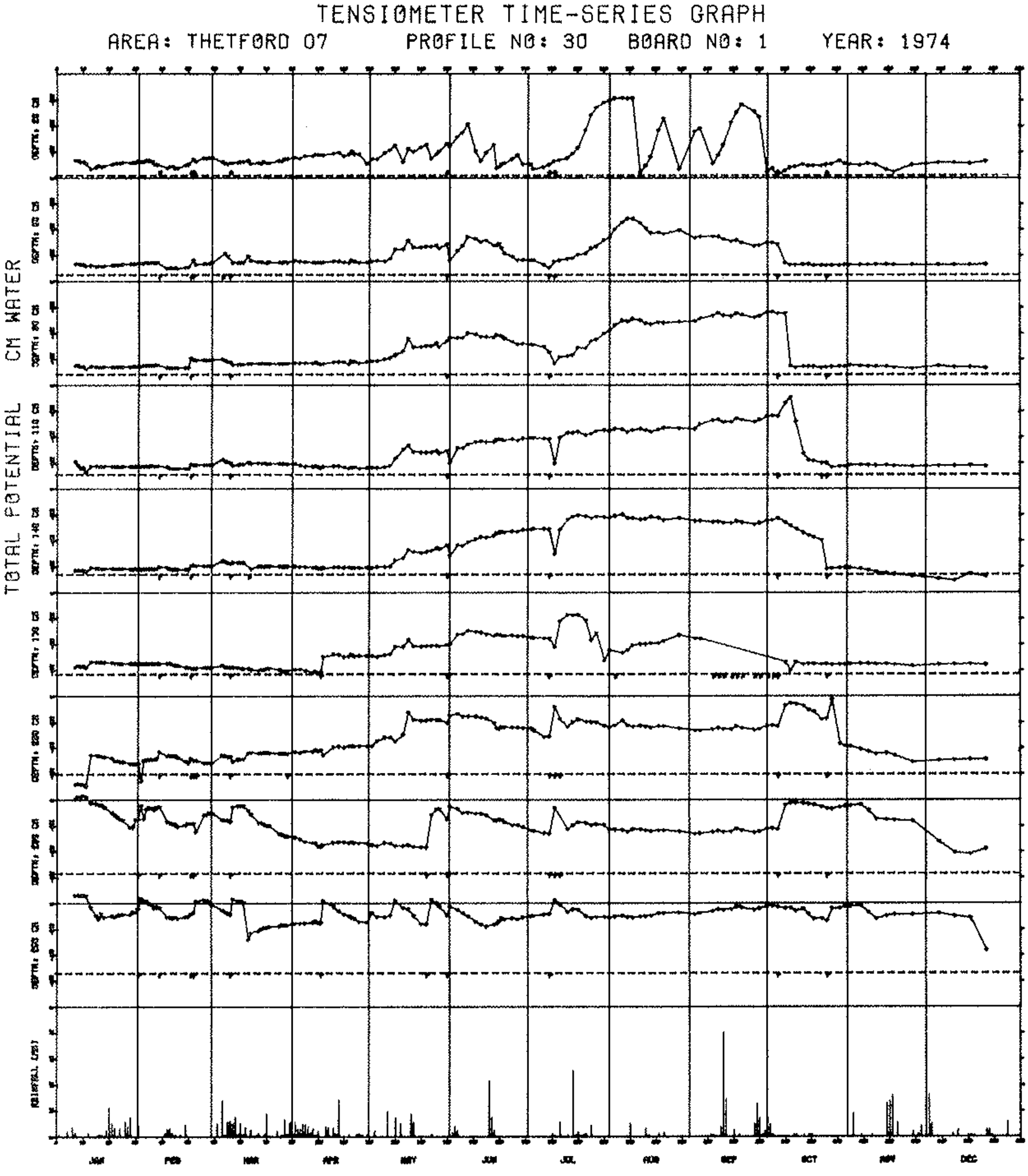

TENSIØMETER TIME-SERIES GRAPH
AREA: THETFØRD 07 PRØFILE NØ: 30 BØARD NØ: 1 YEAR: 1974
TØTAL PØTENTIAL CM WATER

FIGURE 5.7

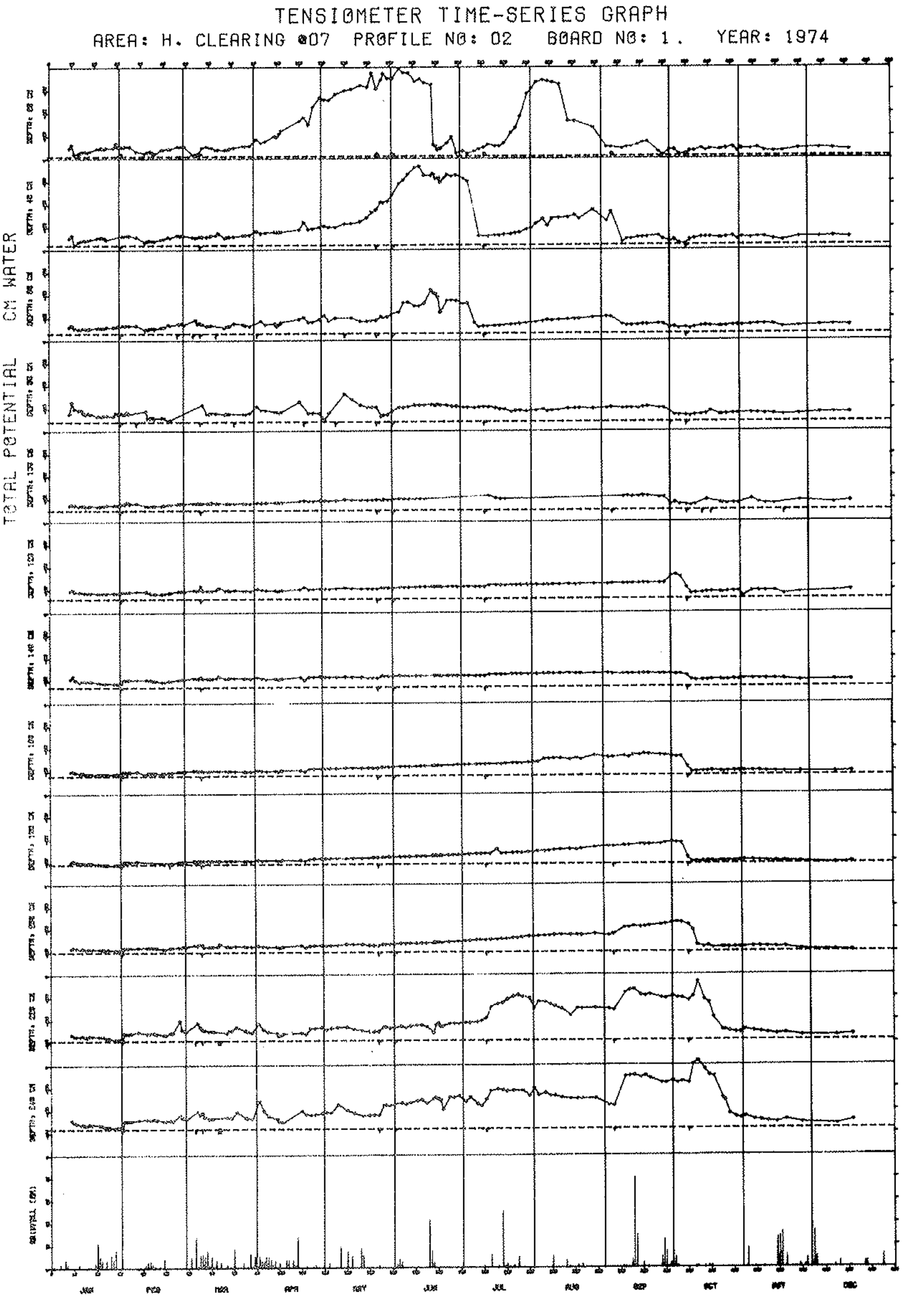

TENSIØMETER TIME-SERIES GRAPH
AREA: H. CLEARING @07 PRØFILE NØ: 02 BØARD NØ: 1. YEAR: 1974
TØTAL PØTENTIAL CM WATER

FIGURE 5.8

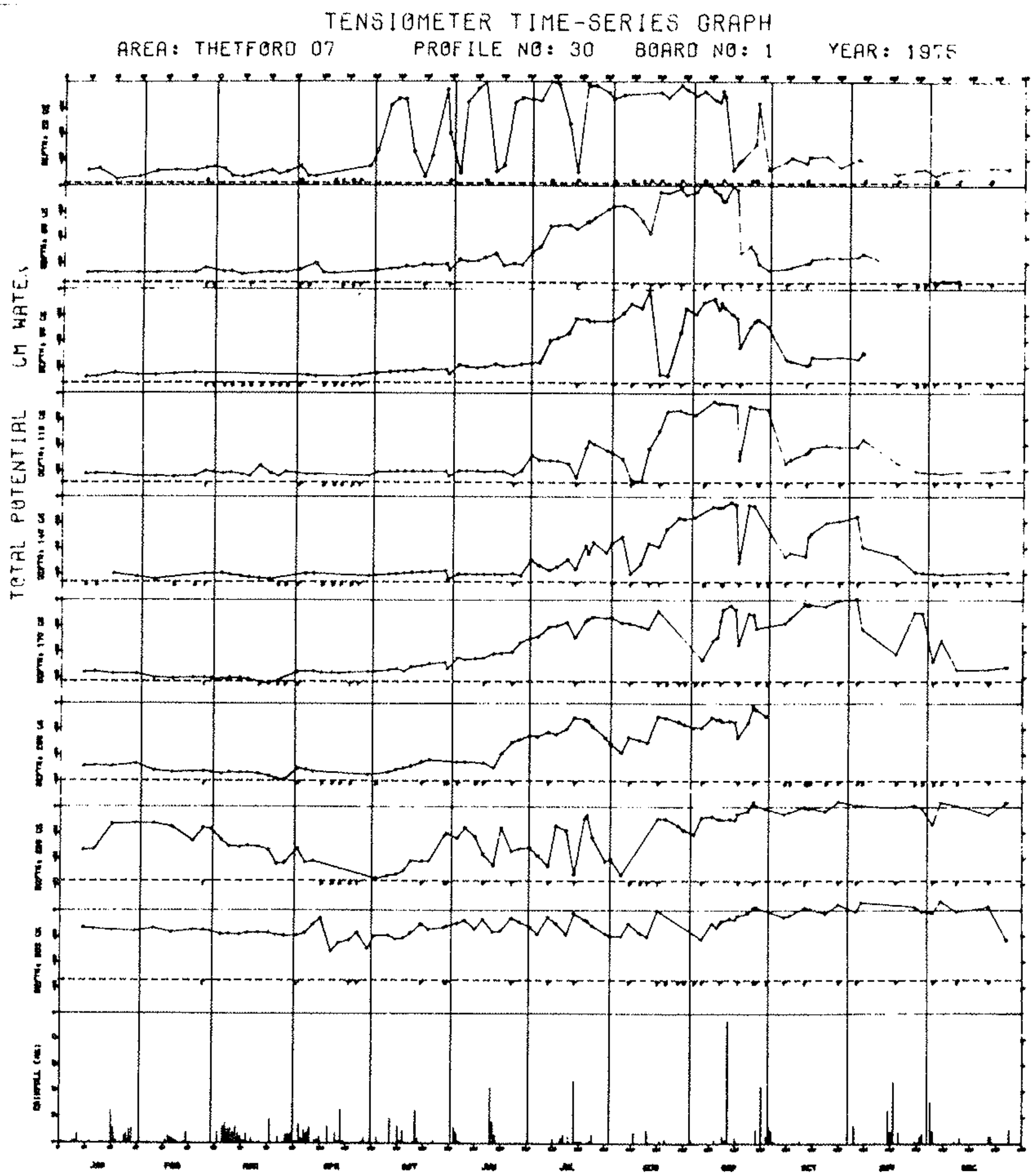

TENSIOMETER TIME-SERIES GRAPH
AREA: THETFORD 07 PROFILE NO: 30 BOARD NO: 1 YEAR: 1975
TOTAL POTENTIAL CM WATER

FIGURE 5.9

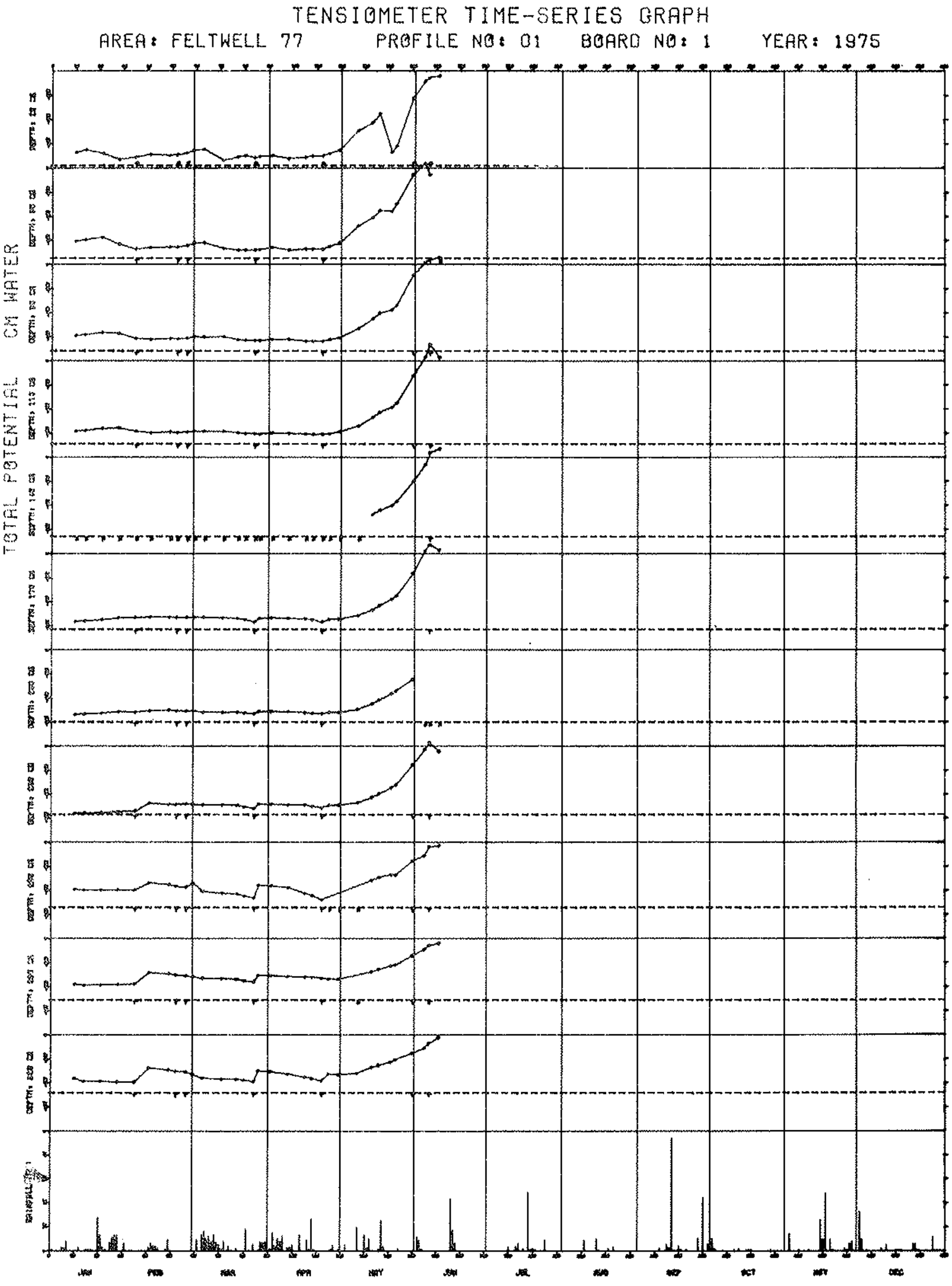

TENSIOMETER TIME-SERIES GRAPH
AREA: FELTWELL 77 PROFILE NO: 01 BOARD NO: 1 YEAR: 1975
TOTAL POTENTIAL CM WATER

FIGURE 5.10

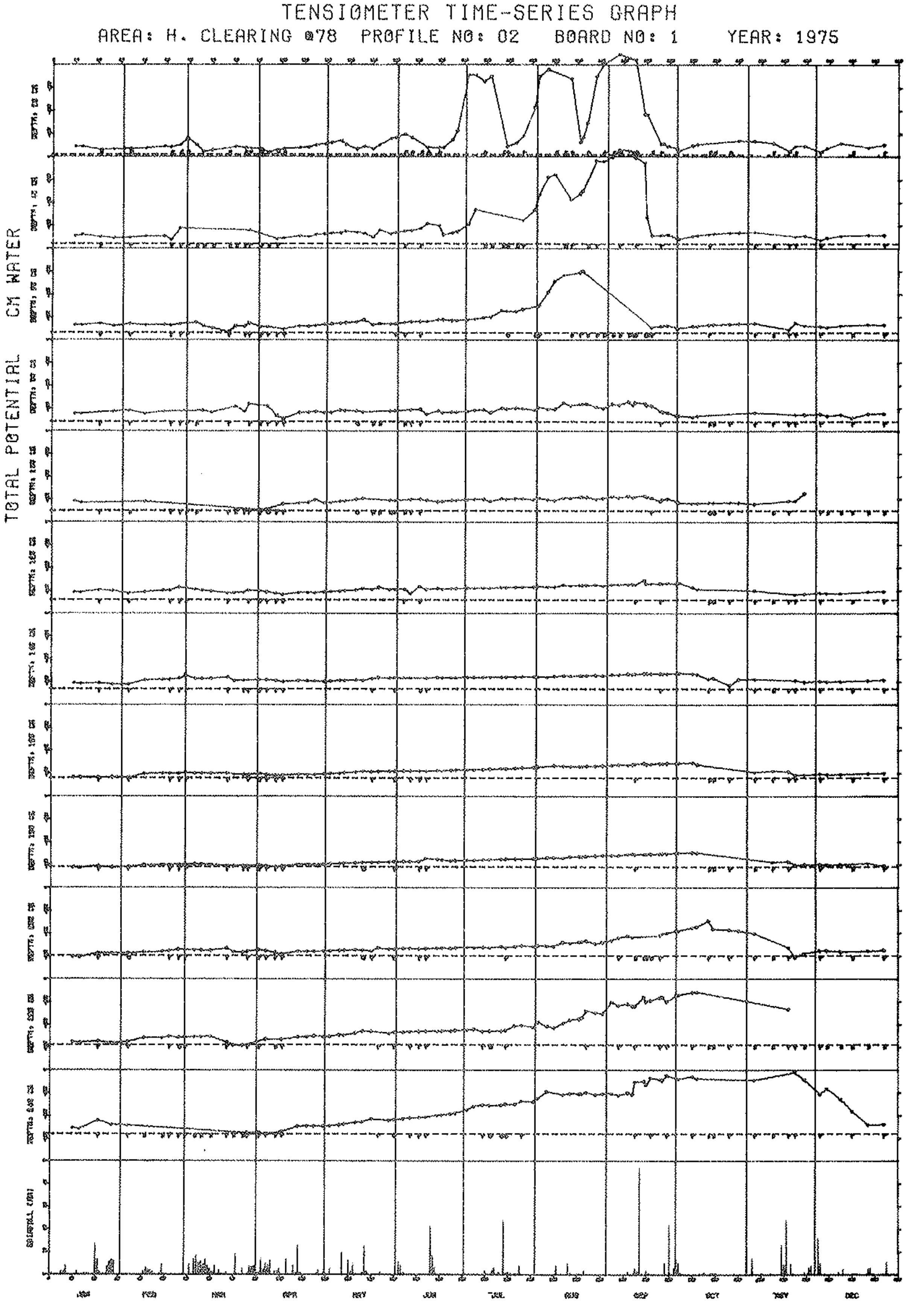

TENSIOMETER TIME-SERIES GRAPH
AREA: H. CLEARING @78 PROFILE NO: 02 BOARD NO: 1 YEAR: 1975
TOTAL POTENTIAL CM WATER

FIGURE 5.11

TENSIOMETER TIME-SERIES GRAPH

AREA: THETFORD 07 PROFILE NO: 30 BOARD NO: 1 YEAR: 1976

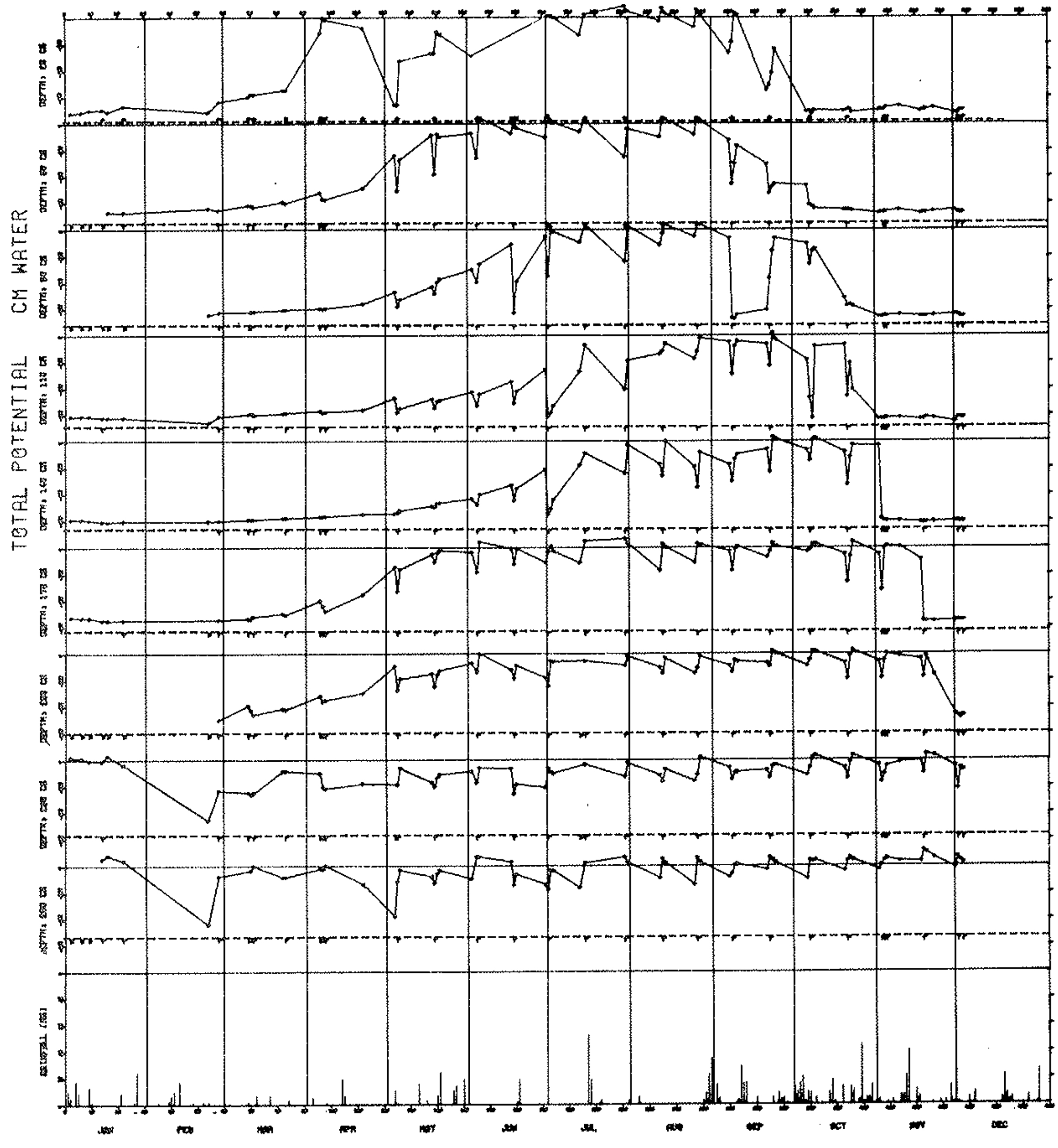


FIGURE 5.12

TENSIOMETER TIME-SERIES GRAPH

AREA: H. CLEARING #78 PROFILE NO: 02 BOARD NO: 1 YEAR: 1976

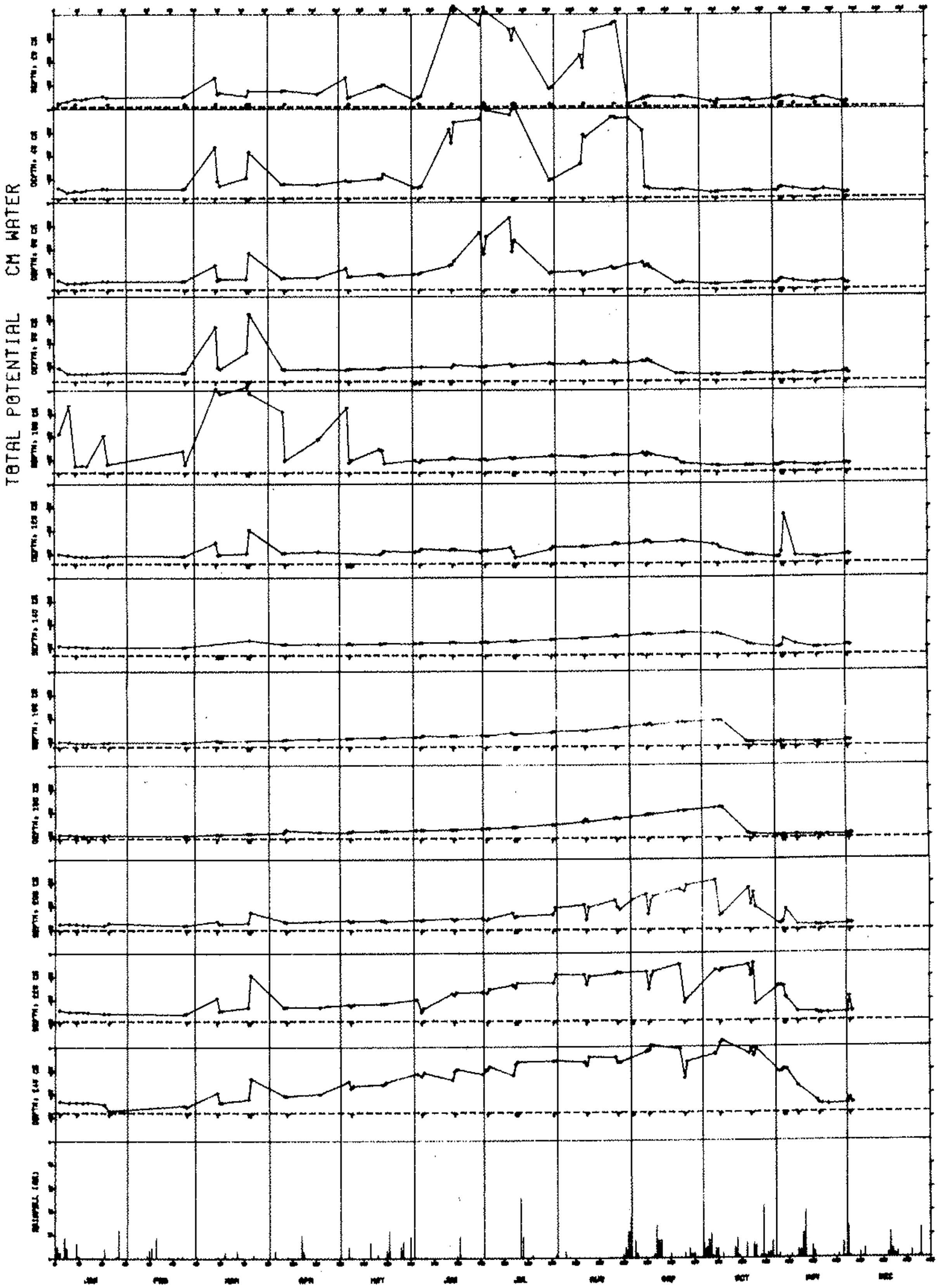


FIGURE 5.13

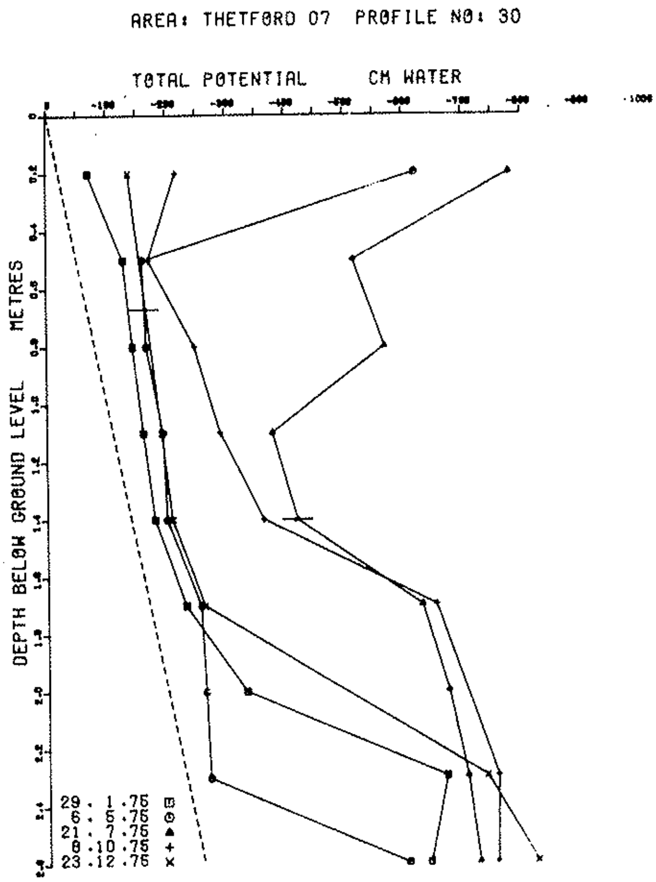


FIGURE 5.14

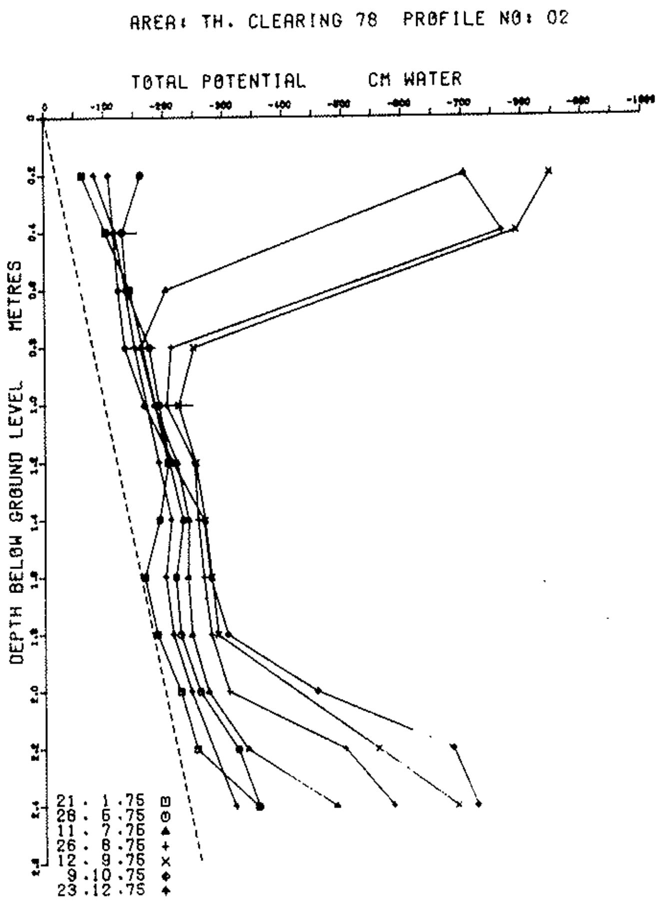


FIGURE 5.15

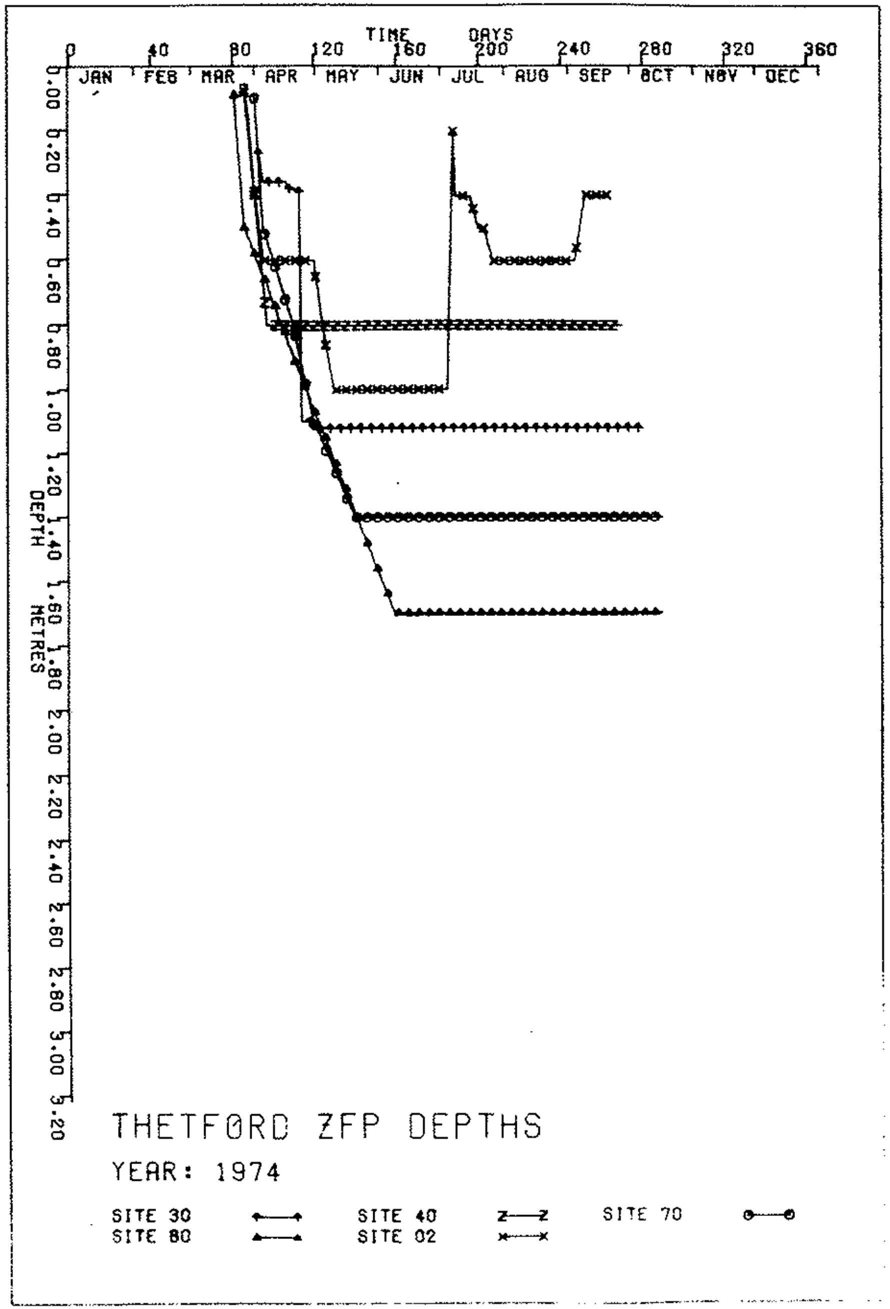


FIGURE 5.16

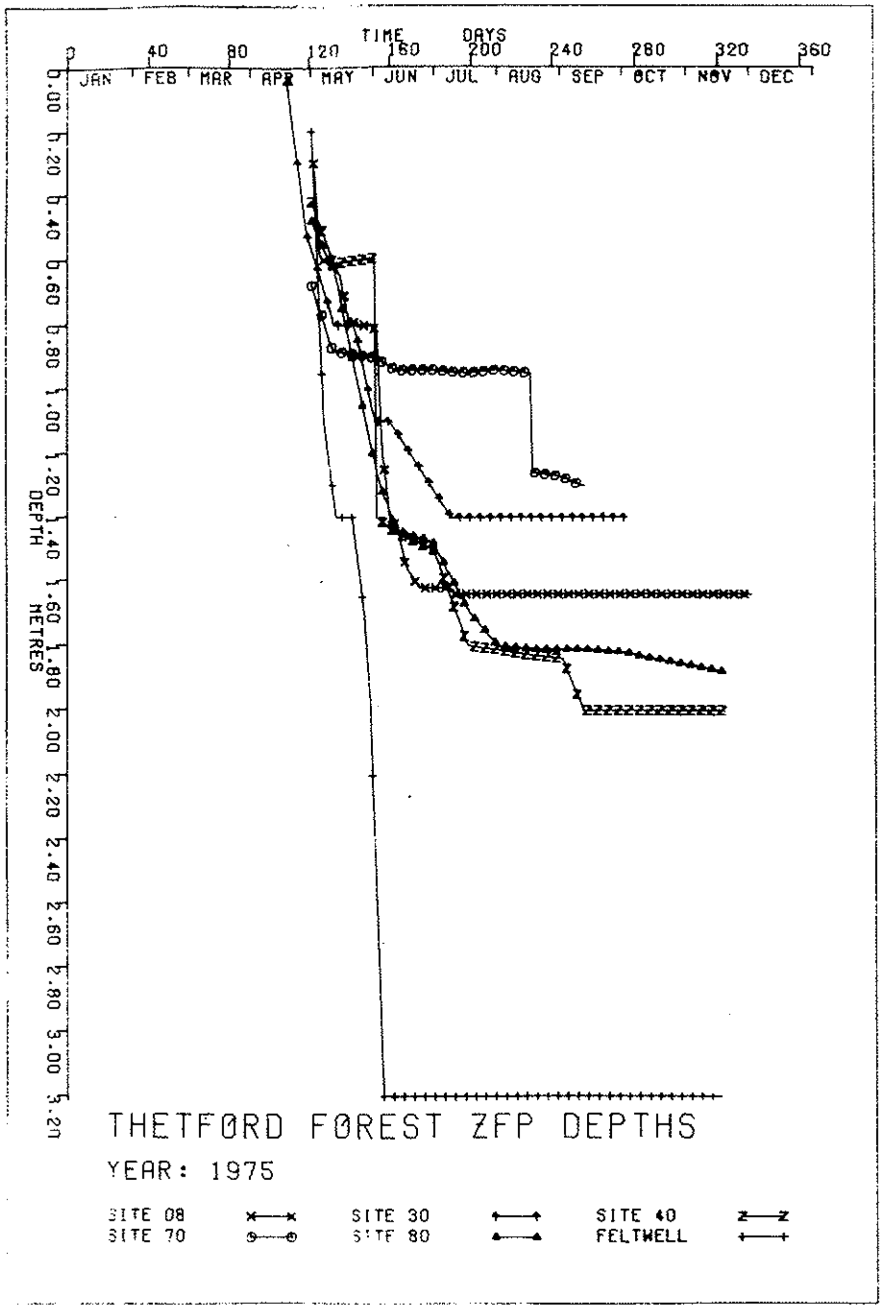


FIGURE 5.17

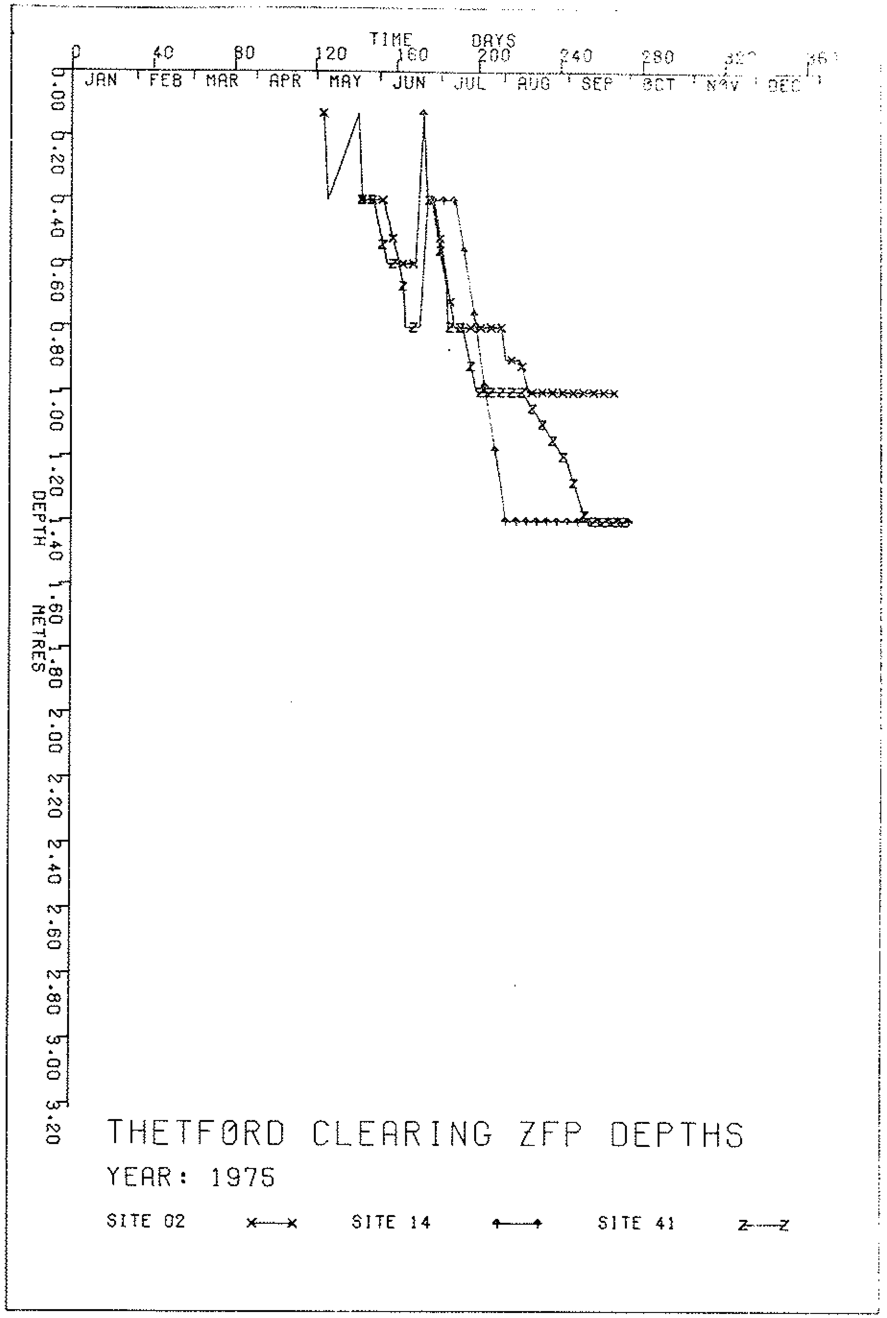


FIGURE 5.18

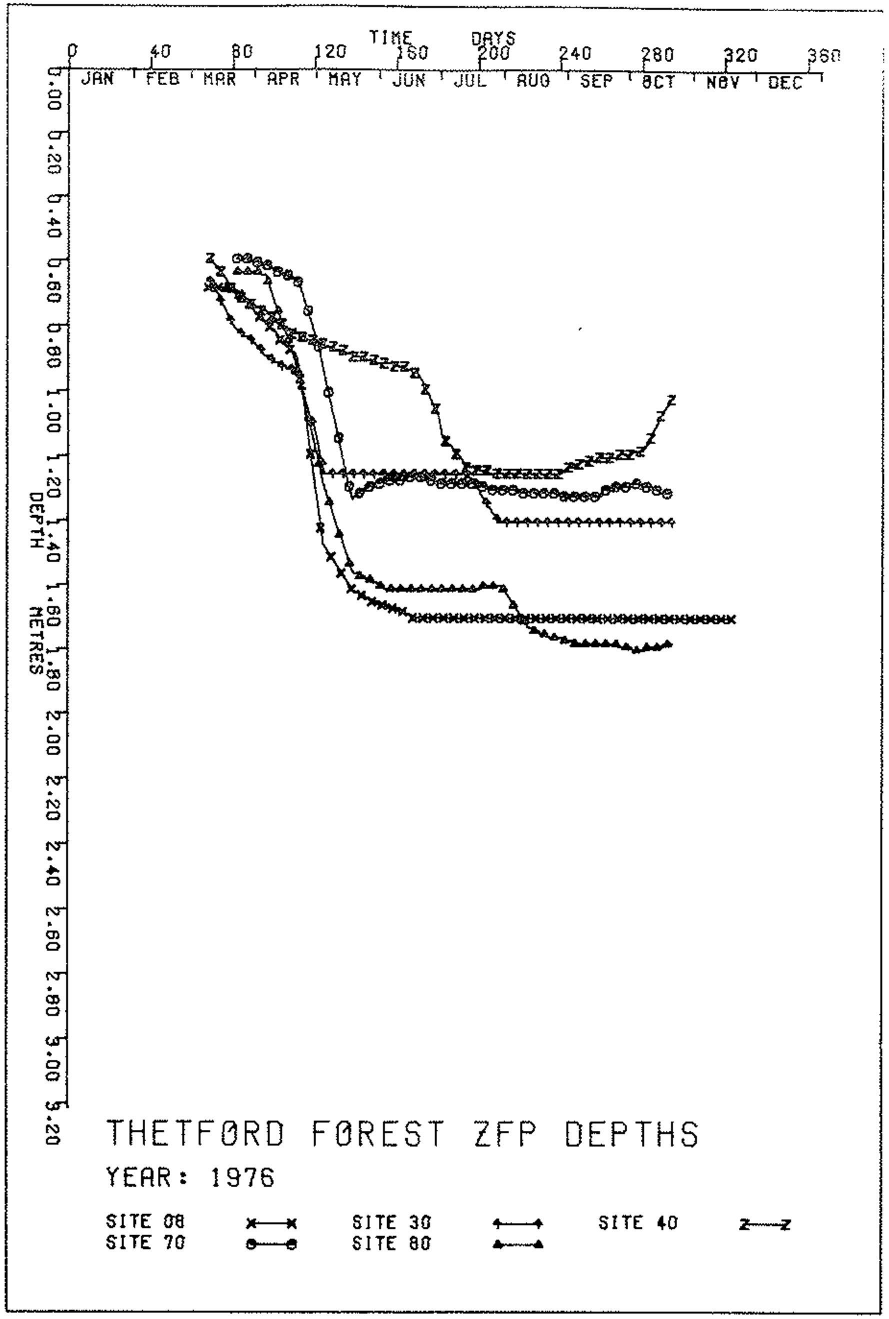


FIGURE 5.19

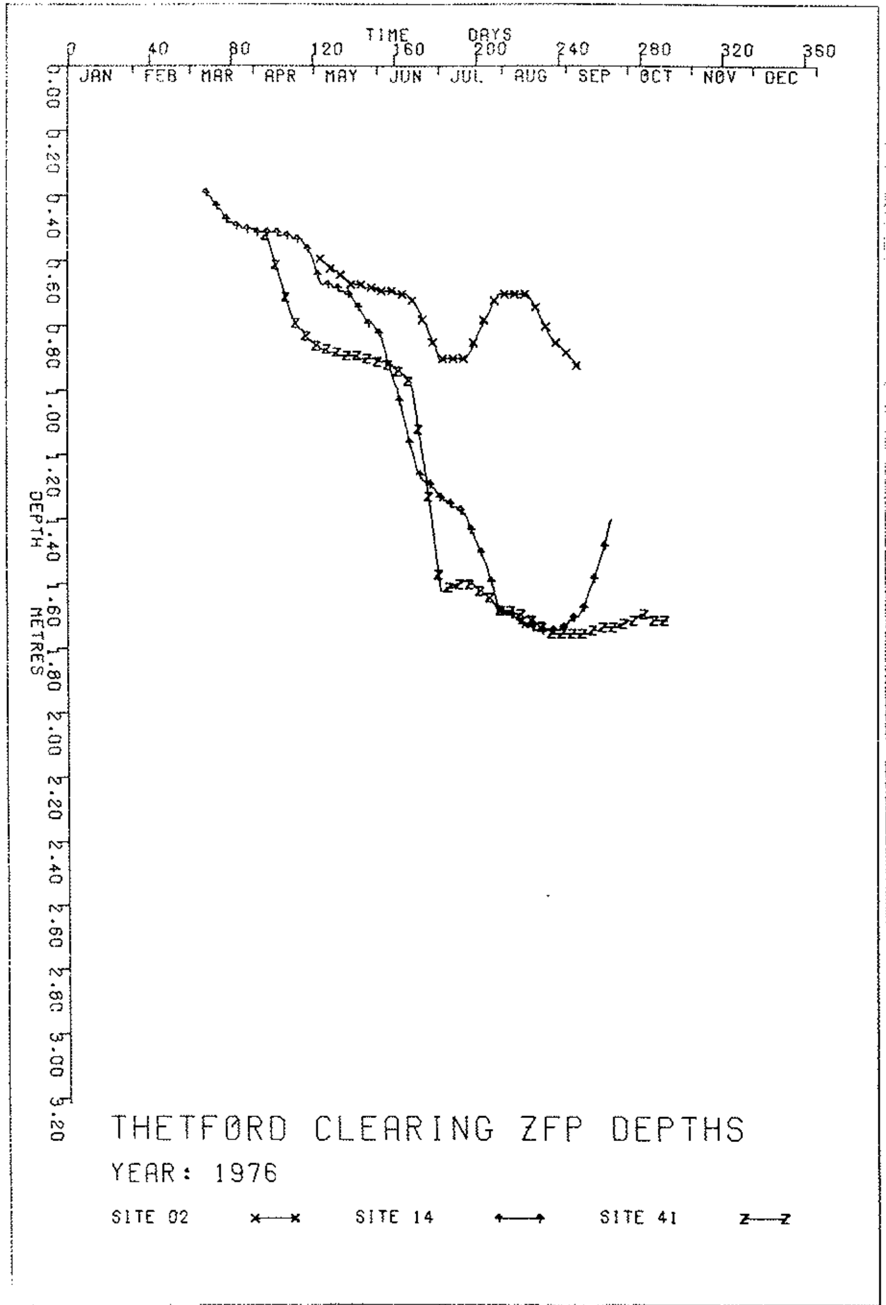


FIGURE 5.20

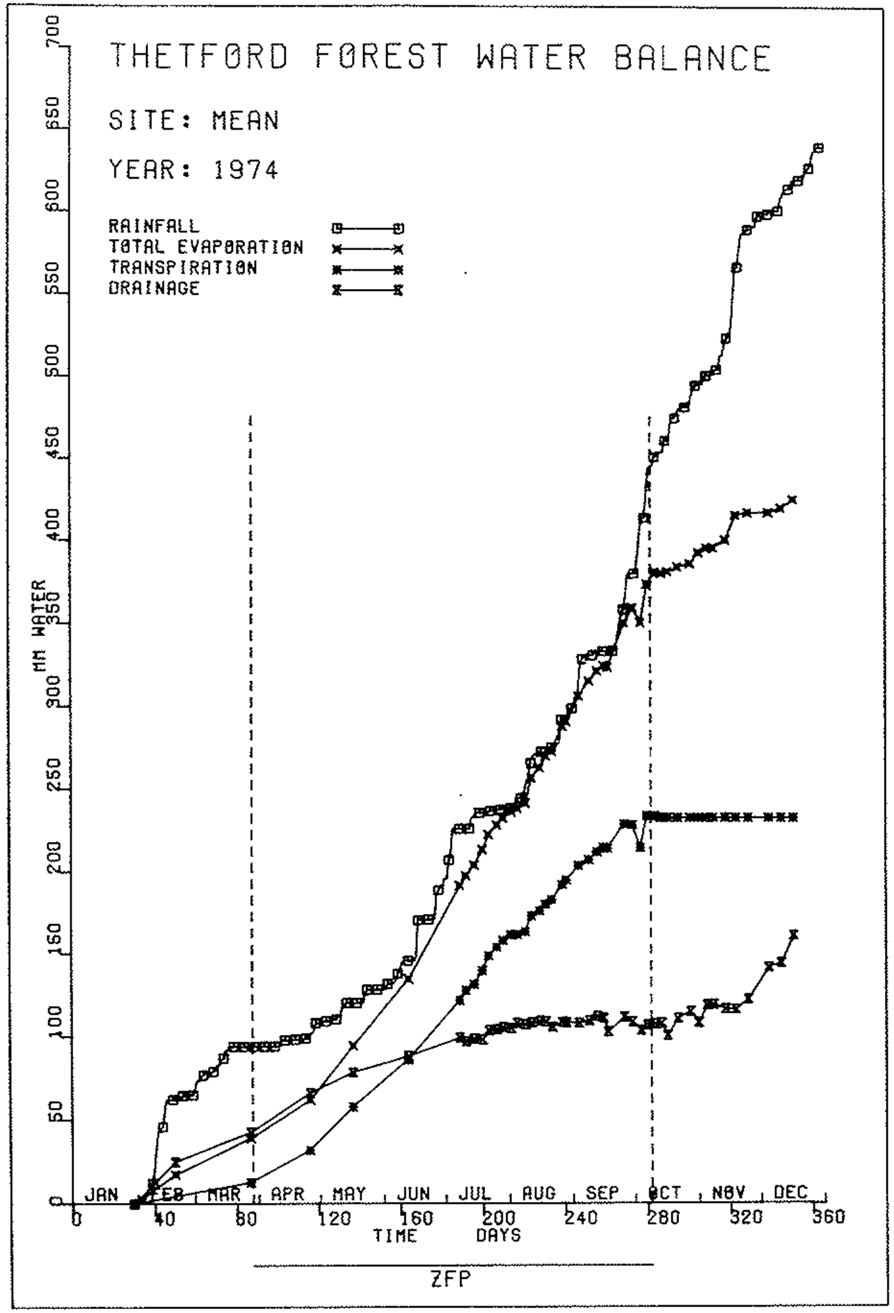


FIGURE 5.21

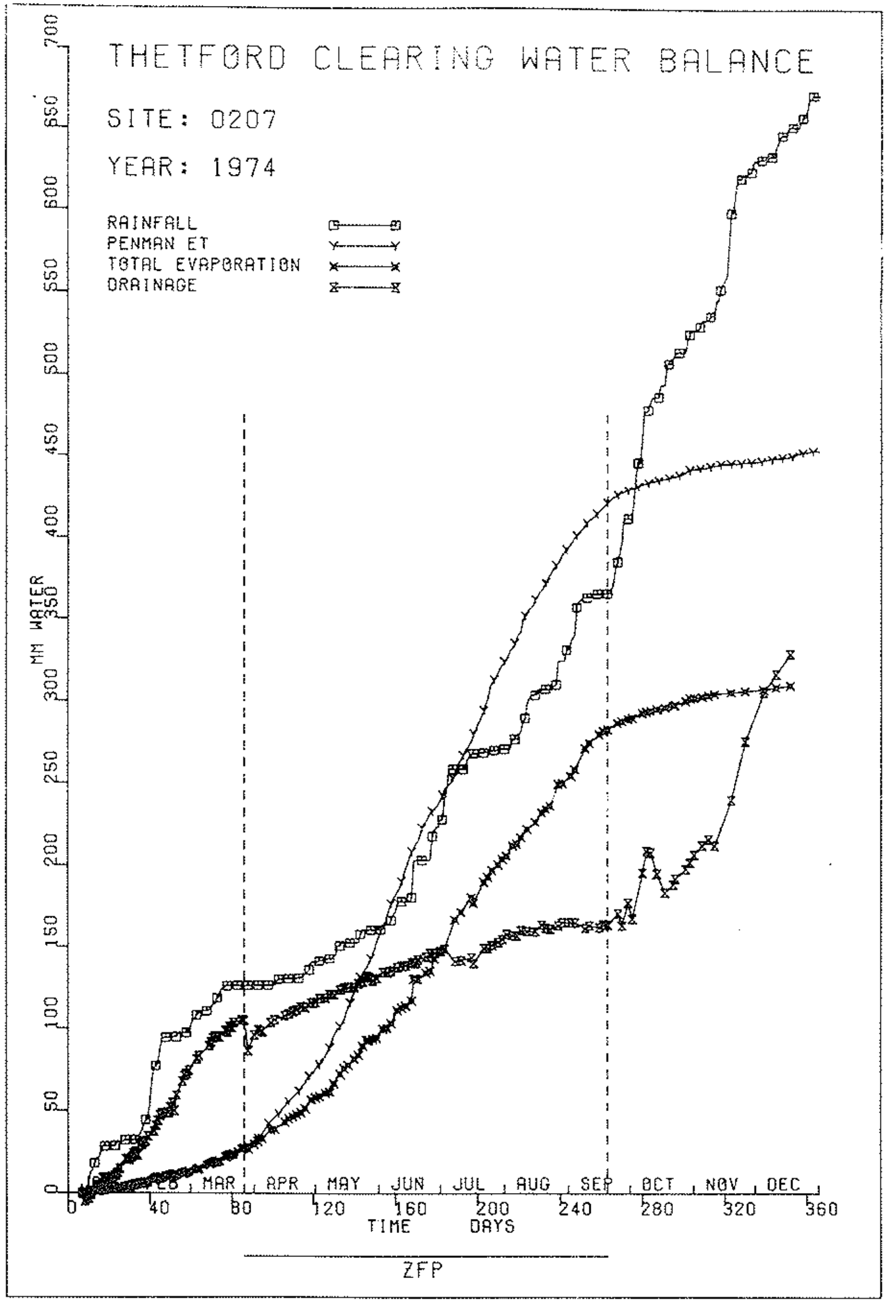


FIGURE 5.22

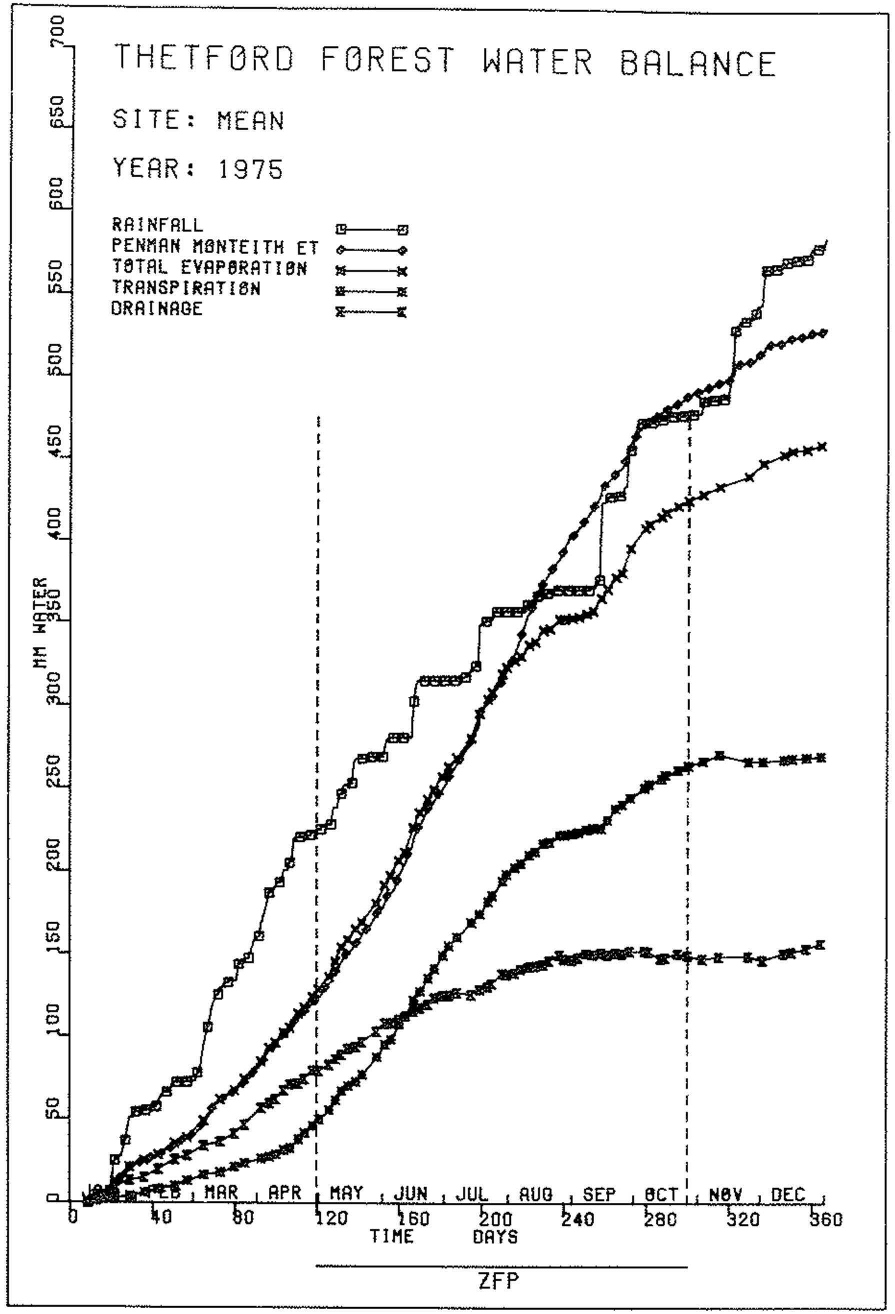


FIGURE 5.23

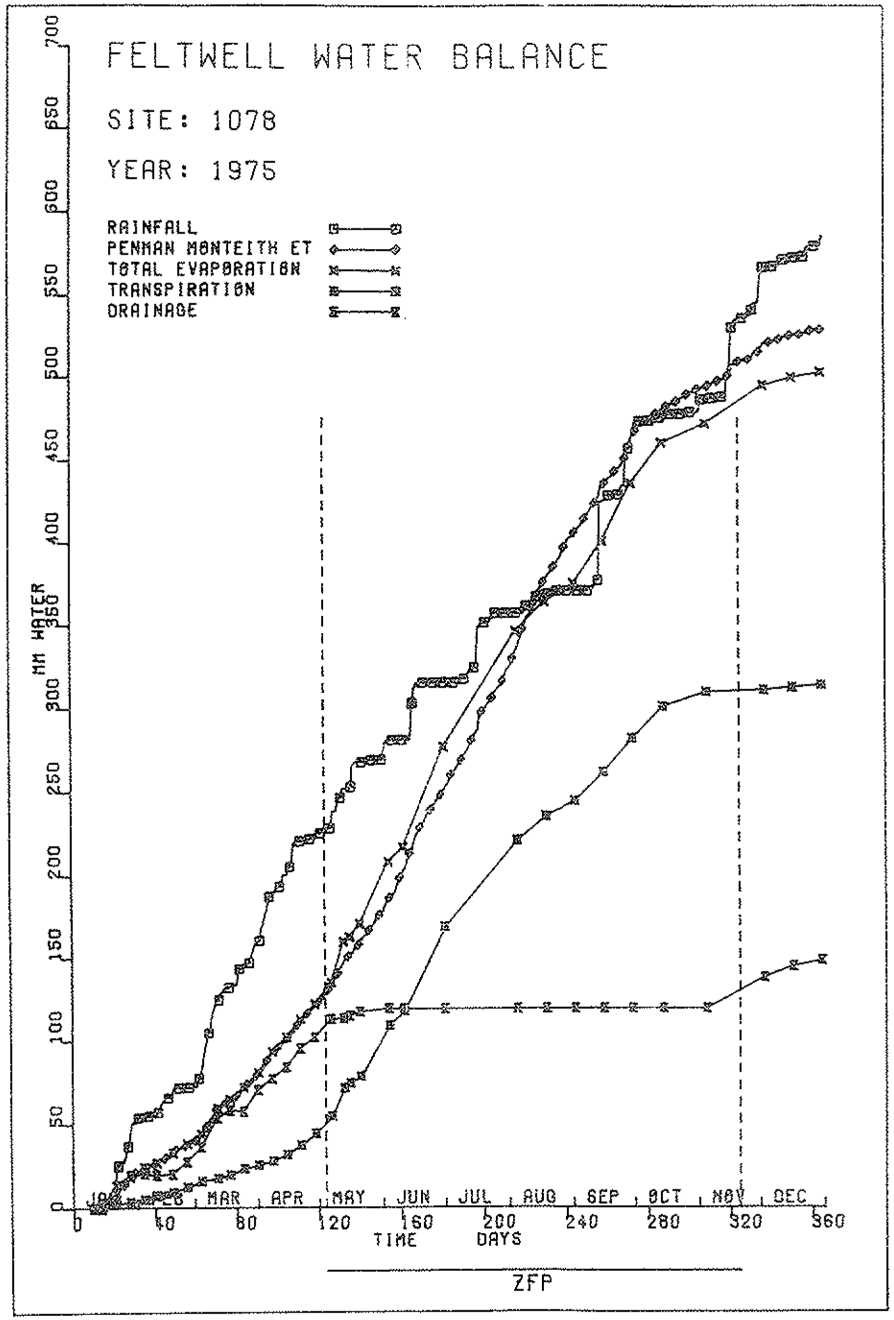


FIGURE 5.24

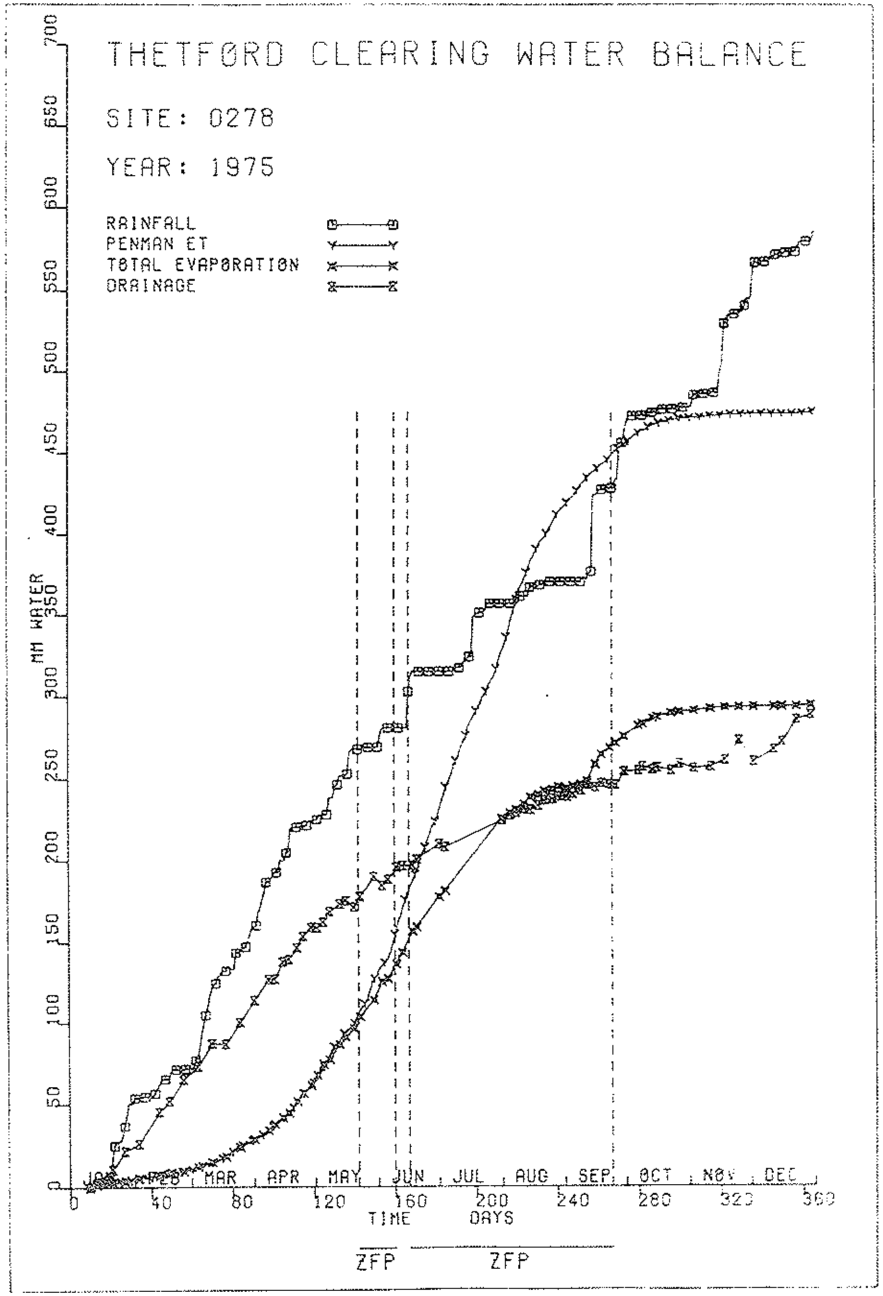


FIGURE 5.25

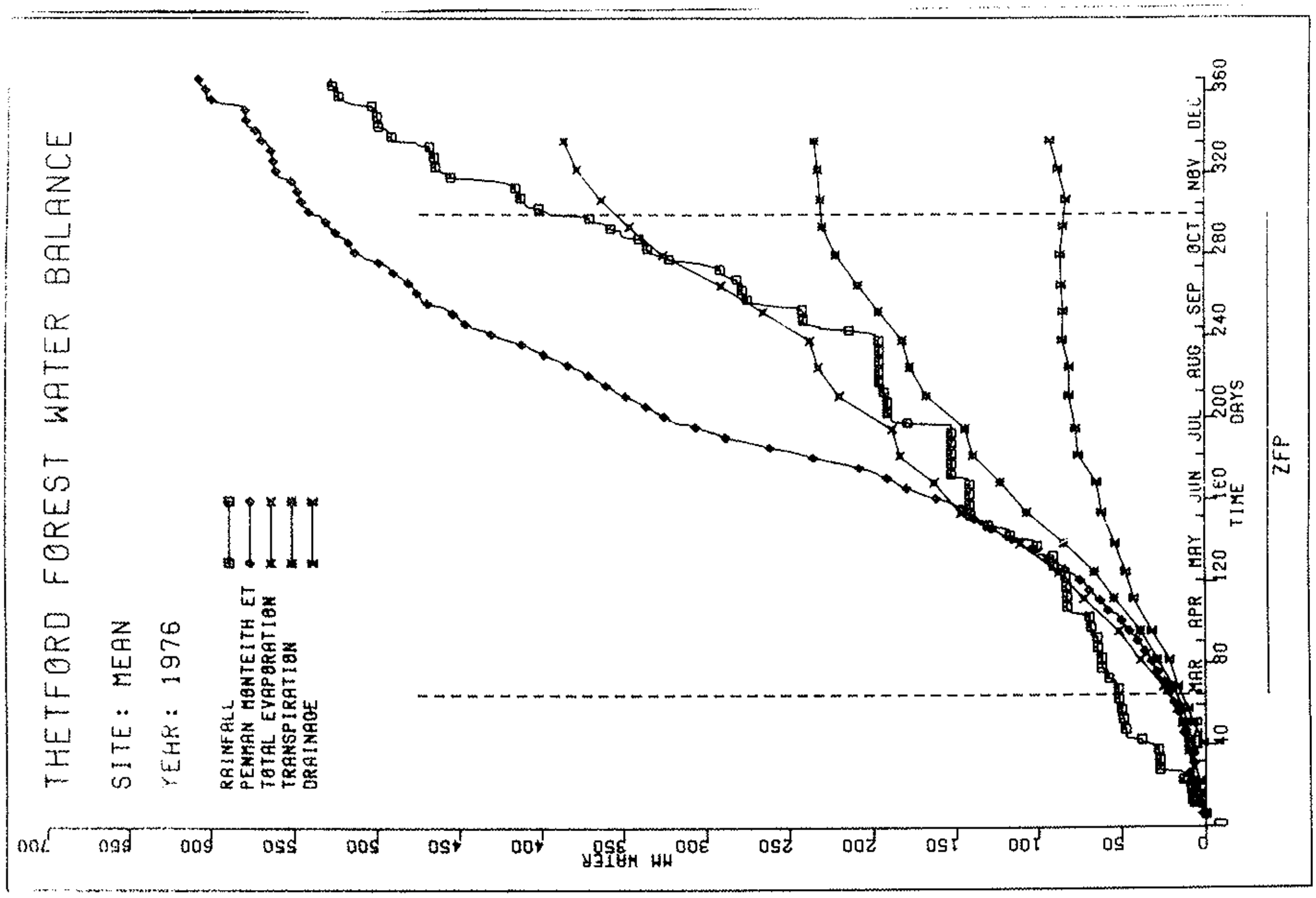


FIGURE 5.26

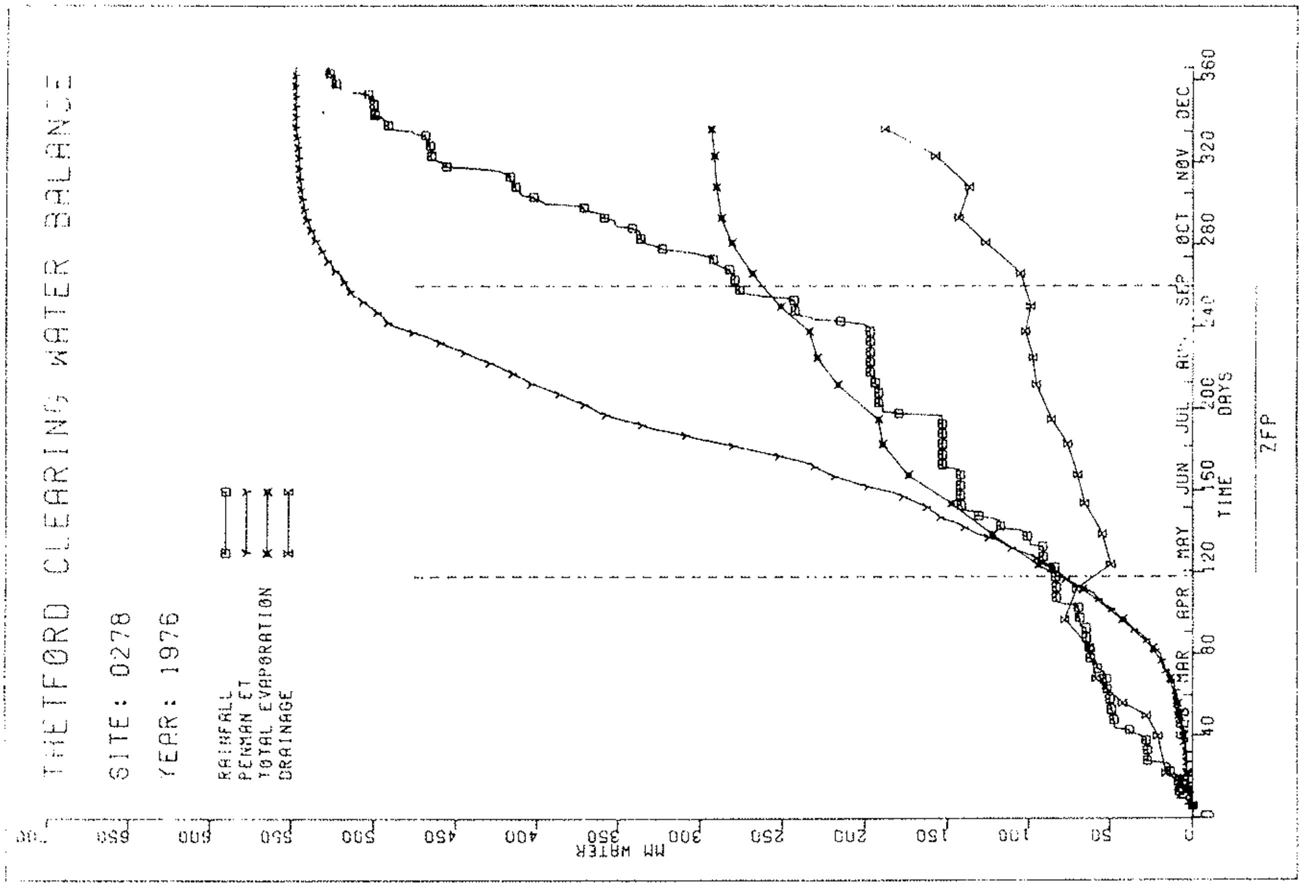


FIGURE 5.27

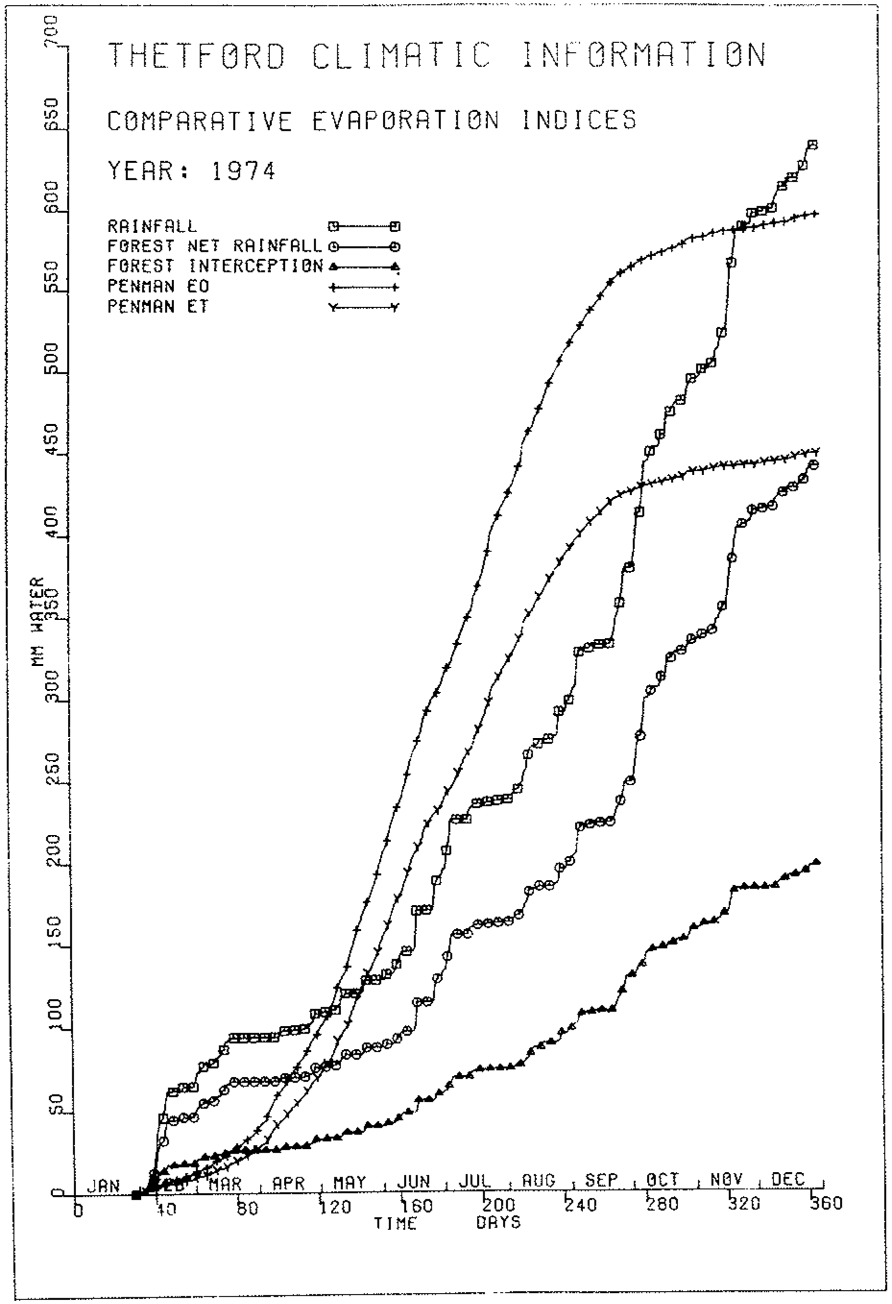


FIGURE 5.28

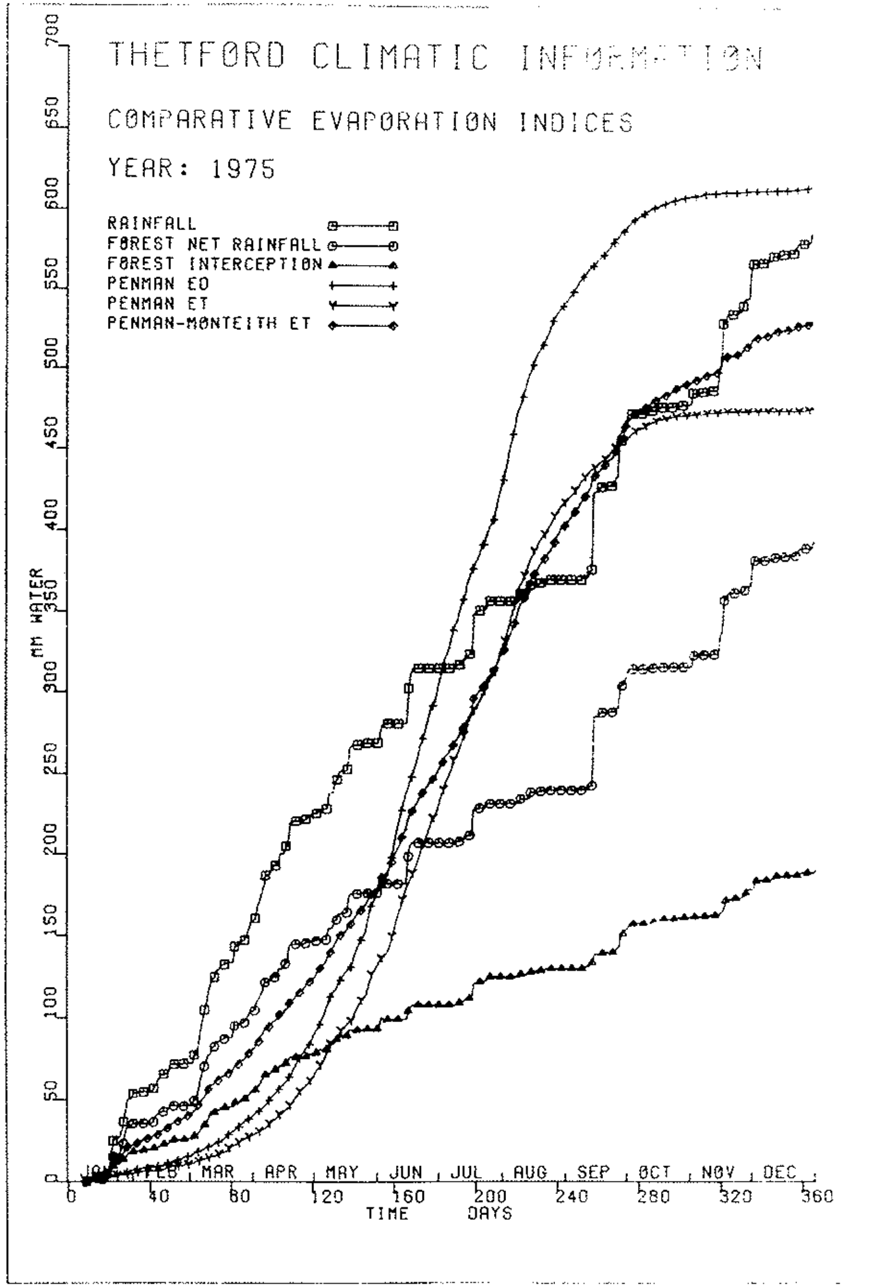


FIGURE 5.29

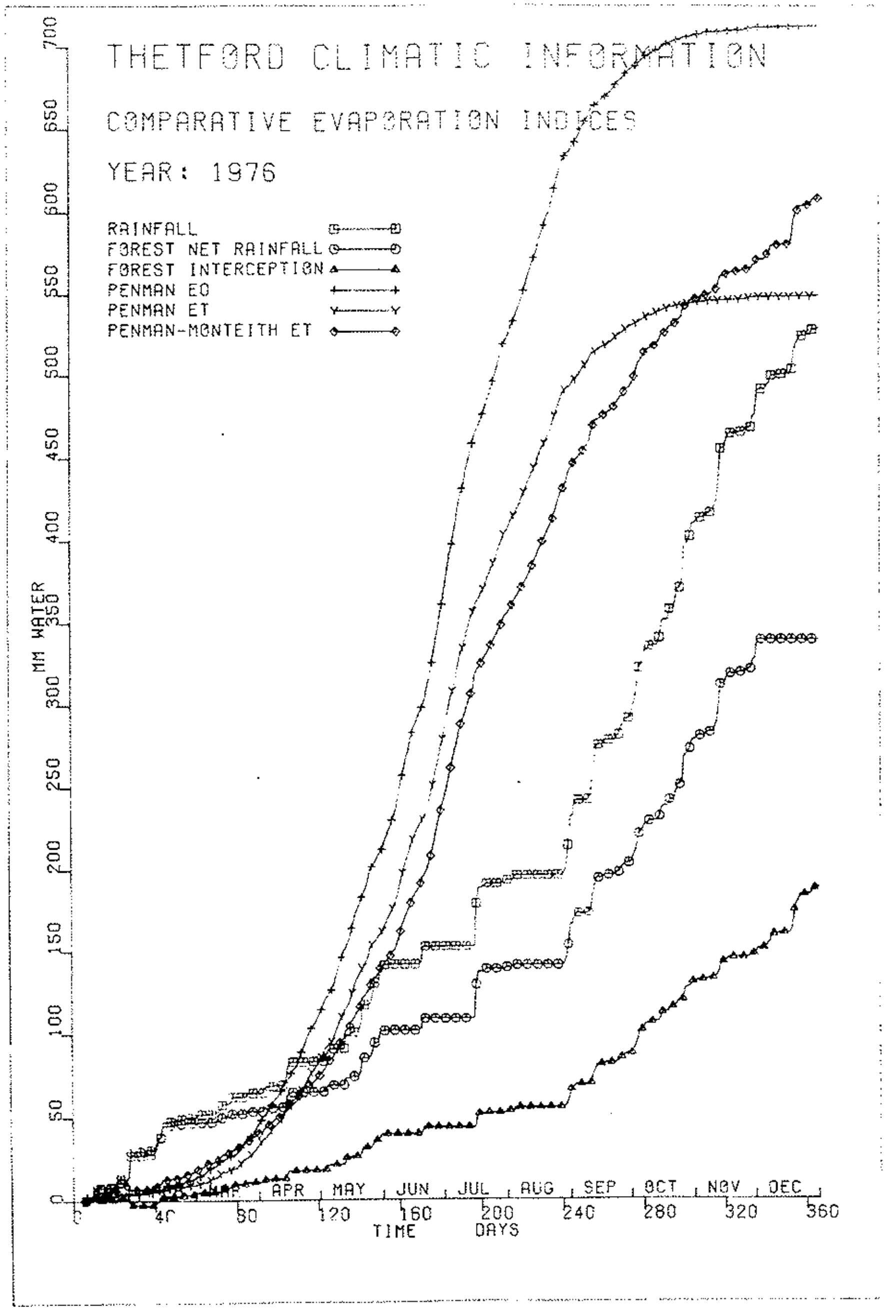


FIGURE 5.30

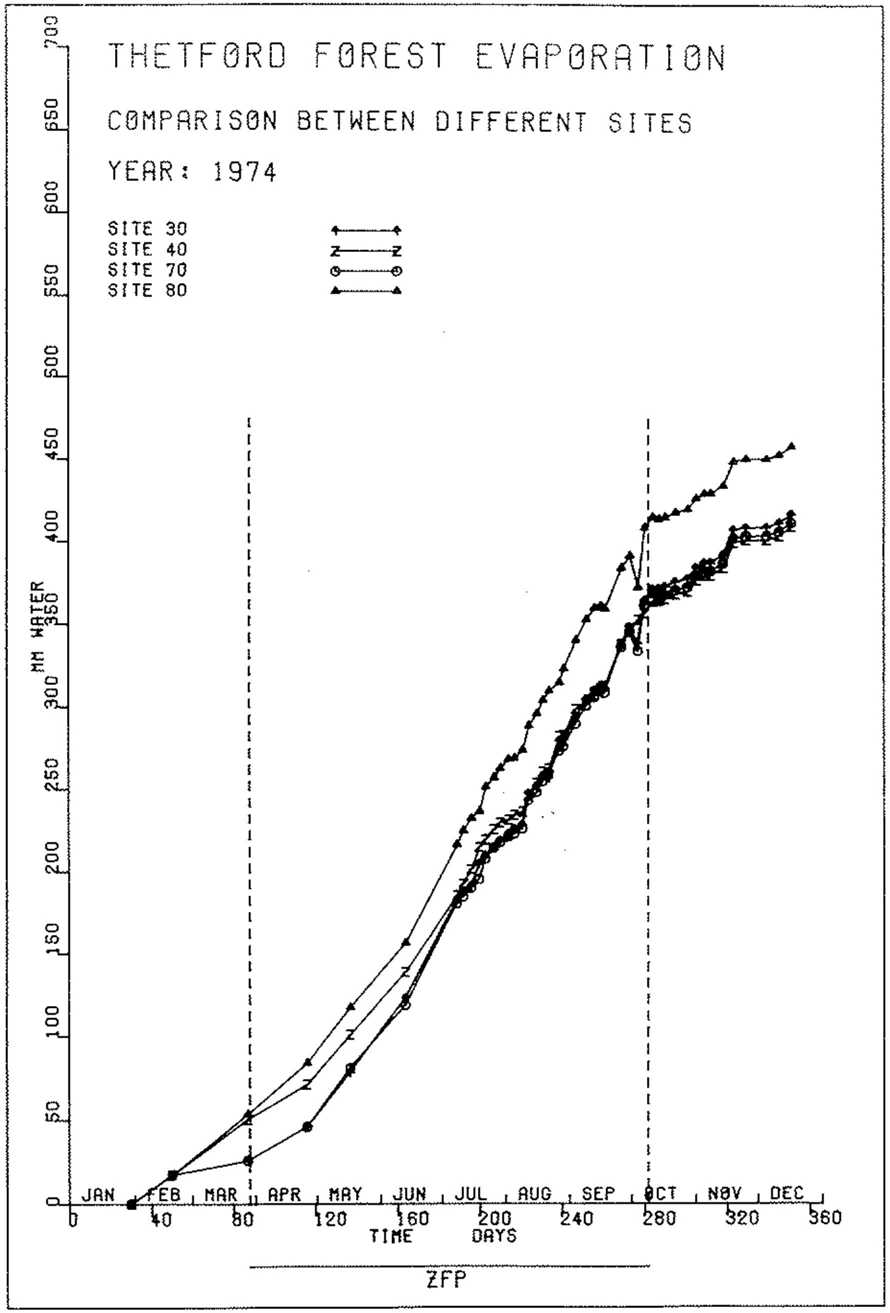


FIGURE 5.31

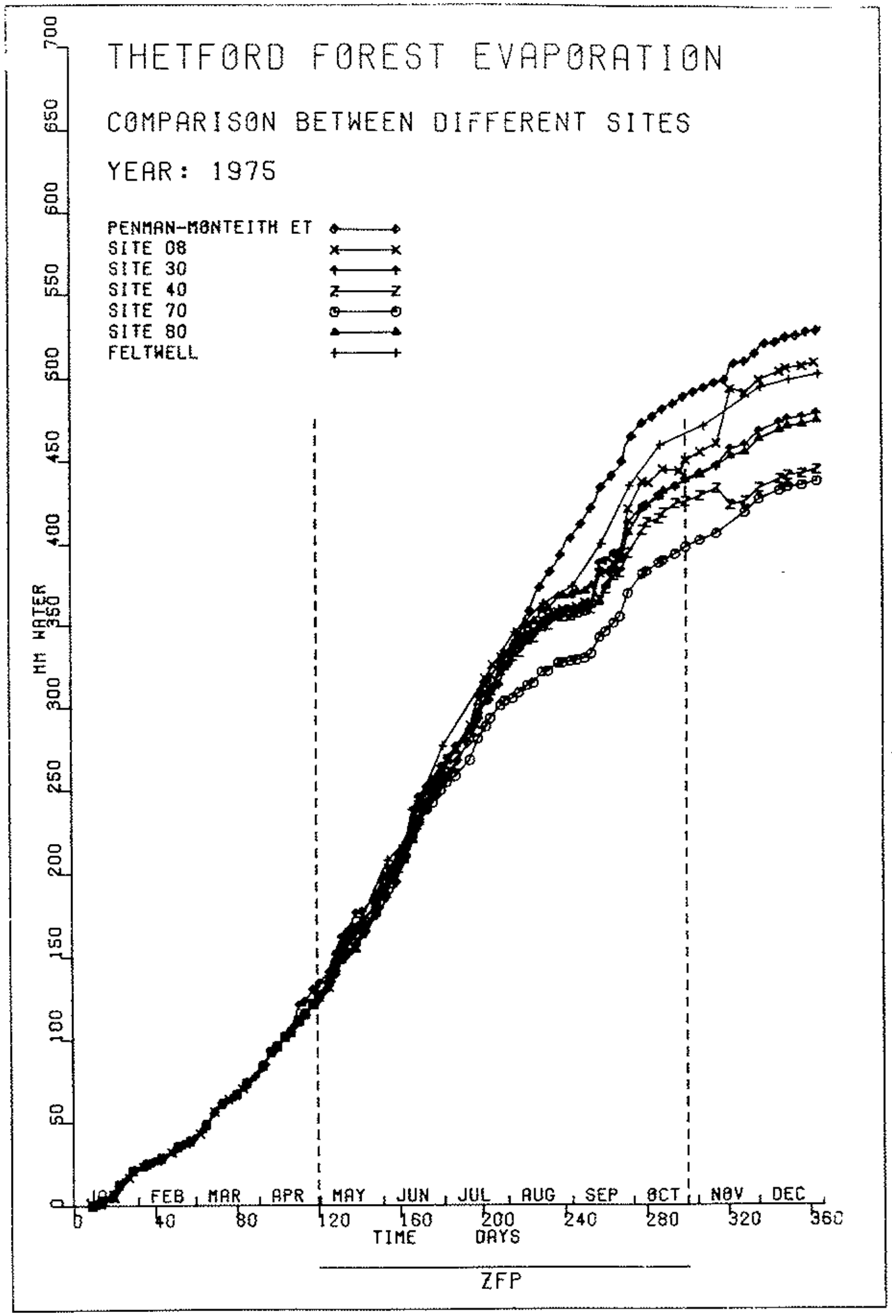


FIGURE 5.32

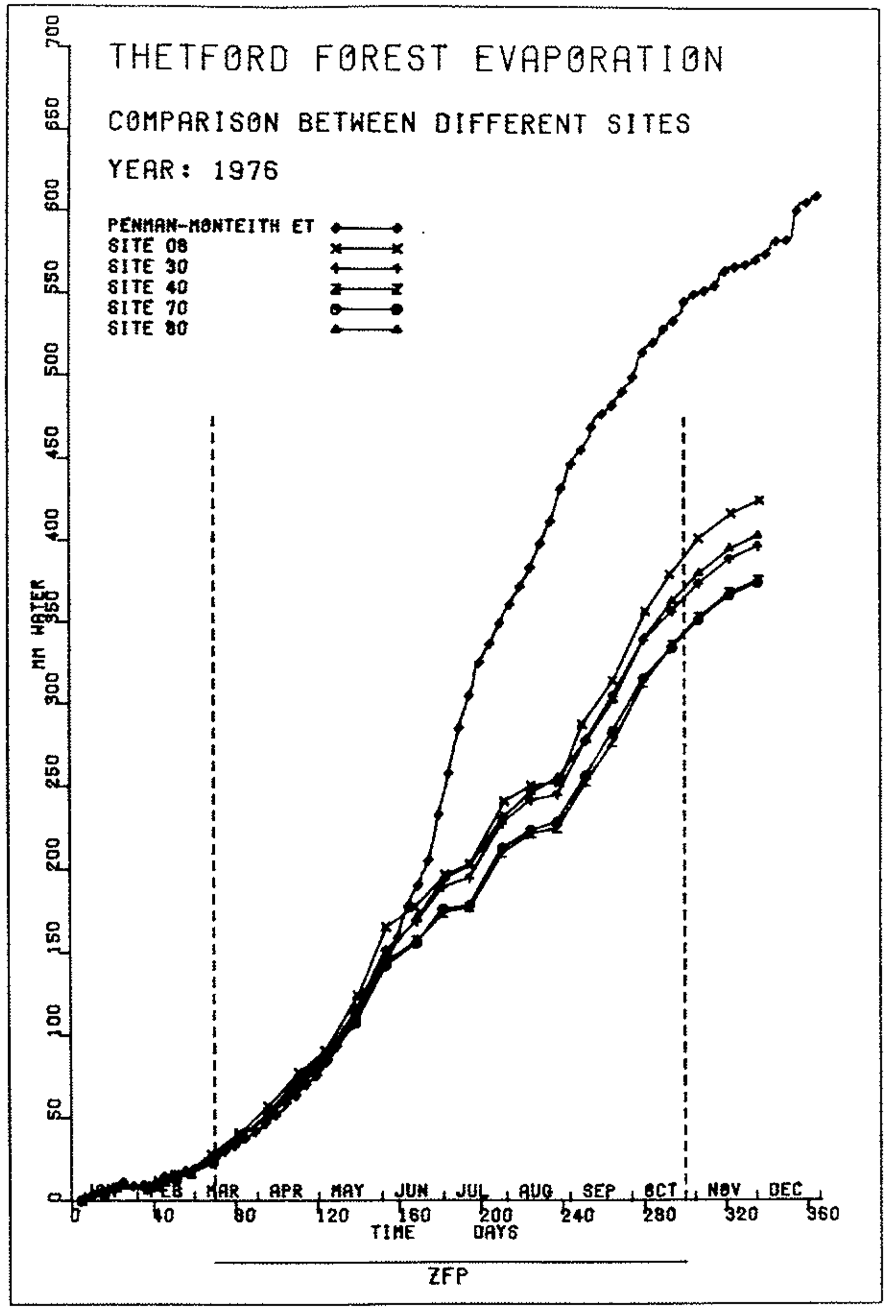


FIGURE 5.33

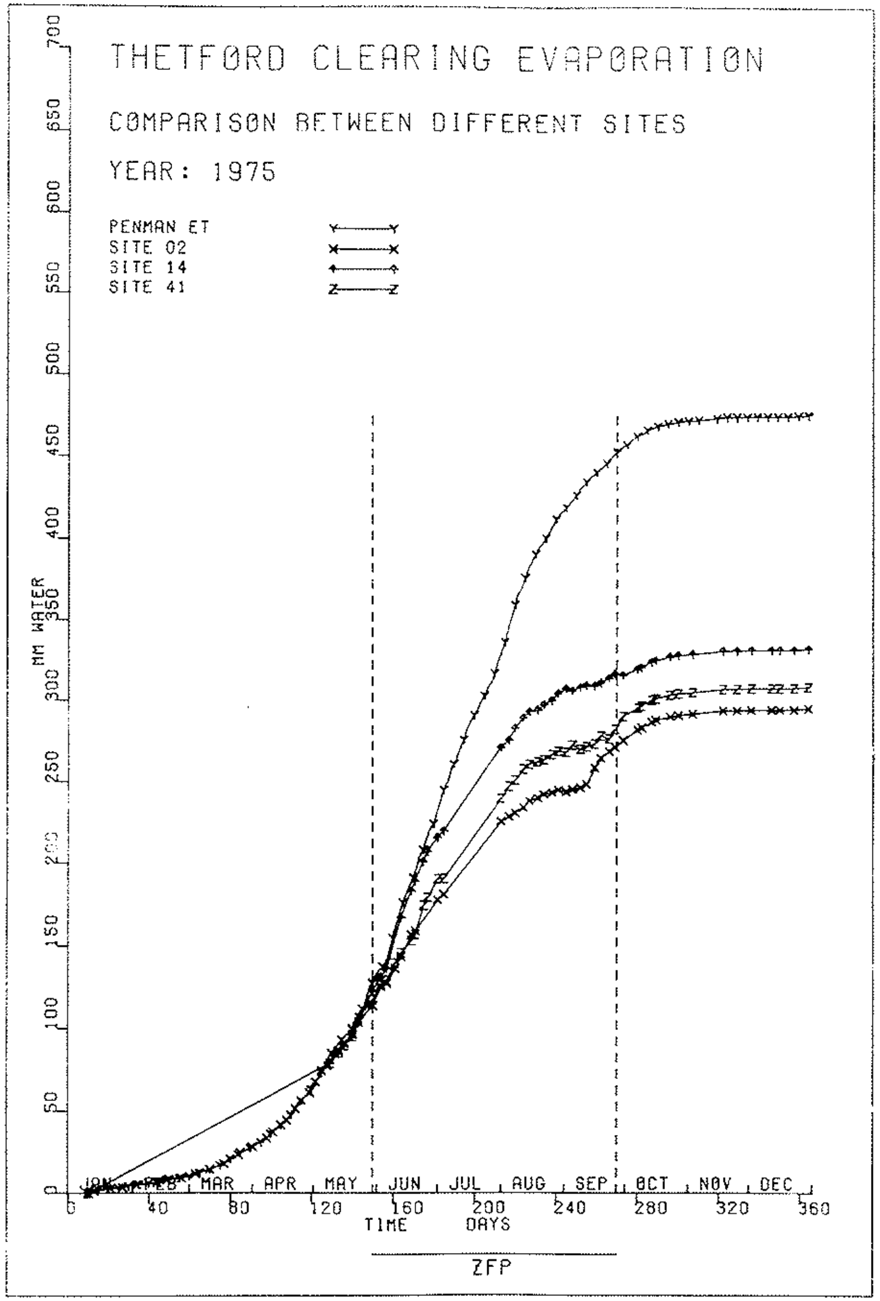


FIGURE 5.34

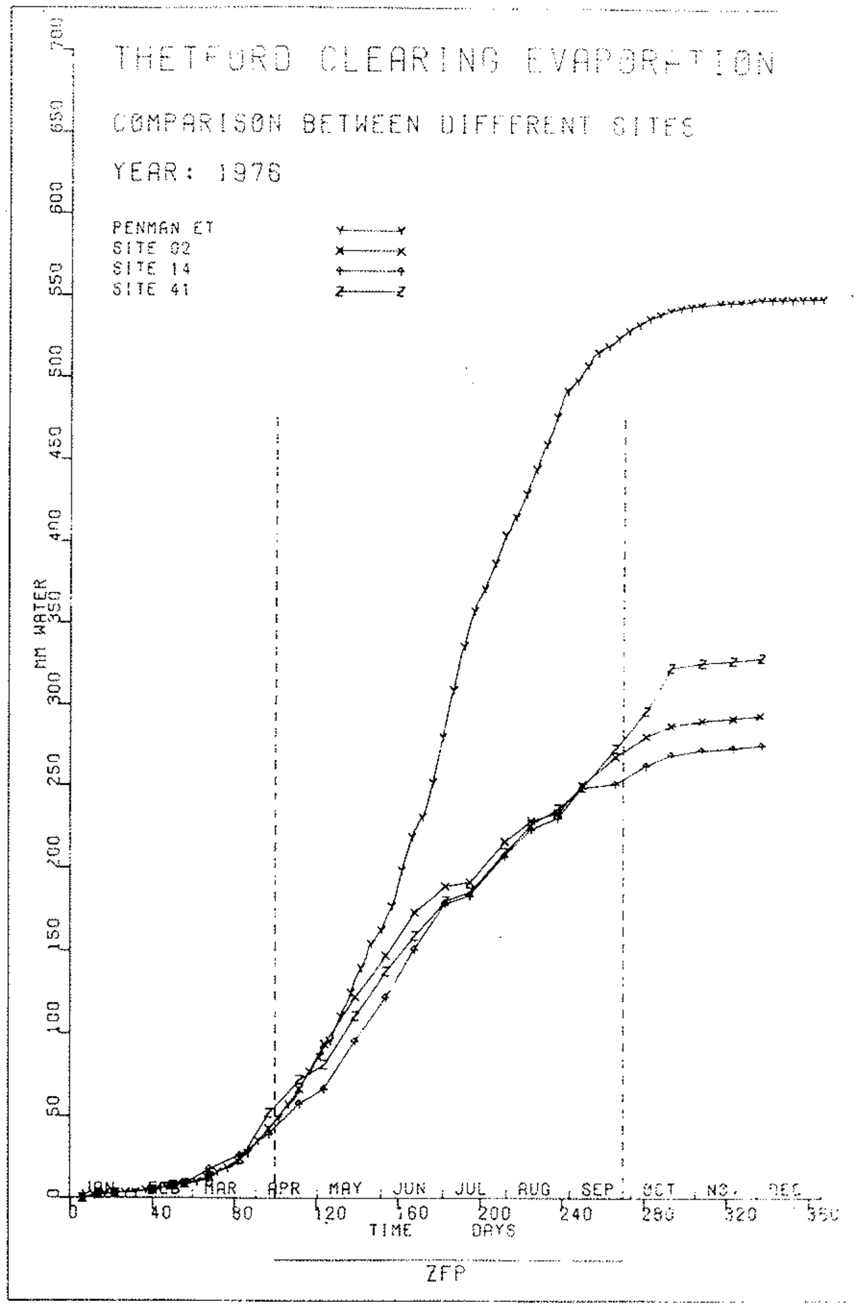


FIGURE 5.35

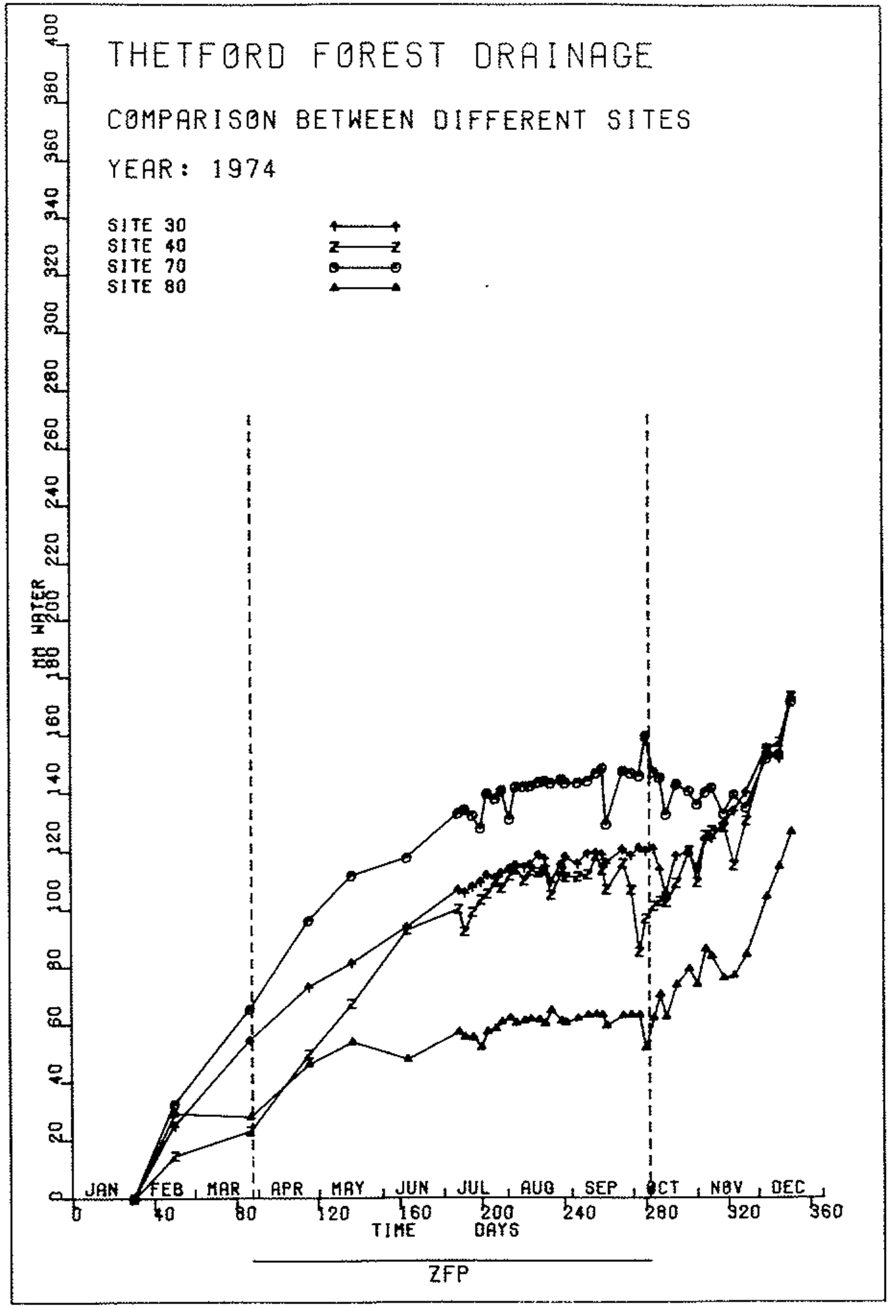


FIGURE 5.36

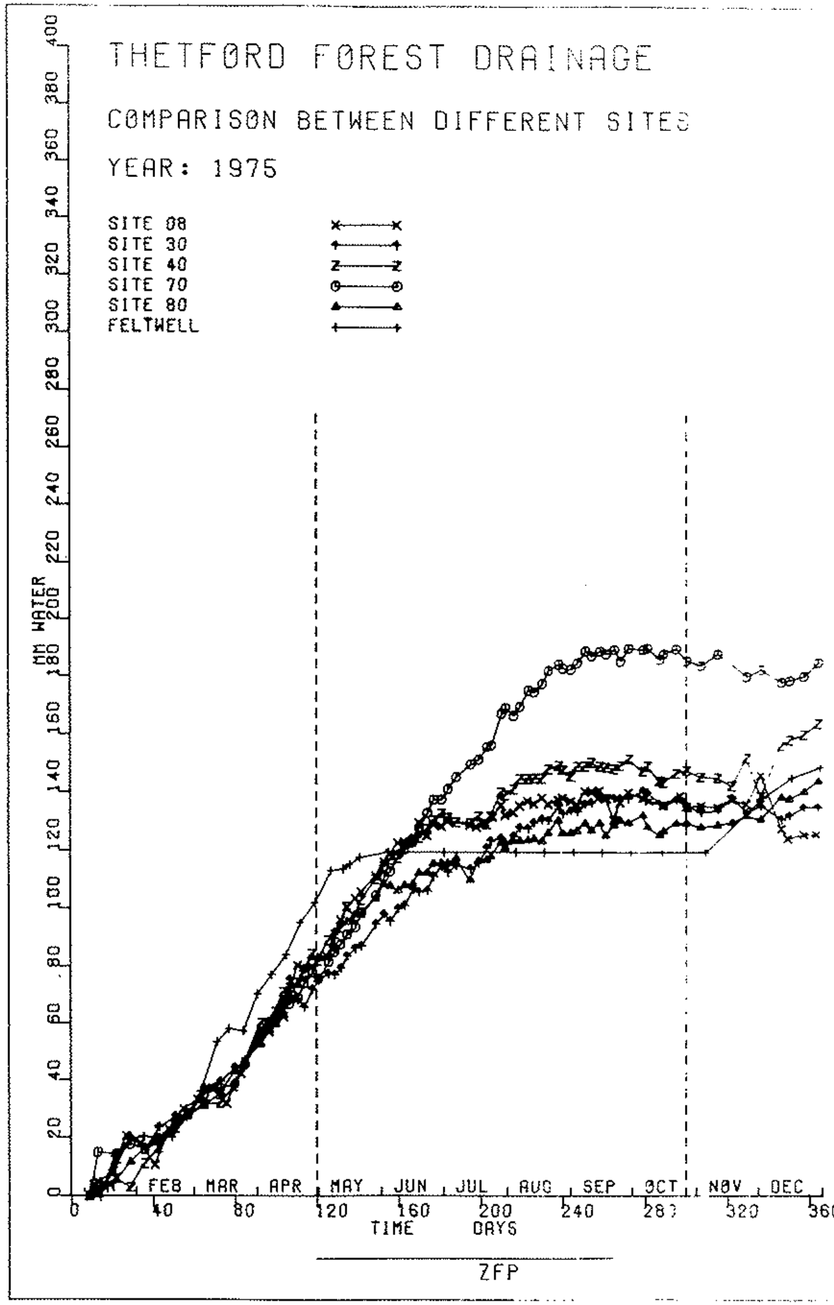


FIGURE 5.37

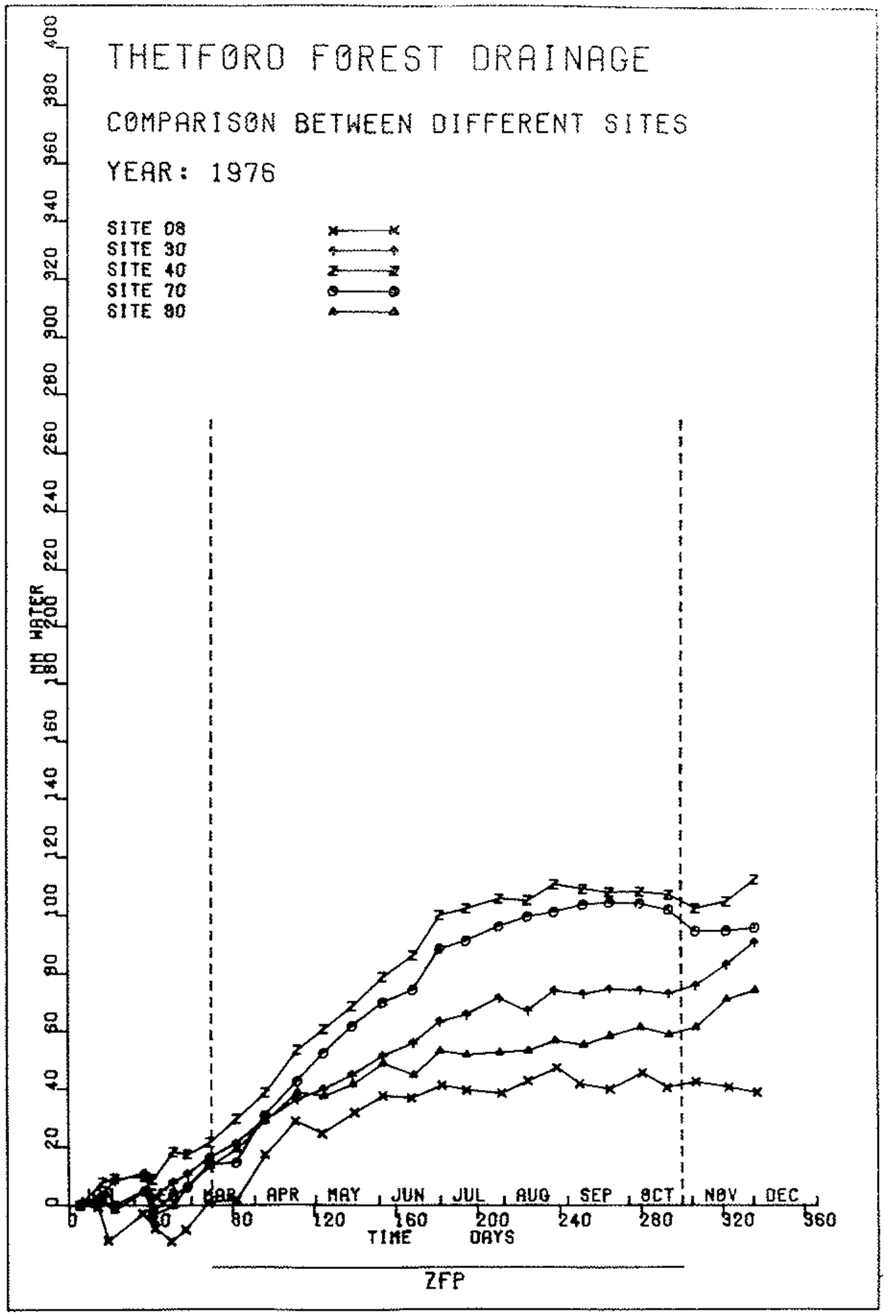


FIGURE 5.38

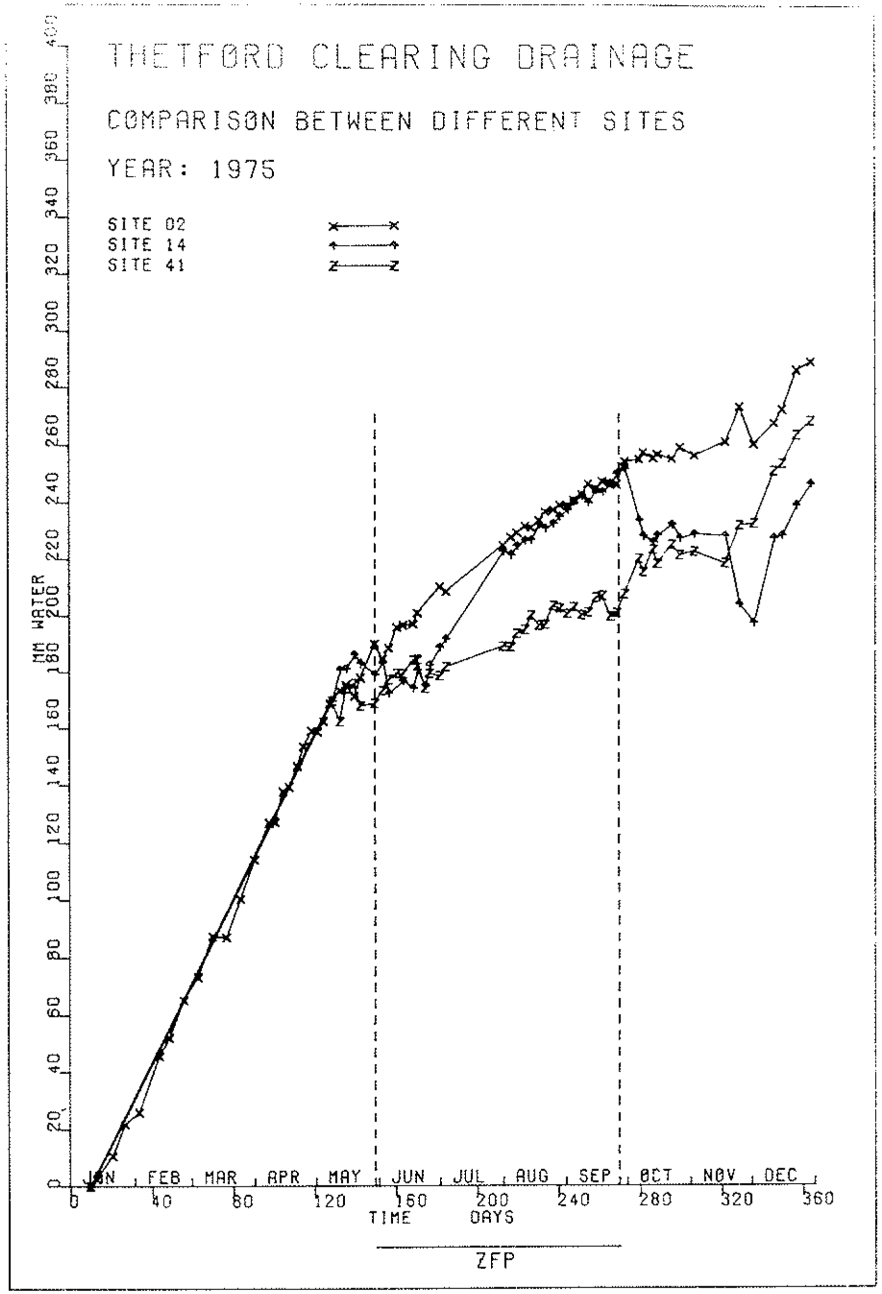


FIGURE 5.39

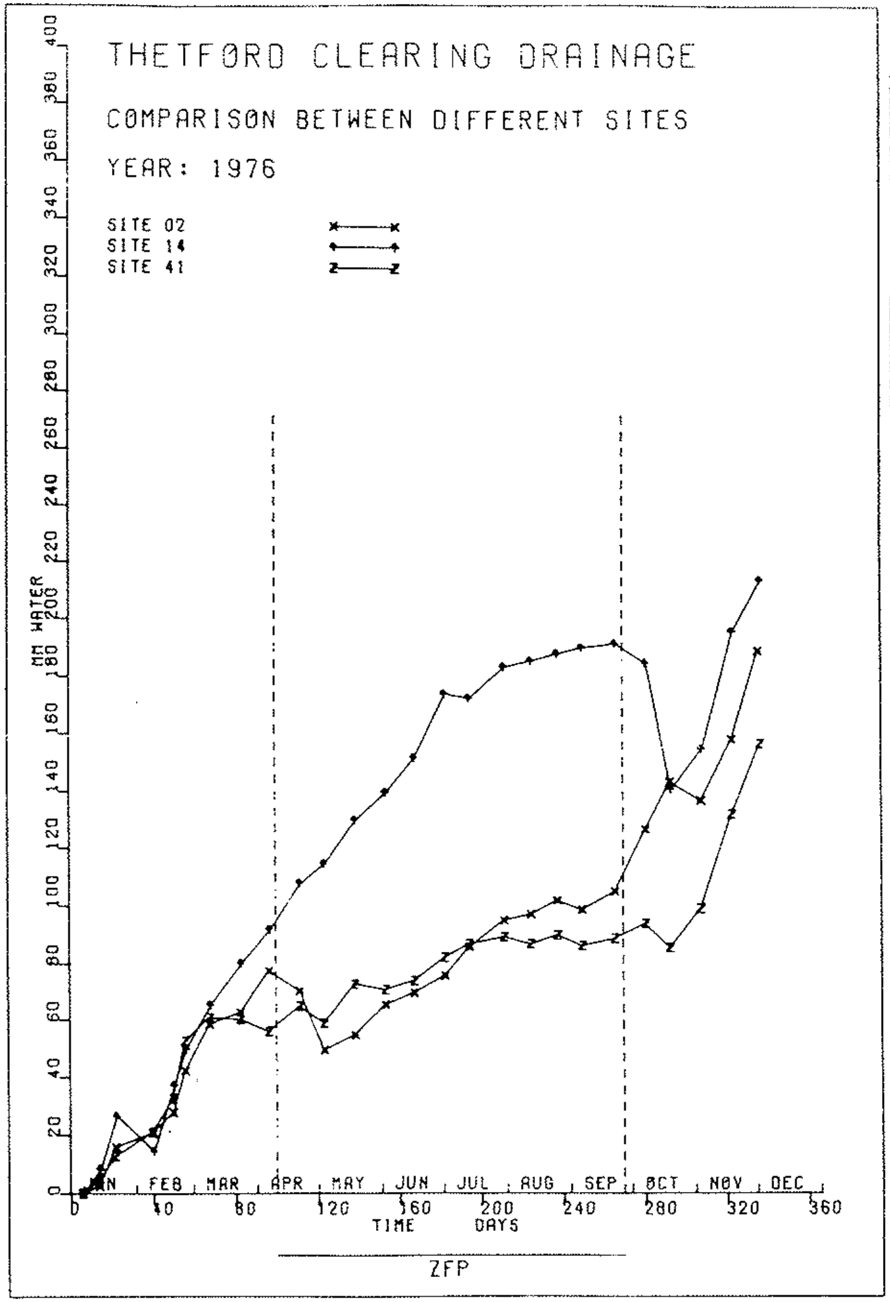


FIGURE 5.40

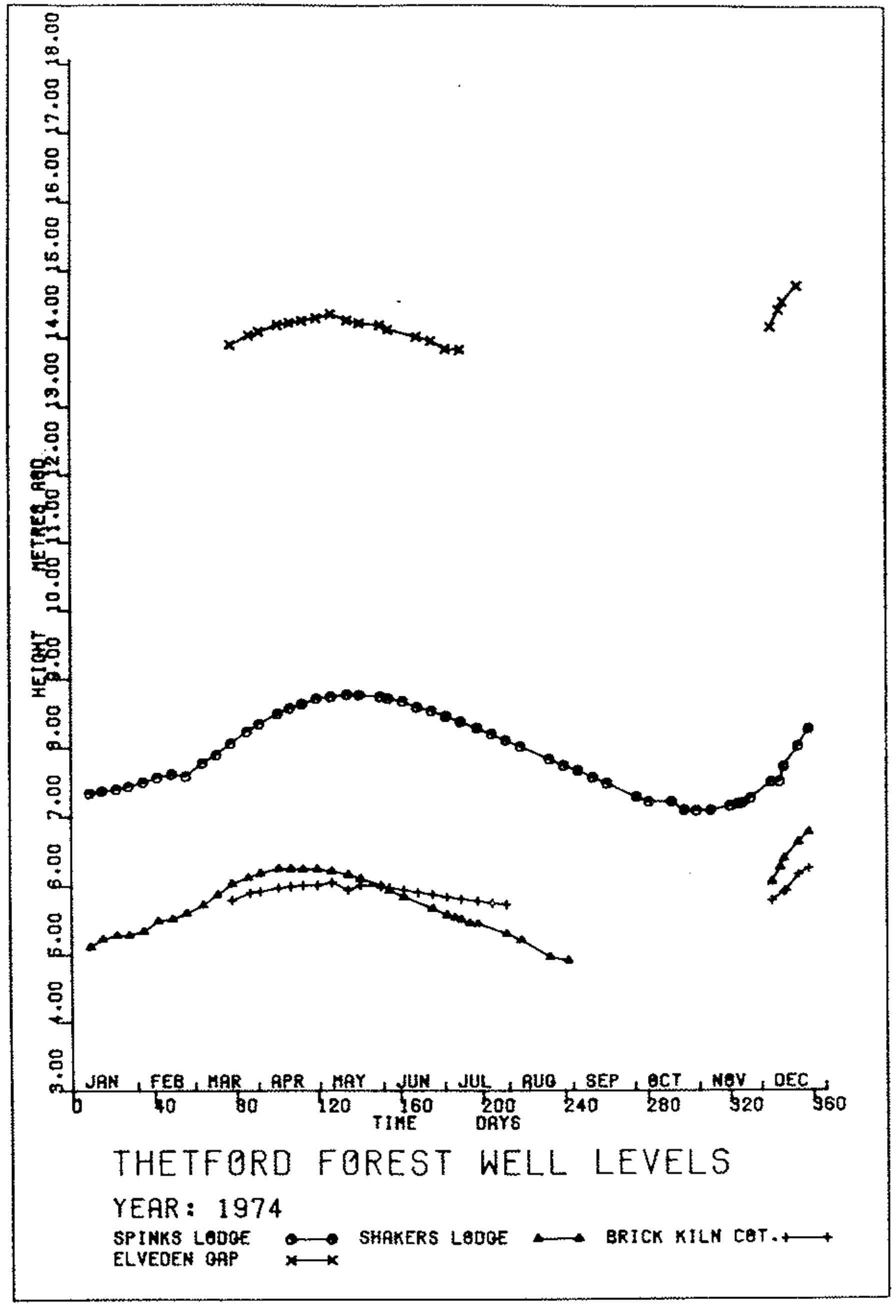


FIGURE 5.41

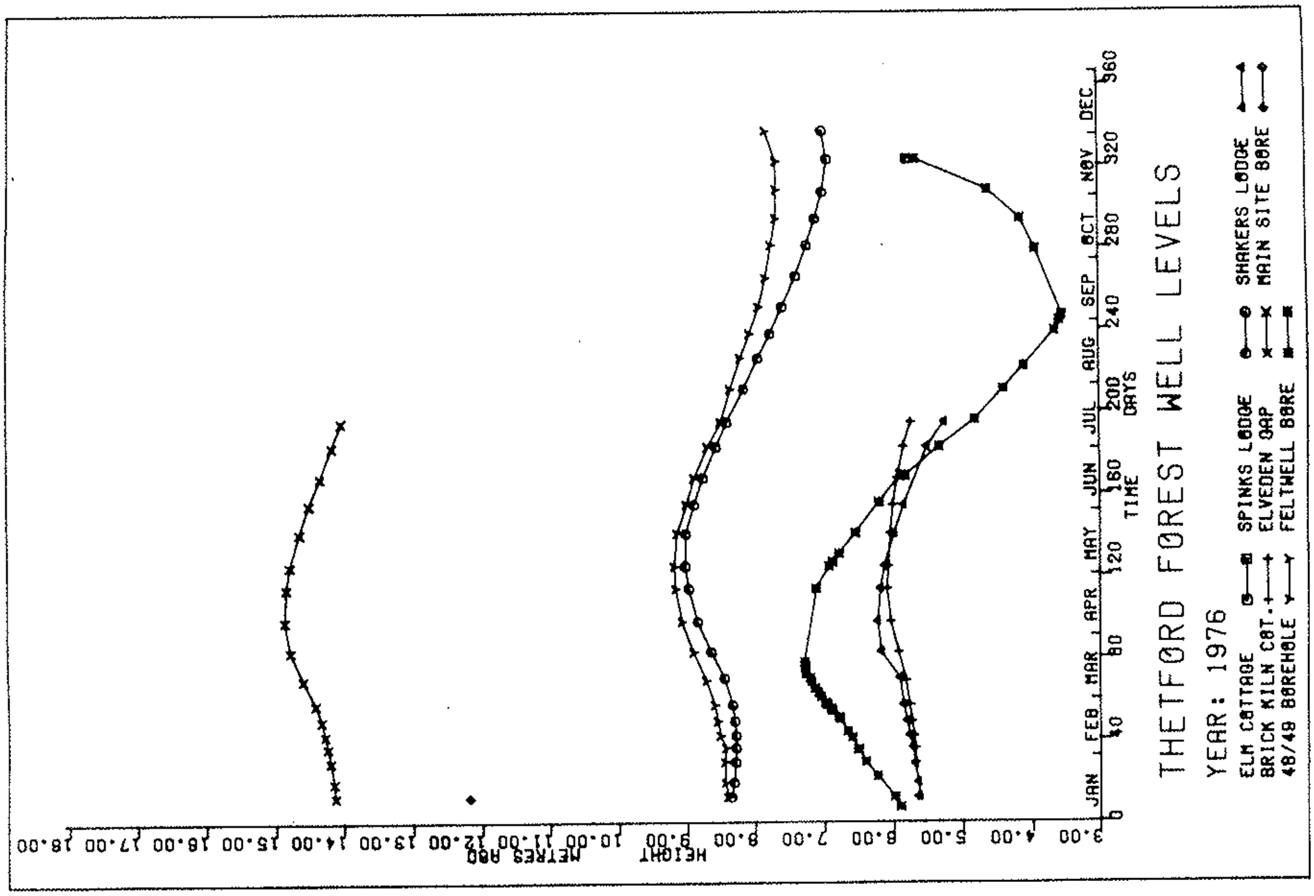


FIGURE 5.43

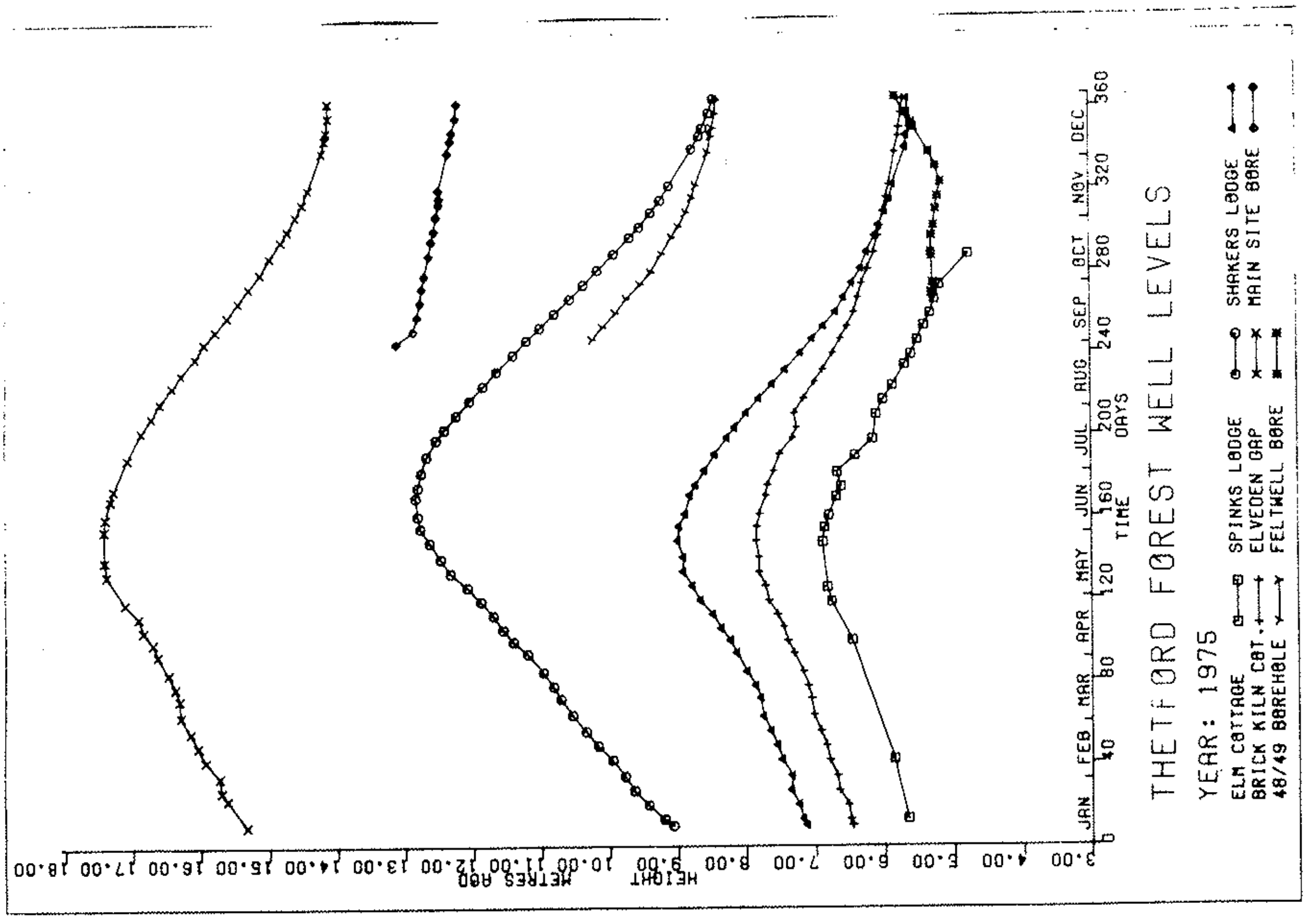


FIGURE 5.42

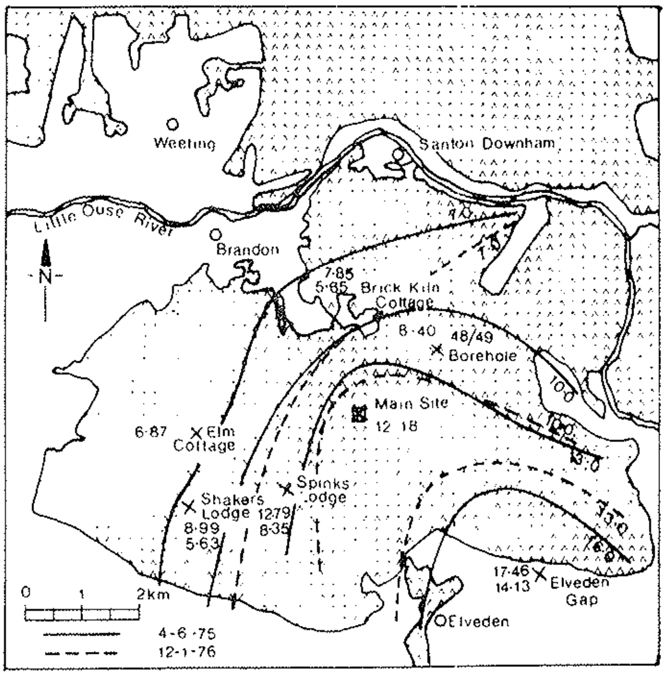


FIGURE 5.44 Water table level contours a.o.d. on 4 June 1975 and 12 January 1976 drawn by eye. Level at individual measurement sites also shown. Where only one value is given the well was dry on the second occasion.

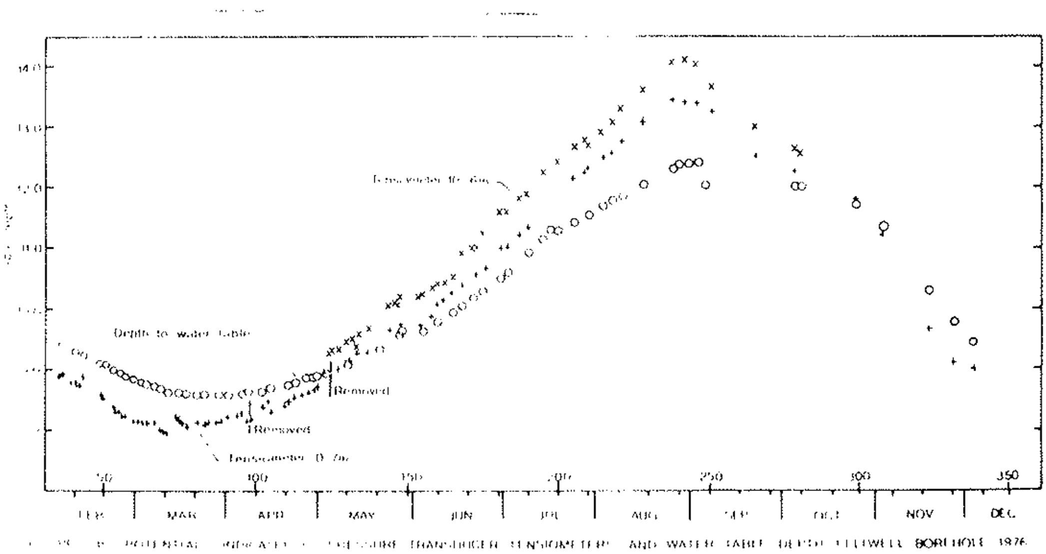


FIGURE 5.45 Potentials indicated by pressure transducer tensiometers and and water table depth, Feltwell borehole 1976.

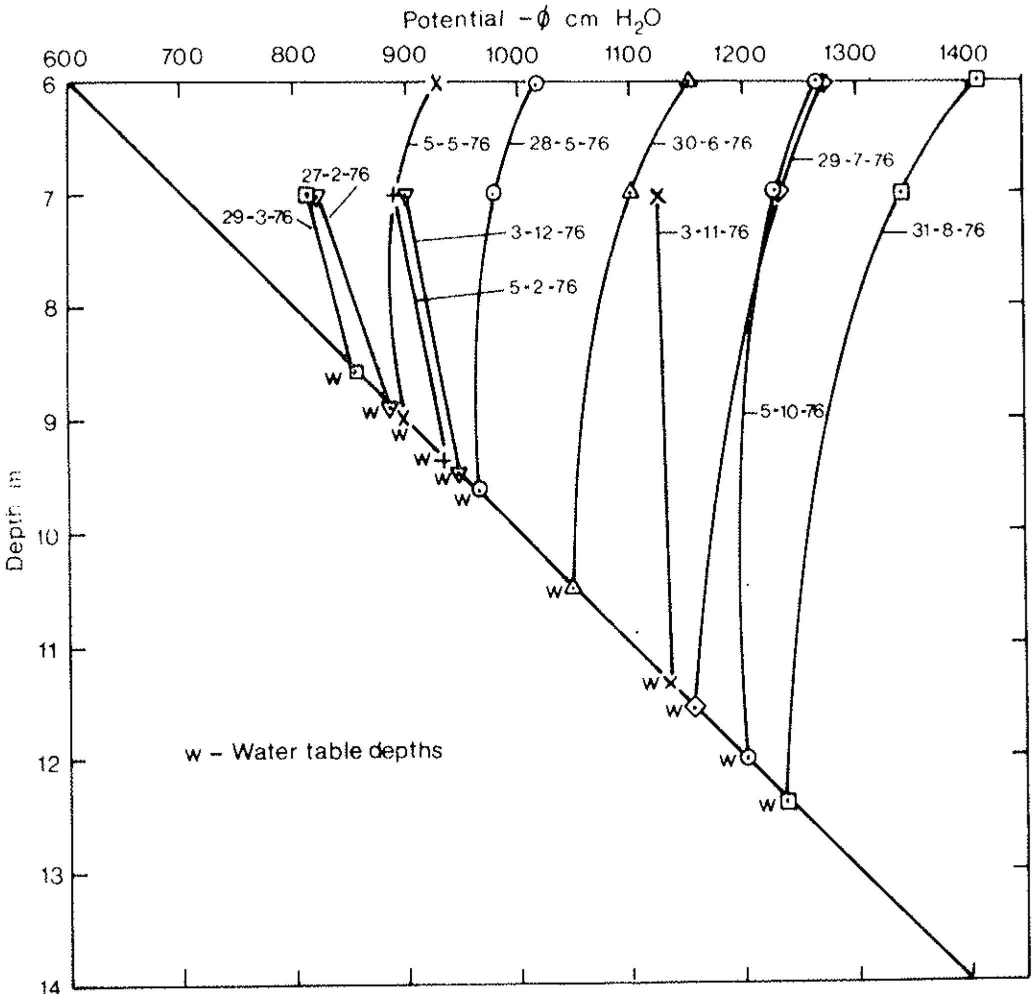


FIGURE 5.46 Potential profiles, Feltwell borehole

6. DISCUSSION

