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WATER RESOURCE IMPLICATIONS OF THE PROPOSED GREENWOOD COMMUNITY FOREST

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Executive Summary

The implications for both water use and water quality of the proposed Greenwood Community Forest (Nottinghamshire) are examined. Of the 44000 ha in the designated area, 2700 ha are already afforested and under the proposals up to a further 10000 ha could become afforested. This would change the forest cover of the Sherwood Sandstone outcrop from its present 10% to 25-35%. This is a significant change in land use and will have implications for the quantity and quality of recharge to the underlying aquifer.

Models of water use for deciduous plantations, developed under a previous contract to NRA, have been adapted to the sandy soils of the Sherwood Sandstone outcrop by assuming that appropriate soil response functions are the same as those found to work successfully in the sandy soils of Thetford Forest. Comparisons of evaporation and drainage from the soil using the model agree reasonably well with those measured using soil physics methods at sites in Thetford Forest and south Devon for coniferous forest and grass. Reasonable agreement between measured and modelled profile water storage was also obtained for sandy soil under both conifers and grass in the Dover Beck catchment within the proposed Community Forest area.

Taking into account uncertainties in species, stocking density and the lack of measurements on deciduous plantations growing on sandy soils, the effect of replacing grass or cereal crops with deciduous plantation is estimated to be a reduction of annual evaporation by between 10 and 110 mm a^{-1}. Drainage from the soil to recharge the aquifer would increase by the same amount. Too little information was found on the effect of other crops (e.g. potatoes) or irrigation, both locally important, to make more than a qualitative estimate of their impact.

The effect on water quality is expected to be beneficial, particularly for nitrate. Estimates based on studies of beech and ash at Black Wood (Hampshire) suggest that the nitrate concentration in water recharging beneath deciduous forest is likely to be less than 10 mg/l NO_3-N. Any changes are, however, only likely to be apparent over a timescale of a decade or longer.

1 Introduction

In the late 1980s the Department of the Environment commissioned the Institute of Hydrology (IH) and British Geological Survey (BGS) to conduct a research study into the likely hydrological effects of planting broadleaf plantations over the lowlands of Britain. This was prompted by the realisation that agricultural output in the European Community was increasing rapidly and was beginning to exceed the likely demand for food. Proposals were made to encourage farmers and planners to find alternative uses for agricultural land. One such proposal was for the planting of relatively large areas of tree plantations in the lowlands of Britain. The likelihood is that such planting would be of broadleaved (deciduous) species. Whilst there had been a lot of work performed on the hydrological effects of coniferous plantations in the UK, mainly but not exclusively in the uplands, there had been little work on the effects of deciduous plantations. Furthermore, the expectation is that the pattern of planting is likely to be of small (a few ha) plantations, rather than of extensive blocks of forest. Potentially this could both enhance evaporation (and hence reduce water resources) and increase the scavenging of atmospheric pollutants (thus increasing the pollutant load of surface and subsurface waters).

The Department of the Environment (DOE) commissioned IH and BGS to set up two experimental sites in existing broadleaf plantations in lowland southern England to study the likely consequences for both water quantity and quality. This work was reported by Harding *et al.* (1992) in a report to the National Rivers Authority (NRA), who had taken over responsibility for the work from DOE. The sites studied were ash and beech stands on chalk in Hampshire and ash on clay in Northamptonshire. The major conclusions from the work were:

annual transpiration from beech and ash plantations on both soil types was in the range 360 - 390 mm;

the understorey in the ash plantations contributed 45% of the transpiration. This was compensated in the beech plantation by a higher leaf area index, which allowed the trees to transpire the extra water required to make up the difference;

soil water stress did not reduce transpiration totals for the forest species on the chalk sites, despite two very dry years. There was a small reduction caused by water stress on the ash site on clay. This contrasts with the situation for grass and cereals, which reduce their transpiration markedly as a result of soil water stress;

annual interception losses were approximately 11% and 16% of rainfall for the ash and beech respectively. This is about half what might be expected for coniferous forest and results in the estimated water use by the broadleaf forest being somewhat lower than that of grass by 60 mm or so on chalk and 20 mm on clay over a long period. Variations of evaporation from year to year of the forest species were found to be smaller than those of grass so that in dry years, the forest species are expected to evaporate more water than grass. Estimated water use by winter wheat was considerably lower than any of the other species studied, but, in the absence of supporting field data, these estimates were regarded as uncertain;

enhanced evaporation at the forest edge was detected only for the outer 20 m of plantation.