Before discussing the water balance data for the various sites it may be helpful to review the 'raw' data leading to these estimates.

6.1 Moisture Content Data

The great heteorogeneity of the soil at the site has been described in Section 3.3. It would be surprising if this were not reflected in the moisture measurements. Considerable variation of moisture content both between different access tubes and different depths in the same access tube is observed (Figures 5.1 to 5.6). Of greater relevance to the present work, there are also substantial differences between changes of moisture content at different places and depths, over the same time interval.

Between years the general patterns of depletion are similar (Figures 5.1 to 5.6) though in the dry years of 1975 and 1976 drying, as expected, was greater in both magnitude and depth than in other years.

6.2 Water Potential Data

Examination of the time series graphs of water potential (Figures 5.8 to 5.13) demonstrates the correspondence between variations of potential and moisture content.

Several anomalies have been edited out of these data but some of the data still show the effects of frost. These can be seen particularly well during March 1976 in the clearing tube O2 (Figure 5.13). The effects of purging are also evident in the 1976 data (Figures 5.12 and 5.13). In the summer, at times when the tensiometers are close to the limit of their range, the readings rise fairly rapidly after purging and then steady after 2-3 days, after which they begin to decline until the next purging. Thus there is a need to examine fairly long runs of data to make a good assessment of the reliability of the reading from each tensiometer.

A further point to note is that readings giving indicated potentials of less than about -700 cm H_2O have been found to be non-reproducible. High points on the graphs should, therefore, be treated with some sceptism, although they give a good qualitative picture of falling potentials, even though the tensiometer may be lagging behind the true soil potential quite considerably.

It is interesting to note from both the potential and moisture content graphs (Figures 5.1 to 5.13) that at the end of the summer, when rainfall starts to exceed evaporation and the surface layers wet up, the soil at the bottom of the profile continues to dry quite steadily for some considerable time before the wetting front reaches it. The converse situation also occurs when in spring the soil at depth may be wetting up whilst the surface is drying rapidly.

The contrast of the Feltwell site tensiometer readings (Figure 5.10) with those from the main forest site (Figures 5.7, 5.9 and 5.12) deserves attention. Not only do the tensiometers rise more rapidly at Feltwell during the late spring but they do so very nearly in unison throughout the profile rather than rising in sequence down the profile, as tends to happen at the main site. Moreover, for depths below about 2 m (i.e. the geological chalk) even short dry periods during the winter are sufficient to cause a noticeable rise in the tensiometer readings. This behaviour has been noted also at the Institute's experiment on Upper Chalk near Winchester.

The potential profiles (Figures 5.14 and 5.15) illustrate many of the same points. In the forest it is apparent that the lower depths wetted considerably between late January and early May, although the upper layers had dried. Near the end of December most of the profile had wetted to a tension in the region of 100 cm H_2O but the lower levels were still very dry.

The potential profile graphs for the clearing (Figure 5.15) perhaps illustrate better the development of the zero flux plane, which first appeared at about 0.4 m in late May. It descended steadily as both surface and bottom of the profile achieved lower potentials and reached a depth of 1 metre by 26 August, where it remained for some time, before disappearing by 9 October. Below 1.6 m this profile was drier than any of those shown in Figure 5.15, illustrating that drying continued at depth whilst the upper part of the profile was wetting up.

6.3 Zero Flux Plane Depths

These show considerable variation between instrument sets, although reasonable consistency between years. Some interesting exceptions to this are, however, apparent. For instance the ZFP at set 40 in 1974 (Figure 5.14) only reached 0.8 m and was the shallowest ZFP on the grid, whilst in 1975 it was the deepest at 2 m. In 1976 it was fairly shallow again. Examination of the potential profiles revealed a long portion which was almost vertical, requiring only small changes of potential at top or bottom to cause the ZFP to change its depth dramatically. Moisture content and tension changes were very small in this region so that no great error occurs in the water balance estimates due to the uncertainty in ZFP depth. In general, ZFP depths beneath the grass are shallower than under the trees, though this is not true in every case.

The fairly steady drop of the ZFPs generally observed at the main forest site is in marked contrast to the rapid plunge at Feltwell (Figure 5.17); this is a consequence of the almost simultaneous fall of the potentials all down the profile. At about the same time as the

ZFP reached 3.2 m (the lowest reading depth) the tensiometers all went off scale. For the purpose of making water balance estimates the ZFP has been assumed arbitrarily to be at that depth from then on, though in reality it was probably much deeper and may have intersected the water table some 10 m below ground, in which case water flow would have been upward throughout the whole 10 m profile.

6.4 Water Balance Estimates

The overall mean water balance for the main forest site is shown in Figures 5.21, 5.23 and 5.26. It should be noted that for 1974 (Figure 5.21) the assumption of zero transpiration during non-ZFP periods has been made and no comparison with theoretical evaporation has been possible. The likely consequences of this neglect are discussed fully on p 69.

The comparisons between total measured evaporation and the calculated transpiration using the Penman-Monteith model plus measured interception (Penman-Monteith ET) for the other two years were very close until about 90 days after the beginning of the ZFP period. Thereafter the measured evaporation rate fell below the Penman-Monteith value until a sufficient amount of rainfall (about 50 mm) had fallen to rewet the upper layers of the soil profile. After this the measured and calculated evaporations once again agreed well in both years.

The large contribution of intercepted rainfall to the total evaporation from the forest is shown by the difference between the cumulative transpiration and total evaporation curves in Figures 5.21, 5.23 and 5.26. Interception is also shown as a separate component in Figures 5.28 to 5.30. Over the whole three years about 41% of the evaporation was accounted for by intercepted water.

Evaporation from the Feltwell site (Figures 5.24 and 5.32) is little different from that at the main forest site.

Drainage from the main forest site continued in all three years throughout most, if not all, of the ZFP period. This is in marked contrast with the prediction of the Meteorological Office model, where drainage ceases abruptly once a soil moisture deficit has appeared and stays zero until the end of the summer when net rainfall exceeds the accumulated deficit. The annual totals of drainage varied markedly from year to year.

Calculated drainage from the Feltwell site ceased quite rapidly (Figure 5.24) once a ZFP had become established. This was a consequence of the rapid fall of the ZFP and the assumption that it stayed at 3.2 m for most of the summer.

In the clearing (Figures 5.22, 5.25 and 5.27) the most striking feature is the extent to which actual measured evaporation fell below the Penman ET estimate, despite the assumption that actual evaporation was equal to this during the periods when no ZFP was detected. Support for this assumption comes from the observed agreement between measured evaporation and ET for some time after the start of the ZFP period in

1974 and 1976, though not in 1975, and that once again there was good agreement after heavy rain towards the end of the ZFP period. This was possibly not the case in 1976, when one might expect the grass to take some time to recover from the effects of the drought, though the low reading frequency in this year makes it difficult to make a judgement. Over all three years actual evaporation was 906 mm, 61% of the total ET of 1479 mm.

Once again drainage from the clearing carried on throughout the summer in all three years.

The water balance results will now be examined in some detail.

Evaporation

(a) Forest

Since no estimates for forest evaporation by the Penman-Monteith method are available for 1974, it will be convenient to deal first with the data for 1975 and 1976. For 1975 (Figures 5.23 and 5.32) the Penman-Monteith estimate of evaporation agreed well with the measured rate until late July or early August, when the measured values fell below the meteorological estimate. Further examination shows that practically all of the discrepancy occurred during the 6-week period from 30 July to 10 September. Following the large storm on 13 September (some 47 mm of rain) the measured evaporation rate corresponded closely to the Penman-Monteith estimate (from 15 September to 11 November the measured evaporation was 69 mm compared with a Penman-Monteith estimate of 64 mm). The measured evaporation over 1975 for instrument set number 70 was markedly lower than that measured by the remainder of the forest instrument sets and the rate fell below the Penman-Monteith estimate some 40 days before the same thing happened at the other instrument sets. For most of the summer set 70 had the shallowest ZFP of all forest tensiometer sets (Figure 5.17), and the date at which the evaporation curve started to diverge from the others (about day number 175) matches the time when all other tensiometer sets indicated a rapid descent of the ZFP which was not observed at set 70. The difference might therefore be construed as due either to lower evaporation at set 70 causing the ZFP to fall less than at the other sets or to an error in the estimated position of the ZFP at set 70. This point is explored further in Section 6.7.

The measured evaporation rate at Feltwell agreed with (and in fact seemed to be slightly higher than) the Penman-Monteith estimate for rather longer than at the main forest site locations. Two points should be borne in mind with regard to this site. Firstly, the ZFP depth was arbitrarily taken to be the deepest measuring depth of the instruments (3.2 m) from the time when it reached that depth (11 June) until the soil was wetted to 3.2 m. Since the ZFP probably went much deeper than this, any moisture changes below 3.2 m would increase the evaporation value. Secondly, there are no independent rainfall measurements for Feltwell. Evaporation during the summer is calculated essentially as the difference between rainfall and soil moisture change and so the accuracy of the evaporation measurement for this period is equal to the accuracy of the assumption that the rainfall at Feltwell was the same as at the main site. In view of these points the difference in the Feltwell evaporation results from those at the main site should be treated with some caution.

In 1976 (Figures 5.26 and 5.33) once again the Penman-Monteith estimate at the main forest site agreed well initially with the measured evaporation. However, the latter began to fall behind the estimate very much earlier (in early June) than in 1975, the measurements from all instrument sets departing from the Penman-Monteith curve at about the same time. Furthermore, the cumulative discrepancy by the time the ZFP disappeared in the autumn was about 184 mm compared with 64 mm in 1975. Once again, though, once the upper layers of the soil were rewetted, the measured and estimated evaporation rates were in close agreement. From 8 September to 20 October (when the ZFP had disappeared at all tensiometer sets on the grid) the measured evaporation was 81 mm compared with a Penman-Monteith estimate of 74 mm. As in 1975 instrument set 70 indicated a low evaporation rate though set 40 gave a practically identical result to that of set 70.

The moisture content of the upper 1.1 m of the profile (corresponding roughly to the root zone) has been examined in relation to the point at which the measured evaporation rate departed from the Penman-Monteith curve. In 1975 the mean moisture content at this time was 55.3 ± 1.0 mm and in 1976 68 ± 4 mm, the larger uncertainty in 1976 being due to the much longer gap (14 days) between readings in 1976 than in 1975 (every 3-4 days). These correspond to deficits from the 'standard value' (described in Section 5.1) of 65.5 mm and 52 mm respectively. Whilst the moisture level at which the departure occurs is not exactly reproducible, it is at least quite comparable in each year and suggests that soil moisture may be an important control on the transpiration rate.

In 1974, during the period before and after the ZFP was observed transpiration has been assumed zero, since no reliable Penman-Monteith estimates are available for these periods. During these times evaporation will have been underestimated and drainage overestimated by the amount of transpiration which has actually taken place. Of course no error will result in the evaporation and drainage estimates for the period when a ZFP was present.

In 1975 there was an estimated 44 mm of transpiration before the onset of the ZFP and 12 mm after it had disappeared, whilst in 1976 there was 18 mm before the ZFP began and 4 mm afterwards. The periods during which a ZFP was observed were from about 29 March to 9 October (194 days) in 1974, 30 April to 27 October (180 days) in 1975 and 10 March to 26 October (230 days) in 1976.

A rough estimate of the amount of transpiration which has not been accounted for may be made by using the Penman ET estimates. Table 6.1 shows comparisons between transpiration estimated from the Penman-Monteith model and Penman ET estimates for the early and late parts of 1975 and 1976. There is rough correspondence between the two, though clearly no more than this. For the period 30 January (the first reading occasion) to 28 March 1974, ET was estimated as 24.2 mm, and

TABLE 6.1 Comparison of Penman-Monteith estimates (Gash & Stewart model) of forest transpiration with Peman ET estimates for winter periods in 1975 and 1976.

Period	Penman ET estimate mm	Penman-Monteith Transpiration estimate mm
9/ 1/75 - 16/ 4/75	42.9	31.9
27/10/75 - 31/12/75	4.8	11.7
5/ 1/76 - 31/ 4/76	40.5	33.0
26/10/76 - 31/12/76	5.2	4.1
TOTAL	93.4	80.7

from 9 October to 16 December (the last reading occasion) 15.6 mm, a total of 39.4 mm. Evaporation is expected to have been underestimated over the year by an amount of this order, and consequently drainage will have been overestimated by the same amount.

Apart from set 80 the other three instrument sets showed good agreement with one another over the year although set 40 showed a rather larger amount of evaporation up to early July. This may be caused by the fact that moisture content readings are only available on a monthly basis at the beginning of 1974, and does not necessarily reflect true differences between the locations of the sets of instruments (see Section 6.8).

For much of the summer period the ZFP is within the root zone of the trees. The method assumes that there is no water uptake by roots beneath the ZFP, since all depletion of water beneath it is ascribed to drainage. In the early part of the summer, when ZFP depths were quite shallow, the measured evaporation rate agreed well with the Penman-Monteith estimate in both 1975 and 1976. Although there were a significant number of roots below the ZFP during these periods (see Section 3.3 and Roberts (1976)) they were presumably playing little or no part in supplying the water requirements of the forest. Later on, when the measured evaporation rate fell below the Penman-Monteith estimate, the measured drainage rates were quite small (only 9 mm from 30 July to 10 September 1975 and 23 mm from 2 June to 8 September 1976) compared with differences between measured and Penman-Monteith evaporation estimates of 64 mm and 184 mm respectively. Moreover the ZFPs were quite deep during these periods (Figures 5.17 and 5.19) and only a negligible number of roots would be expected below this. It is concluded, therefore, that any water extraction by roots beneath the ZFP has an insignificant effect on the forest water balance.

The important role of interception of rain by the forest vegetation is clearly demonstrated by comparing the total evaporation and transpiration curves in Figures 5.21, 5.23 and 5.26. The amount of water intercepted is plotted separately on Figures 5.28 and 5.30 and amounted to 539 mm over the periods reported. This represents about 32% of rainfall, 41% of total forest evaporation and 70% of transpiration over the same period.

(b) Clearing

Perhaps the most striking point about the measured evaporation from the clearing is that in all three years it was considerably lower over the year than the Penman ET estimate. Interestingly, the ranking of amounts of actual evaporation is in inverse order to that of potential evaporation, with the year of lowest potential evaporation, 1974 (453 mm), having the highest measured evaporation (310 mm) and the year of highest potential, 1976 (549 mm) having the lowest actual (294 mm). Results from instrument set 02 are quoted in each case.

In all years the measured evaporation rate (Figure 5.22, 5.34 and 5.35) fell behind the Penman estimate very shortly after the initiation of the ZFP. In fact in 1975 (Figure 5.34) all three instrument sets did not follow the Penman curve at all once the ZFP period had begun (a ZFP was not observed at set 14 until 25 June), suggesting that the assumption of an evaporation rate equal to ET before the ZFP was observed may not have been valid. There is, however, no evidence of a reduction in evaporation rate at the beginning of the ZFP period so that any discrepancy between real and estimated rates is probably small before this. It should be borne in mind that because of the very wet spring a ZFP was not observed in this year until the end of May, when quite high ET estimates were being recorded (almost 3 mm per day) whilst in both the other two years the average ET estimates about the time when the ZFP started were between 1 and 2 mm per day.

That the evaporation estimates do, with the exception of the 1975 data just discussed, follow the ET curve for at least a short while, suggests that the meteorological conditions in the clearing are not too seriously disturbed to cause gross errors in ET or to make the evaporation rate measured differ from that of an extensive area of grass by a significant amount.

The trees surrounding the clearing will provide some shading of the site in early morning and late evening, but only for solar angles above the horizon less than about 13°, when solar radiation is of relatively low intensity. The amounts of direct and indirect solar radiation intercepted by a horizontal surface at the centre of the clearing are both about 5% less over a year that they would have been had the trees around the edge not been there.

Potentially more serious is the disturbance to the wind profiles. On the one hand they will shelter the clearing, leading to lower wind speeds, and hence a lower aerodynamic component of evaporation. On the other hand, the surrounding forest will introduce large amounts of turbulence into the airstream passing over the clearing, thus increasing the efficiency of water vapour transport away from the surface and tending to raise the evaporation rate.

Some idea of the effect of clearing conditions as opposed to a large area of grassland may be obtained by comparing the Penman ET estimates from the Forestry Commission's Santon Downham meteorological site with those from the synoptic station at Honington some 12 km to the SE of the main experimental site. The Santon Downham site is itself in a clearing (albeit rather larger than the one from which measurements are reported here) whilst Honington is on an airfield. Estimates from Honington were quoted by Gash and Stewart (1977) for comparison with their model. For the three years for which data are quoted in this report the annual totals of ET were:

	Santon Downham	Honington
1974	453	641
1975	476	643
1976	549	699

Examination of the data shows that by far the most important contribution to the differences between the estimates from these sites is the wind run which in the case of Honington is about twice that of Santon Downham. There may also be a difference of a few per cent caused by slight differences in the methods of calculation. The Santon Downham figures were calculated using the program described by Plinston and Hill (1974) whilst those from Honington were obtained from the Meteorological Office's published figures of potential evaporation.

Nevertheless, since most (67%) evaporation occurred during the ZFP period, an increase of ET does not necessarily imply an increase in actual evaporation, particularly since the measured values of evaporation are so much lower than the ET estimate. It seems quite likely that evaporation over the summer for a soil of this nature is determined by the actual amount of water available within the upper layers of the soil, rather than being climatically controlled. Alternatively, or perhaps additionally, evaporation may be controlled during some periods by the rate at which the soil can conduct water to the grass roots. Thus a possible explanation for the early divergence of the ET and actual evaporation curves during 1975 (Figure 5.25) is that the soil cannot supply water at a rate faster than about 2 mm d^{-1}.

This low measurement of annual evaporation compared with the annual ET estimate is in marked contrast with the assumption of Gash and Stewart (1977, see also Calder 1979). They considered that the ET estimate was a good approximation to the actual evaporation from grass and therefore that there was little difference between forest and grassland water use, with the grass probably using slightly more. It should, however, be borne in mind that the upper metre or so of the soil at the site is almost pure sand and will therefore be expected to dry out quickly, leading to the early onset of water stress on the plants. On soils with more typical water holding capacities the reduction of actual evaporation below ET would probably be much less, but will clearly vary from soil to soil. The drawing of general conclusions is clearly very hazardous since the type of soil has a strong influence on the water yield. This is likely to be especially true in drier areas where the water yield is relatively quite small and hence sensitive to small differences in evaporation.

Generally speaking the three sets of instruments show good consistency between evaporation measurements (Figures 5.34 and 5.35). Two major discrepancies are apparent in these figures. In 1975 instrument set 14 showed a higher evaporation rate in the early summer than that measured at the other two sets. On examination it is found that a ZFP was not observed with this set of tensiometers until 25 June (day number 176). The evaporation rate has been maintained by the calculation program at ET up to this point, whilst a lower evaporation rate was actually observed at the other two sets of instruments. After 25 June all three sets agreed very well with one another. A similar state of affairs occurred in the autumn of 1976 in the case of instrument set 41, where the measured evaporation in a period of high rainfall (c.f. Figure 5.29) was much higher than the ET estimate. In this case a ZFP was still being observed on the tensiometers up to 27 October (day 300), whereas it had disappeared at the other two sets some 30 days earlier. Some increase of water contents had been observed below the ZFP depth at the associated neutron probe access tube leading to an apparently high amount of evaporation and a low (in fact negative, see Figure 5.40) drainage measurement. This illustrates one of the limitations of not being able to place tensiometers and access tubes at physically coincident points, particularly in a heterogeneous soil.

Drainage

It is immediately apparent from Figures 5.21 to 5.27 and 5.36 to 5.40 that drainage occurred throughout most - if not all - of the years studied and that a substantial amount of water was released from the lower part of the profile to drainage during the summer, when a ZFP was present. According to the soil moisture deficit model of calculating recharge, drainage stops abruptly when deficit conditions appear, an event that corresponds approximately to the onset of the ZFP. Table 6.2 shows the amount of drainage calculated for both forest and clearing during the times when a ZFP was and was not present. It is seen that at the main forest site 43% of the total drainage at 3.1 m depth over the whole period reported occurred whilst ZFP conditions prevailed, ie during late spring, summer and early autumn. The corresponding figure for the clearing was 19%. At Feltwell, however, owing to the rapid plunge of the ZFP there was virtually no drainage at this time. Indeed if the ZFP were deeper than the deepest measuring depth (3.2 m), which seems probable, flow would have been upward at this time, (ie negative drainage) although it has not been possible to measure this flow.

As noted previously a direct comparison between forest and clearing water balances should be treated with caution because of the shading and sheltering by the trees at the edge. However, if the results may be regarded as at least approximately representative of an extensive area of grassland then they indicate a considerable reduction of natural drainage due to afforestation in a particularly dry part of the country. The data in Table 6.2 indicate that over the periods reported here drainage from the forest was only 56% of that from the clearing. However, two winter months (January 1974 and December 1976), when drainage is expected to be high, are not represented in the forest data and five weeks (1-7 January and December 1976) are missing from the clearing data to make three complete years. Extrapolation of drainage rates suggests that for the forest 20 mm would be a reasonable estimate for drainage in each of the two 'missing' months, but this would be almost exactly offset by the 40 mm overestimate of drainage in 1974 by not having any transpiration estimates. Drainage in the clearing should be increased by almost 40 mm to take account of the extra five weeks data needed to complete a three year record so that the proportion of drainage from forest compared with that of grass is probably rather less, at about 54%, although it will vary from year to year.

Inspection of Figures 5.39 and 5.40 reveals that in the autumn of both 1975 and 1976 there was a sharp drop in the measured cumulative drainage curve for site 14 in the clearing, which later recovered. This particular access tube was situated within a deep pocket of sand to 2.8 m and the dip in the cumulative drainage curve corresponded in both years to the time when the wetting front reached that depth.

This was outside of the ZFP period and hence drainage was being calculated as:

$$D = P - T - \Delta S \quad (6.1)$$

The negative estimate of drainage is, therefore, a result of the measured change of moisture content in the profile exceeding the rainfall. It is suggested that this was due to lateral flow of water along the top of the clay-rich B_t horizon, which was very thick (0.35 m) at this point. This water then collected in the bottom of the pocket. During the ensuing drier weather it drained away and so the phenomenon is not expected to cause an appreciable long-term discrepancy.

6.5 Implications for Water Resources Management

Evidence is accumulating that afforestation in the wet, upland areas of Britain causes a considerable reduction in water yield (see eg. Calder, 1979). It appears that even in the drier areas the same effect may be occurring. Indeed, in some respects the results could be more serious. Calder (1979) found a greater total extra loss of water due to afforestation in the uplands than found here (1368 mm in Mid-Wales and 950 mm in the Upper Pennines for the three years 1974-76 compared with about 450 mm in this study). However, in terms of total water yield this extra loss represents a reduction of 28% in mid-Wales, 43% in the Upper Pennines and 46% at Thetford. Conversely, the increase in evaporation in the three cases was 90%, 70% and 49%.

If these figures are typical for the area, then significant afforestation of the eastern lowlands would have serious water resources implications. Wright (1974) has used the method of analysis of river flows to estimate long-term water balances for several catchments on the Chalk outcrop and drift-covered chalk area in East Anglia. In terms of the classifications he used the area studied in this report would be on Chalky Boulder Clay. The central forest block appears to coincide fairly well with his catchment 45.

Wright found that a good fit to river flow data was obtained by assuming, for the Chalky Boulder Clay:

Annual evaporation = 470 mm
Annual deep infiltration (groundwater recharge) = $0.202\ \bar{R} - 70$ mm
Annual direct runoff = $0.798\ \bar{R} - 400$ mm

where $\bar{R}$ is the annual rainfall in mm.

He recognised that evaporation from the forest areas could be rather higher than that for other land uses and that the proportion of water going to recharge compared with direct runoff may be higher in forest areas, but was not able to show statistically that either effect occurred, although none of the catchments examined had more than 16% of its area forested.

With a three year rainfall of 1894 mm one would expect on this basis total evaporation of 1410 mm, recharge of 173 mm and direct runoff 311 mm and total water yield of 484 mm. Comparison with table 6.2 and adding about 50 mm to the forest evaporation to take account of the assumption of no transpiration in non-ZFP periods in 1974 and the two months extra required to make a full three-year record, and about 40 mm to the clearing drainage shows that the two sets of figures agree quite well for the forest, although no direct runoff was observed at the experimental sites. For the clearing, however, evaporation is much lower and drainage much greater than Wright's figures.

The probable major reason for this is the very sandy nature and low water holding capacity of the top metre of the soil, which is expected to lead to the very early onset of water stress. It should also be borne in mind that most of the areas studied by Wright would have been under arable farming, whilst the clearing was grassed.

It therefore appears that the clearing results are unlikely to be typical of the area as a whole.

6.6 Precision and Accuracy of Water Balance Estimates

It is somewhat easier to discuss the precision of estimates of components of the water balance, since these are amenable to checks of internal consistency, than their accuracy which relies on comparison with an external standard which may itself be subject to appreciable error.

TABLE 6.2 Comparative evaporation and drainage in forest and clearing according to the presence or absence of a ZFP

FOREST (mean of 4 grid instrument sets)					CLEARING (instrument set 02)				
Period	Evaporation		Drainage		Period	Evaporation		Drainage	
	No ZFP	ZFP	No ZFP	ZFP		No ZFP	ZFP	No ZFP	ZFP
30/1/74-29/3/74	39.2*		43.6*		7/1/74-27/3/74	27.3		104.9	
29/3/74-9/10/74		339.3		63.7	27/3/74-20/9/74		255.3		59.0
9/10/74-17/12/74	52.5*		97.5*		20/9/74-18/12/74	27.0		164.5	
17/12/74-9/1/75	15.6		19.1		18/12/74-10/1/75	5.3		28.3	
9/1/75-30/4/75	128.5		79.0		10/1/75-22/5/75	104.0		178.2	
30/4/75-27/10/75		297.3		70.5	22/5/75-24/9/75		166.8		68.6
27/10/75-30/12/75	34.1		7.4		24/9/75-30/12/75	24.7		42.6	
30/12/75-6/1/76	12.3		3.7		30/12/75-6/1/76	1.4		12.2	
6/1/76-11/3/76	25.0		17.0		6/1/76-27/4/76	78.3		70.3	
11/3/76-26/10/76		335.0		69.0	27/4/76-17/9/76		185.5		33.7
26/10/76-1/12/76	27.8		7.3		17/9/76-1/12/76	30.1		84.6	
TOTALS	335.0	971.6	274.6	203.2		298.1	607.6	685.6	161.3
Total Evaporation and Drainage	1306.6		477.8			905.7		846.9	
% During ZFP Period	74		43			67		19	

* Transpiration assumed zero during this period.

Precision of flux estimates

Table 6.3 shows evaporation estimates for individual instrument sets in the forest and clearing on as closely comparable a basis as possible. Note that the forest results for 1974 are calculated on the basis of zero transpiration during the winter and that instrument set 08 on the main forest site had only one access tube associated with it whilst all others at this site use the mean of the readings from four access tubes.

TABLE 6.3 Total evaporation and drainage measured by each set of instruments over each year

SITE	INSTRUMENT SET	PERIOD	TOTAL EVAPORATION mm	DRAINAGE mm
1974				
MAIN FOREST	30	30/1/74 - 17/12/74	417.0	172.9
	40	30/1/74 - 17/12/74	409.5	173.4
	70	30/1/74 - 17/12/74	411.9	171.5
	80	30/1/74 - 17/12/74	458.8	126.8
CLEARING	02	7/1/74 - 18/12/74	309.6	328.4
1975				
MAIN FOREST	08	10/1/75 - 29/12/75	510.3	125.7
	30	9/1/75 - 30/12/75	479.8	135.0
	40	9/1/75 - 30/12/75	445.9	163.8
	70	9/1/75 - 30/12/75	438.8	185.0
	80	9/1/75 - 30/12/75	475.3	144.0
FELTWELL		10/1/75 - 31/12/75	503.2	148.7
CLEARING	02	8/5/75 - 30/12/75	218.1	120.4
	14	9/5/75 - 30/12/75	253.2	77.1
	41	9/5/75 - 30/12/75	229.7	99.1
1976				
MAIN FOREST	08	5/1/76 - 2/12/76	424.5	38.9
	30	6/1/76 - 1/12/76	397.0	90.8
	40	6/1/76 - 1/12/76	376.2	112.3
	70	6/1/76 - 1/12/76	374.7	95.8
	80	6/1/76 - 1/12/76	403.4	74.4
CLEARING	02	6/1/76 - 1/12/76	293.9	188.6
	14	6/1/76 - 2/12/76	275.7	213.3
	41	6/1/76 - 2/12/76	329.2	156.3

In Table 6.4 the means, variances, standard deviations (n-weighted) and standard errors of the mean have been calculated for the data in Table 6.3. The data for set 08 has been treated exactly as for the others even though it had only one access tube.

The results show a very encouraging degree of uniformity, especially considering the great heterogeneity of the soil at the site. In the forest the standard deviation of the flux estimates is almost constant from one year to the next at about 20 mm. Thus it appears that with a given complement of instruments the water balance components can be determined to a given absolute precision despite wide variations in magnitude from year to year.

TABLE 6.4 Variability between water balance components measured by each set of instruments over each year

SITE	COMPONENT	NUMBER INSTRUMENT SETS	MEAN mm	VARIANCE mm^2	STANDARD DEVIATION mm	STANDARD ERROR mm
1974						
FOREST	TOTAL EVAPORATION	4	424.3	404.1	20.1	11.6
	DRAINAGE	4	141.2	393.8	19.8	11.5
1975						
FOREST	TOTAL EVAPORATION	5	470.0	660.5	25.7	12.9
	DRAINAGE	5	150.7	452.9	21.3	10.6
CLEARING	TOTAL EVAPORATION	3	233.7	213.2	14.6	10.3
	DRAINAGE	3	98.9	312.5	17.7	12.5
1976						
FOREST	TOTAL EVAPORATION	5	395.2	342.0	18.5	9.2
	DRAINAGE	5	82.4	620.1	24.9	12.5
CLEARING	TOTAL EVAPORATION	3	299.6	493.3	22.2	15.7
	DRAINAGE	3	186.1	544.7	23.3	16.5

Perhaps surprisingly the standard deviations of flux estimates in the clearing are not markedly lower than in the forest. Inspection of Figures 5.34, 5.35, 5.39 and 5.40 shows that in 1975 most of the variation was due to instrument set 14 and in 1976 to set 41. The likely causes of these discrepancies have been discussed in Section 6.4.

Accuracy

The best evidence of the accuracy of the methods described in this report is the comparison with evaporation estimates made by micrometeorological methods. The excellent agreement in 1975 up to the beginning of August provides convincing evidence that, at least under conditions of moderate soil moisture deficit, the soil moisture method provides estimates of the moisture fluxes of accuracy comparable with that of the micrometeorological method. Under drier conditions it appears more plausible that the micrometeorological model would break down, since water stress must result in a reduction of transpiration at some point, than that the soil moisture flux measurements should become invalid.

Unfortunately no independent information on drainage fluxes is available so that the only control on the accuracy of the method rests on comparison with the micrometeorological measurements.

6.7 Variability in Water Balance Estimates

Comparisons between total evaporation and drainage estimates for different instrument sets in forest and clearing are shown in Figures 5.31 and 5.40. The annual totals are tabulated in Table 6.3 and the variations in the estimates of these components from different instrument sets are tabulated in Table 6.4

Since there is known to be considerable variability in both moisture content and tension measurements at a single depth and also of ZFP depth over a site (Figures 5.16 to 5.20) it seems worthwhile to examine which of these factors contributed most to the variability of estimates of water balance components.

Accordingly, for one year (1976) comparisons have been made of the water balance calculated using, for each set of ZFP depth data, on the one hand the mean moisture content measured from the four access tubes immediately surrounding that tensiometer set (ie the normal water balance for that instrument set) with, on the other hand, the mean moisture content of all sixteen forest grid tubes which comprise the four instrument sets.

The cumulative total evaporation, transpiration and drainage compared in this way are shown in Figures 6.1 to 6.4, where 'mean' refers to the water balance calculated using the individual instrument set ZFP data with the 16-tube mean moisture contents.

Over the year differences in any of the components are almost insignificant, being a maximum of 8.9 mm and having a root mean square deviation of 5.3 mm.

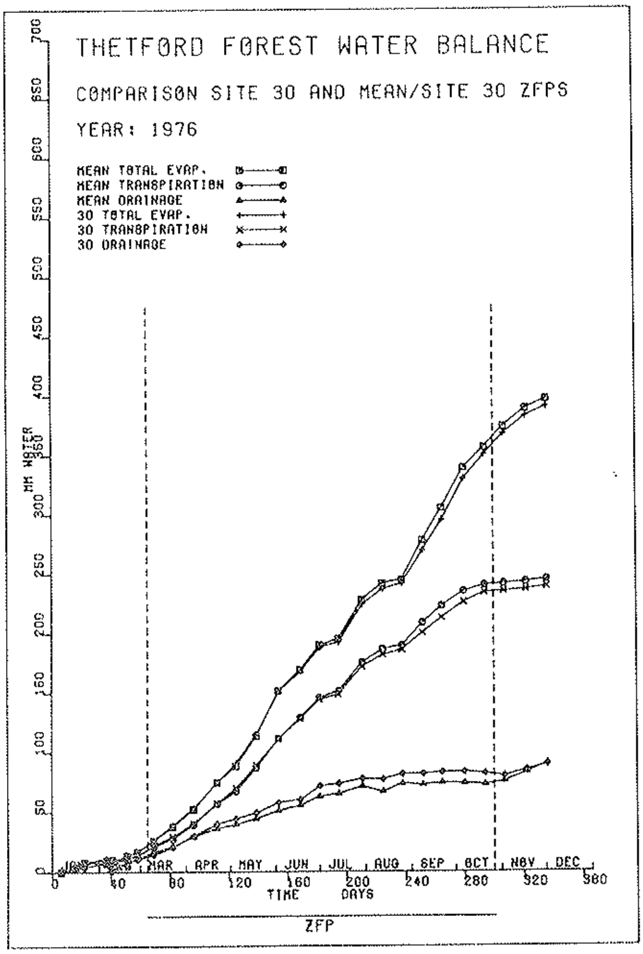


FIGURE 6.1

Comparison between evaporation and drainage fluxes using the mean moisture contents of the four tubes at instrument set 30 with those using the mean of all sixteen tubes. Set 30 ZFPs used in each case.

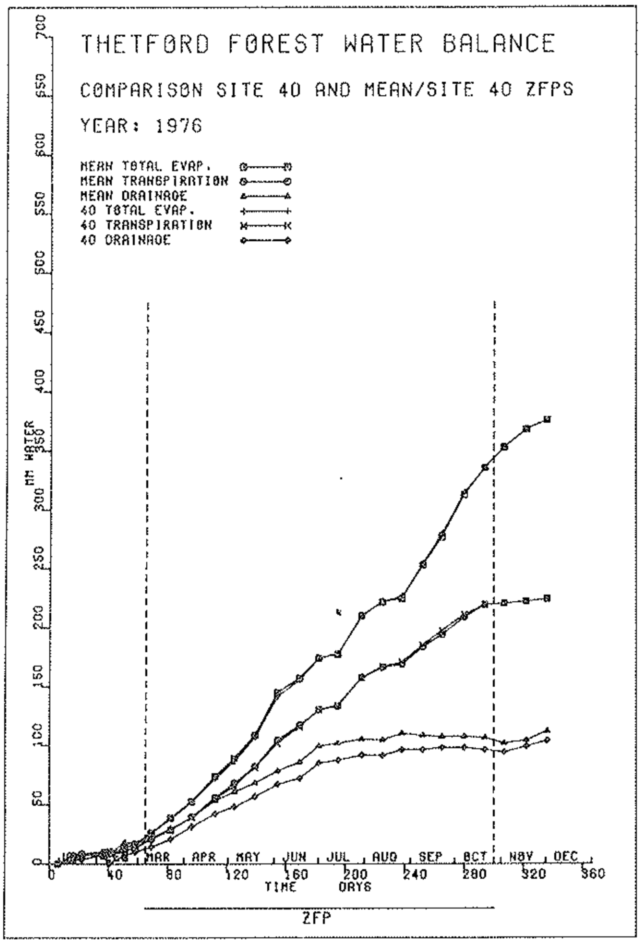


FIGURE 6.2

Comparison between evaporation and drainage fluxes using the mean moisture contents of the four tubes at instrument set 40 with those using the mean of all sixteen tubes. Set 40 ZFPs used in each case.

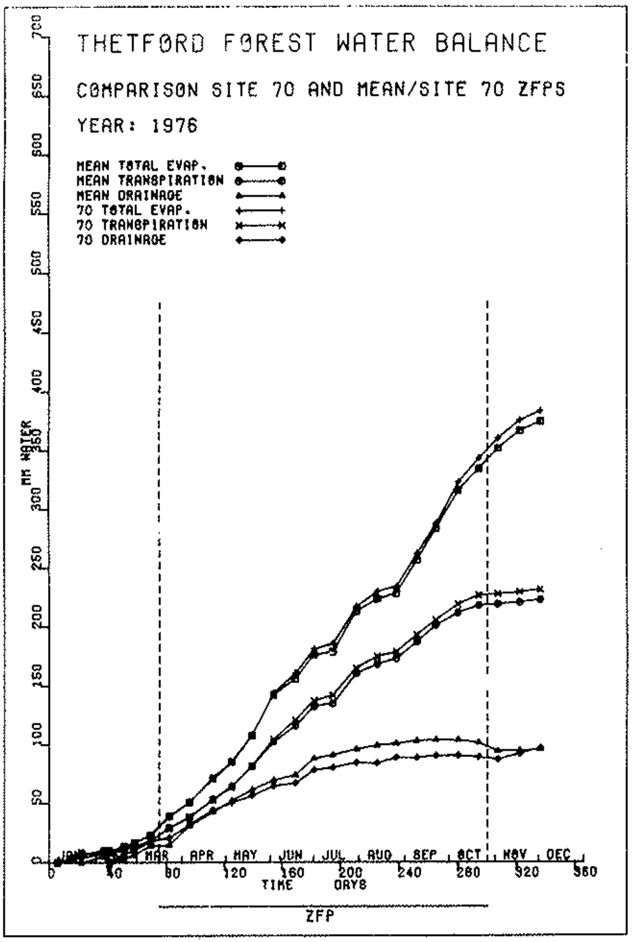


FIGURE 6.3

Comparison between evaporation and drainage fluxes using the mean moisture contents of the four tubes at instrument set 70 with those using the mean of all sixteen tubes. Set 70 ZFPs used in each case.

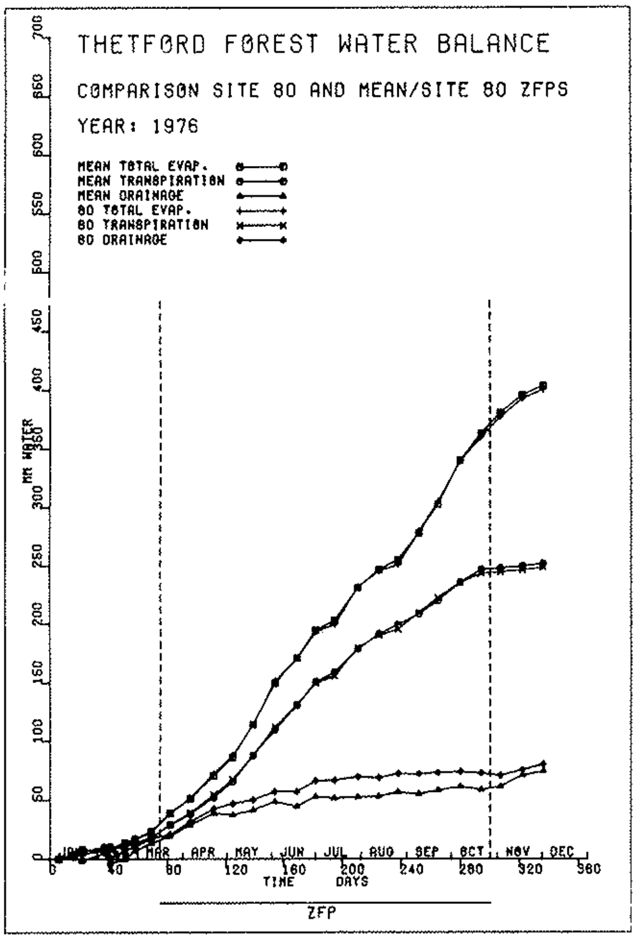


FIGURE 6.4

Comparison between evaporation and drainage fluxes using the mean moisture contents of the four tubes at instrument set 80 with those using the mean of all sixteen tubes. Set 80 ZFPs used in each case.

The largest discrepancy occurs in the cumulative estimate of drainage up to the middle of August. For example on 12 August the maximum difference is 16.3 mm with a root mean square deviation of 13.9 mm.

These differences are, however, considerably smaller than the range of the drainage estimates derived from individual instrument sets (c.f. Figure 5.38) which, in the same year, had standard deviations of 13.5 mm for the full year and 21.7 mm for the period up to 12 August.

Tables 6.5 to 6.7 list the effects on the variability of moisture flux estimates of the two different methods of using the moisture content data described above.

TABLE 6.5 Comparison between water balance components for each set of tensiometer data using the appropriate 4-tube mean moisture contents and the 16-tube mean moisutre contents. Main forest site, Grid 1976.

ZFP		30		40		70		80	
Moisture Content		4-tube Mean	16-tube Mean	4-tube Mean	16-tube Mean	4-tube Mean	16-tube Mean	4-tube Mean	16-tube Mean
6/1/76 to 1/12/76	EVAP	397.0	390.8	376.2	376.2	374.7	383.6	403.4	400.2
	DRAIN	90.8	89.9	112.3	104.4	95.8	97.0	74.4	80.4
6/1/76 to 12/8/76	EVAP	241.9	237.1	221.8	222.7	223.7	230.3	246.7	245.6
	DRAIN	67.0	77.4	105.0	91.9	99.4	84.2	53.3	69.0

TABLE 6.6 Variability between water balance components calculated using 4-tube and 16-tube mean moisture contents. Main forest site, Grid 1976.

Period		4-tube* Mean	16-tube* Mean	$SSQS = \sum_i (d_{\theta i})^2$	$MSQ = \frac{SSQS}{4}$	$RMSQ = \sqrt{MSQ}$
6/1/76 to 1/12/76	EVAP	387.8	387.7	127.89	31.97	5.65
	DRAIN	93.3	92.9	100.66	25.17	5.02
6/1/76 to 12/8/76	EVAP	233.5	233.9	68.62	17.16	4.14
	DRAIN	81.2	80.6	757.3	189.33	13.76

TABLE 6.7 Variability between water balance components measured at different instrument sets for 4-tube mean and 16-tube mean moisture contents. Main forest site, Grid 1976.

		Individual site moisture contents				Mean moisture content data			
		MEAN M	VARIANCE σ^2 mm^2	STD DEV σ mm	C.V. $\sigma/M \times 100\%$	MEAN M	VARIANCE σ^2 mm^2	STD DEV σ mm	C.V. $\sigma/M \times 100\%$
6/1/76 to	EVAP	387.8	158.54	12.59	5.3	236.1	78.73	8.87	3.8
1/12/76	DRAIN	93.3	182.68	13.52	14.5	92.9	78.58	8.86	9.5
6/1/76 to	EVAP	233.5	119.43	10.93	6.1	178.6	71.38	8.45	4.7
12/8/76	DRAIN	81.2	469.43	21.67	26.7	80.6	71.36	8.45	10.5

Table 6.5 lists the values of evaporation and drainage obtained while Table 6.6 shows the mean values and the variability between the estimates using the two methods.

Table 6.7 shows the variability between cumulative evaporation and drainage measured at different instrument sets using each method of calculating fluxes. Using the sixteen tube mean moisture content data the variance between evaporation and drainage estimates is seen to be the same. This is because the sum of evaporation and drainage for each set is the same (being fixed by rainfall and total profile moisture change). Thus an estimate of drainage greater than the mean by a specific amount will be accompanied by an evaporation estimate which is less than the mean by the same amount. Thus both will contribute an identical term to the variance.

The difference between variance estimates using the different four tube mean moisture contents and those using sixteen tube mean moisture contents may be used to estimate the relative contributions of variability in ZFP estimates and in moisture content measurements to the overall flux estimates.

Assume that the deviation from the mean of a flux measurement using individual site moisture content measurements may be expressed as the sum of a contribution due to the moisture content data (including random errors) and one due to the ZFP depth data, i.e.:

$$d_i = d_{\theta i} + d_{zi} \qquad (6.2)$$

where d_i = deviation from the mean of the estimate of site i

$d_{\theta i}$ = deviation due to the use of moisture contents for site i

d_{zi} = deviation due to use of ZFP data for the site i.

This is illustrated in Figure 6.5.

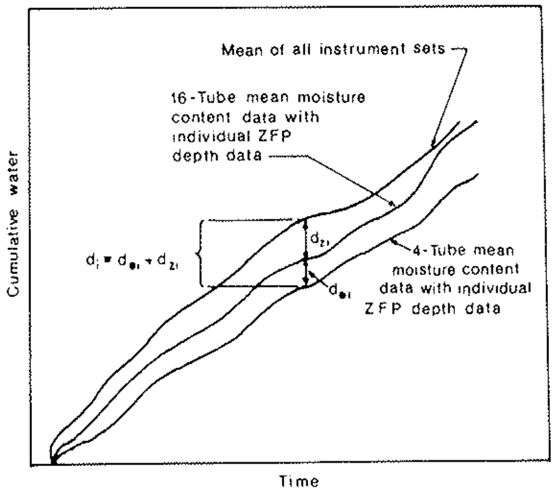


FIGURE 6.5

Partition of variability of moisture flux estimates into components due to moisture content data and ZFP depth data

Then the overall variance will be:

$$\sigma^2_{tot} = \frac{1}{n} (\sum_i d_i^2) \tag{6.3}$$

$$\sigma^2_{tot} = \frac{1}{n} (\sum_i d_{\theta i}^2 + \sum_i d_{zi}^2 + 2 \sum_i d_{\theta i}\, d_{zi}) \tag{6.4}$$

where σ^2_{tot} is the variance in the estimates using individual site moisture contents and n is the number of sites (4 in this case).

Now by inspection of Figure 6.5 it can be seen that the variances $\frac{1}{n} \sum_i d_{zi}^2$ and $\frac{1}{n} \sum_i d_{\theta i}^2$ may be estimated by calculating the sum of squares of deviation between the mean and flux estimate using the mean moisture content data (as in Table 6.7), and between the flux estimates using individual site moisture contents and those using mean moisture contents (as in Table 6.6).

Thus we have estimates of the first three terms of equation 6.3 and the covariance, $\frac{1}{n} \sum_i d_{\theta i}\, d_{zi}$ can be estimated. These are tabulated in Table 6.8.

In general terms the contents of Table 6.8 show that the estimates of variance due to the zero flux plane depth are, except in the case of the mid-year drainage estimate, considerably greater than those due to the moisture content data. For the mid-year drainage data, however, the situation is reversed and the moisture content data contribute by far the largest part of the total variation. In all cases the covariance between d_θ and d_z is positive indicating that there is a tendency for

TABLE 6.8 Components of total variability between moisture balance components measured using different instrument sets. Main forest site, Grid 1976.

		$\sigma^2_{tot} = \frac{1}{n} \sum_i d_i{}^2$	$\sigma^2_\theta = \frac{1}{n} \sum d_{\theta i}{}^2$	$\sigma^{2*}_z = \frac{1}{n} \sum_i d_{zi}{}^2$	$\mathrm{cov}\ (\theta,z) = \frac{1}{n} \sum_i d_{\theta i} d_{zi}$
to	EVAP	158.54	31.97	78.73	23.92
1/12 [illegible]	DRAIN	182.68	25.17	78.58	39.47
to	EVAP	119.43	17.16	71.38	15.45
12/8/76	DRAIN	469.43	189.33	71.36	104.37

* Differences in these components are due to rounding errors.

either a higher or lower than average flux estimate to be due to both the ZFP data and the moisture content data. For instance a deeper than average ZFP would tend to increase the evaporation estimate and decrease that of drainage. This would tend to be accompanied by a higher than average rate of water depletion near the surface and a lower than average depletion rate close to the bottom of the profile. The correlation is not, however, statistically significant so that any further discussion would not be warranted.

Data from many more sites are needed before one can determine whether in general the variability of flux estimates due to ZFP depth variations is more important than that due to moisture content measurements. One might expect in more homogeneous soils that ZFP depths would tend to be much more uniform spatially whilst moisture content variations would be only moderately so. If this were the case then the more important source of variation would probably be the moisture content data.

For the forest at Thetford, however, it is clear that, over a full year at least, ZFP depth variations contribute more to the uncertainty of mean moisture flux estimates than moisture content measurements (when taken as the mean of four access tubes). To improve the estimates of the mean moisture flux, therefore, it would be better to install extra sets of tensiometers than to have more access tubes for moisture content measurements.

6.8 Frequency of Reading Instruments

The accumulated flux at depth Z is (Equation 2.6):

$$F(Z) = \int_{z_o(t_1)}^{Z} \theta\ (t_1)\ dz - \int_{z_o(t_2)}^{Z} \theta\ (t_2)\ dz - \int_{z_o(t_2)}^{z_o(t_2)} \theta\ (t(z_o))dz. \qquad (6.5)$$

If a long interval occurs between readings, i.e. the gap between t_1 and t_2 is long, then the only term in the above equation which may be in error is the last one. This is because this term should be a continuous integration of moisture content with respect to change in ZFP depth. The accuracy of the estimation of this term will depend on the method of interpolating the moisture measurements between reading occasions. The particular algorithm used (described in Section 4.5) is perhaps the simplest form of interpolation possible.

The effect of reducing the reading frequency from approximately once every three days to once per month for one forest instrument set (30) in 1975 is shown as an example in Figure 6.6. In this figure the first moisture content reading in each month has been used plus the last reading in December. As expected from the above discussion marked discrepancies only occur during periods when there are large changes in ZFP depth. In particular the periods during which the ZFP appears and disappears produce relatively large discrepancies, with only minor effects in other periods and none at all when the ZFP is at constant depth or absent through the whole period. In the example presented the discrepancies on appearance and disappearance of the ZFP are in opposite directions, leading only to a small (12 mm) discrepancy over the year as a whole. There seems no particular reason why this should be so, however, and in many cases the errors may be expected to reinforce one another.

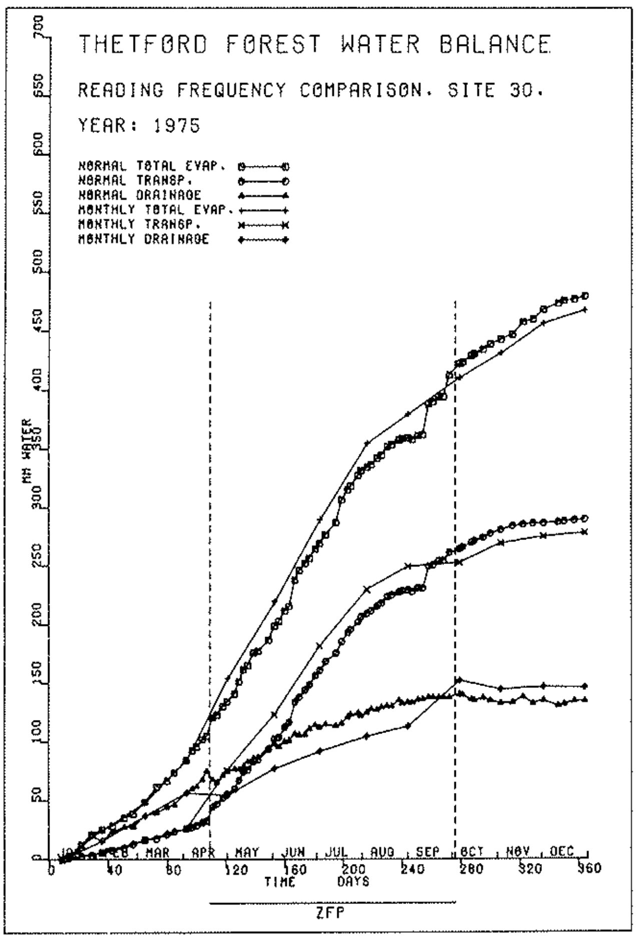


FIGURE 6.6

Choice of reading frequency will depend to a large extent on the objectives of a study. If good time resolution of fluxes is required then frequent readings will clearly be necessary. On the other hand, if only long-term total amounts are needed, readings may be collected perhaps weekly or fortnightly, although periods during which rapid changes of the ZFP depth are expected should, if possible, be sampled more frequently.

Even with the frequent (twice weekly) reading schedule practised in 1975, significant kinks tended to occur at the times of appearance and disappearance of the ZFP (Figures 5.32, 5.34, 5.37 and 5.39). With the tensiometer spacings adopted the shallowest ZFP which could be observed was about 0.3 m, so that at the beginning of the ZFP period an appreciable correction term was included in Equation 6.5, an error in which could have a serious effect on the flux estimate. The end of the ZFP period was normally marked by a period of wet weather which wetted the profile rapidly, leading once again to difficulties in estimation of the correction term. When the mean of several instrument sets is taken (Figures 5.21, 5.23 and 5.26) these individual inconsistencies are smoothed out suggesting that over- and under-estimation of fluxes are equally likely. It is interesting that the reduced reading frequency for 1976 does not give rise to very much more serious inconsistencies than are apparent in the 1975 data, though it may mask more serious systematic errors.

No investigation of other methods of interpolation of moisture content readings and hence estimating the final term in Equation (6.5) has been made.

6.9 Well and Borehole Levels

Figures 5.41 and 5.43 show the records of water table level observations collected in 1974, 1975 and 1976. The water table contours have been plotted onto the map of Figure 5.44 for 4 June 1975, when all the wells were at or near to the maximum level recorded over the period, and for 12 January 1976, which was close to the minimum level before they started rising again. Considerably lower levels were reached, both in 1974 and later in 1976, but several of the observation holes dried up at these times, making the interpolation of isopleths very hazardous.

Examination of Figures 5.41 and 5.43 shows that there is a wide range of amplitudes of well fluctuation. Attempts to correlate these with ground level, or depth to water table have not proved fruitful. For instance, Shakers Lodge and Spinks Lodge wells are at almost the same height above ordnance datum (50.71 m and 50.45 m) and are only 1.6 km apart. The amplitude of water table variation at the latter is, however, some 30% greater. For this particular well the times of the peaks and troughs appear to be retarded by some 20 days with respect to the other observations in this part of the forest.

Figure 5.44 shows that the hydraulic gradients of the groundwater are directed predominantly to the north and west and also that there is considerable groundwater flow into the forest area from the mainly arable farming area to the south. In view of this groundwater levels in the forest are expected to be strongly affected by inflow from beneath the surrounding agricultural land and to attempt more than a qualitative correlation between drainage beneath the forest and measured groundwater levels would probably be fruitless.

The general correspondence between drainage rates and well level observations is evident. Comparing Figures 5.21, 5.23 and 5.26 with Figures 5.41 to 5.43, the slow rate of drainage at the beginning of 1974 is matched by a slow rise of water table level to a peak about the end of April, after which the rate of loss of groundwater to the river system exceeds the recharge rate and the water table declines. The sudden steep rise of drainage rate in mid-November is matched by an equally steep rise in water table level. The water table is, in fact, rising somewhat before any significant drainage from the forest takes place, indicating that this is caused by inflow from agricultural land to the south, where recharge may be expected to have started earlier (c.f. Figure 5.22 for the clearing water balance). In early 1975 the high initial drainage rate is accompanied by a steeply rising water table level to the end of May, after which drainage decreases rapidly and the water table descends at a similar rate to that at which it rose earlier and does not reach a minimum level until early in 1976, reflecting the late onset of drainage in this winter. Once again the water table is rising some six weeks or so before any significant drainage from the forest occurs. The relatively small amount of drainage from the forest during this winter is accompanied by only a small rise in the water table, which peaks in late April.

6.10 Pressure Transducer Tensiometers at Feltwell

The records from these tensiometers during 1976 are shown in Figures 5.45 and 5.46. The general correspondence of tensiometer reading with water table level is evident from these figures. From early May the 7 m tensiometer indicated a lower potential than at the water table indicating that water was moving upwards from part at least of the profile between 7 m and the water table (at about 9 m at this time). At about the same time the records from the 6 m depth tensiometer began and these all indicated lower potentials than at 7 m until the transducer became faulty in early October. Thus over this entire period upward movement occurred between 6 m and 7 m.

The water table reached its lowest level almost coincident with the lowest potential recorded by the tensiometers, after which the moisture potentials rose rapidly and became greater than the water table potential in early November. From this time on downward flow was re-established to the water table. Up to this point, however, the rising potentials in the chalk a few metres above the water table had been due to the rising water level and not to drainage from above.

The implication of these observations is that upward movement of water was taking place from the water table at a depth of about 12 m to the surface. No value of hydraulic conductivity for the chalk in the region is available so that the flux must remain unmeasured. By adopting a ZFP depth of 3.2 m for most of 1975 a total evaporation amount slightly higher than that at the main site was calculated. If this was being supplemented by water flowing upwards from the water table the amount would have been even greater. In 1976, on the other hand, an upward flux from the water table could have helped to maintain the evaporation rate close to that at which moisture deficits were not limiting.

7. CONCLUSION

7.1 Experimental Results

Water balance components in a stand of Scots Pine and in a grass clearing within Thetford Forest have been measured for a period of 2 years 10 months using the zero flux plane technique in summer and a straightforward water budget approach using estimated evaporation rates in winter. Additionally the water budget for a further forest site under Corsican Pine near Feltwell has been measured in 1975.

The purpose of the study was primarily to evaluate the use of a soil water balance method to measure aquifer recharge. Unfortunately no independent drainage estimates were available with which the measurements could be compared to assess their accuracy. However, the good agreement obtained with independent evaporation estimates in early summer suggests that the method gives results of good accuracy and hence drainage is expected to be measured accurately as well.

For annual totals of evaporation and drainage the method described gives results of considerably improved accuracy compared with the likely errors involved in the use of a meteorological model to estimate evaporation over the whole year, combined with measured rainfall to estimate drainage. This is mainly because the method avoids uncertainties involved in estimating actual crop evaporation during periods of water stress which may be expected to differ markedly from the potential rate.

At the main forest site five sets of instruments provided replicate measurements of annual evaporation and drainage of good consistency. The standard deviation of the individual measurements of each of these components for each year was about 20 mm. This is the likely error in each component if only one set of instruments were used. For comparison the mean annual evaporation was about 467 mm and drainage 159 mm.

For 1975 and 1976 good agreement was found between an estimate of evaporation from the forest using the method of Gash and Stewart (1977) and the soil moisture derived measurements up until a soil water deficit of about 60 mm was reached. Beyond this the evaporation as measured from soil water observations fell below the estimated rate until rewetting commenced in the autumn when agreement was restored.

At the Feltwell site the soil water conditions were markedly different. In particular, due to the much thinner and chalkier top soil, a very rapid rise of tensiometer readings occurred in spring accompanied by a very rapid plunge of the ZFP. Nevertheless the total evaporation was remarkably similar to that at the main site (Figure 5.32).

In the clearing the evaporation rate appeared to follow Penman's ET estimate for about 10 days after the start of ZFP conditions in 1974 and for 6 weeks in 1976. In 1975, however, this was not so, measured evaporation being less than the potential rate from the first appearance of a ZFP. This may have been caused by the wet spring which delayed the appearance of a ZFP until potential evaporation rates were already high. As with the forest site there was also very good consistency between evaporation measurements from the three different instrument sets in both years during the ZFP period.

Over the period reported total drainage from the forest was measured as 478 mm compared with 847 mm from the clearing. The planting of the forest has thus reduced the water yield of the area by about 46% when allowance has been made for periods missing from a complete 3-year record and assuming that the clearing represented the behaviour of an extensive area of grass.

This large reduction of water yield is caused principally by the high rate of evaporation of intercepted water from the forest, which accounted for 41% of evaporation at this site.

It has been shown that drainage occurs beneath both forest and clearing throughout most of the summer, in contrast with the traditional Meteorological Office type model which treats the soil as being essentially zero dimensional, and in which the drainage ceases abruptly when deficit conditions appear. The results presented have shown that overall 43% of the drainage in the forest and 19% in the clearing occurred during the period when deficit conditions prevailed.

Examination of the sources of variability in the total evaporation and drainage determined from different instrument sets for one year in the forest has shown that, using the mean moisture content of a set of four access tubes with one set of tensiometers, the dominant source of variation is the ZFP depth estimate. It is not known to what extent this reflects the real variability of moisture fluxes or is due to instrumental effects.

An examination of the effects of reducing the reading frequency of instruments to once per month has shown that, provided only long-term water balance estimates are required, the precision of the flux measurements is not seriously degraded, except at the times of appearance and disappearance of the ZFP.

In addition to the water balance results, well level data have been collected over the forest area, mainly south of the River Little Ouse. Large variations in the amplitude of water table level fluctuations, the frequent drying up of several wells and the strong influence of surrounding agricultural areas on the levels has precluded more than a qualitative comparison between water table levels and measured drainage rates beneath the forest.

A novel design of tensiometer has been developed to make measurements in the vicinity of a water table at depths of several metres from the surface. The tensiometer operates from an uncased borehole and represents an economical method for making deep moisture potential measurements. Several instruments may be installed within the same borehole. Readings from two of these tensiometers, together with water table level observations, have been used to show that at the Feltwell site during the summer of 1976 there was an upward water flux from the water table, at 12.4 metres, to the roots of the trees above.

7.2 Recommendations for Future Work

The results presented demonstrate an encouraging possibility for soil moisture-based techniques of drainage flux measurements to be used as the basis for an operational method for assessing aquifer recharge. Indeed, there are wider applications of the techniques. Other uses which would require the same kind of measurements or fairly straightforward extensions of them include, for example:

measurements of movement of pollutants in the unsaturated zone;

investigation of the relative roles of fissure and matrix flow in unsaturated chalk, a topic of considerable importance and controversy;

irrigation scheduling;

crop water use efficiency measurements.

However, the methods described have only been applied to three sites within a comparatively close distance of one another. Any aquifer of economic interest is liable to underlie a wide variety of crops and soils, all of which may be expected to contribute different quantities of drainage water to the total recharge of the aquifer. Clearly it would be impractical to set up replicate measurement stations on all crop/soil units of interest and more research is needed to quantify the range of variation over all these possible combinations. Modelling studies can be expected to contribute considerably in this area to limit the amount of experimental work needed.

Savings of experimental work would also result from a reduction of the frequency of reading of instruments, of the number of sets of instruments at each site and of increasing the automation of readings. The results of this project suggest that frequent (e.g. daily) instrument readings are probably not necessary for good accuracy of flux measurements. Indeed, during 1976 readings were made only once per fortnight, apparently without the introduction of major errors. The fact that only a moderate degree of intra-site variability of annual fluxes has been found for the forest, despite the great heterogeneity not only of the soil but also of throughfall and of root distribution, suggests that large numbers of replicate instruments are not necessary for any given crop/soil combination. However, variability at the clearing site was not markedly less although heterogeneity of throughfall and of root distribution were not important factors. The factors controlling the variability of flux may not therefore be simple and investigations in other locations are needed before any general conclusions can be drawn.

Pressure transducer tensiometers lend themselves well to automatic logging and several designs for field instruments are in existence (e.g. Watson 1967; Strebel *et al.* 1970) in addition to those in use at the Institute of Hydrology. An automatic neutron probe has been developed in France and a design has been under development at the Institute of Hydrology for some considerable time. Thus the automatic acquisition of both moisture content and potential data should be possible on a routine basis within the next few years. Another possibility here is for the automatic and frequent collection of potential data using logging tensiometers with relatively infrequent (say monthly) manual neutron probe readings. The tensiometer data could then be used to interpolate moisture contents between occasions when neutron probe readings are available.

The study reported here used climatic data to provide an estimate of winter evaporation. It seems likely that this procedure will result in only a small error in evaporation estimates during this period. It depends on having an appropriate model, such as that of Penman for short crops and those of Gash and Stewart (1977) and Calder (1977) for forests, to relate evaporation to weather conditions. For tall crops the model must include reliable interception measurements or predictions. It would be desirable therefore to have an alternative method for use during the winter period which was more compatible with the measurements used for the ZFP method. The direct solution of Darcy's Law would appear to be the most promising in this respect. Its use in the present experiment was not possible for reasons already outlined. Furthermore, data published by Nielsen and co-workers (Nielson *et al.* 1973, Biggar and Nielsen 1976) suggest that spatial variability problems may be more severe when using this method than appear to be attendant on the ZFP technique. Further research is needed to evaluate this method for use as an operational tool.

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