The effect is, therefore, only likely to be of significance for very small plantations;

scavenging of atmospheric pollutants by the plantations was found to be very efficient, particularly of nitrogen compounds and chloride ions. This was enhanced considerably at the forest edge;

this enhanced scavenging was reflected in elevated concentrations of some pollutants in the unsaturated zone beneath the plantations. Nitrate, however, was lower beneath forest than below agricultural land surrounding it; this was especially true under ash with its dense understorey. High nitrate concentrations were, however, found beneath clearings where the cycling of nitrate had been disrupted.

Since this work was performed, proposals have been made for the establishment of a number of community forests in Britain, and for a National Forest in the Midlands. One of these community forests is proposed for an area of Nottinghamshire between Nottingham and Ollerton. Much (approximately 60%) of the area is underlain by the outcrop of the Sherwood Sandstone. Of the 44,000 ha in the designated area, 2,700 are already afforested, mainly with coniferous species. Under the Community Forest proposals, another 10,000 ha could become afforested, mainly with broadleaf species. Availability of land may well mean that the vast majority of this 10,000 ha will be on the Sherwood outcrop, which is a major aquifer for water supply. Under these circumstances, new forestry would cover 35% of the Sherwood Sandstone outcrop in the area of the forest. NRA is understandably concerned to know the likely impact on both water quantity and quality of planting on this scale and has asked IH and BGS to make a brief study.

The previous broadleaf study (Harding *et al.*, 1992) was conducted on chalk and clay soils, which are expected to have much greater available water than the very sandy soils which cover the great majority of the outcrop of the Sherwood Sandstone. Whilst water stress was found to have little or no effect on the water use of the forest plantations studied previously, it seems unlikely that this would be the case for the soils of the Sherwood Sandstone outcrop. However, very little information is available on water use or aquifer recharge on this formation, so that any conclusions drawn at present must be regarded as very tentative.

2 Previous Work

The most relevant work to this problem is the study performed for NRA by IH and BGS (Harding *et al.*, 1992), described briefly above. In addition to this, IH has been involved in other studies which have some relevance to the problem. These concern either data taken from the area of interest or work performed on soils in other areas of the UK which are expected to behave similarly. These are:

2.1 THE THETFORD EXPERIMENT

This was a combined micrometeorological, plant physiology and soil physics study carried out in the early and mid 1970s by IH in a Scots Pine stand in Thetford Forest, Norfolk

(Stewart & Thom, 1973). Cooper (1980) used soil physics measurements, supplemented by meteorological estimates of evaporation for winter periods, to derive a water balance for the forest stand and for a grassed clearing close by over a period of three years from 1974 to 1976. Dolman *et al.* (1988) later demonstrated that the summer transpiration estimates for the Scots pine stand, derived solely from soil physics and rainfall measurements, were in excellent agreement with meteorological estimates of transpiration using the surface conductance model of Stewart (1988) and standard daily meteorological records from a nearby synoptic station.

The soil in this study is a sandy podzol overlying chalky sand drift at about 1.2 m depth, itself overlying chalk at about 3 m. From an evaporation/recharge point of view, the sand in the upper part of the profile is believed to be the dominant control.

This dataset therefore gives a detailed record of evaporation, drainage and soil moisture deficit from a Scots Pine stand on a sandy soil over a period of three years, which has been used to verify a model of evaporation.

Calder *et al.* (1983) used the soil water content measurements from the grassed clearing to calibrate a simple evaporation model, which forms the basis of the model used in the NRA broadleaf project (Harding *et al.*, 1992). This gives a set of parameters which may be used in the model for grass on a sandy soil.

2.2 THE IH SOIL MOISTURE DATABANK

As part of a project to validate the then new MORECS model, Gardner (1981) assembled a databank of soil water content measurements from a large number of sites, mainly in southern England and the Midlands. Some of these measurements were from the area of the proposed Greenwood Community Forest. They were collected by or under the direction of G Chubb of the then Severn-Trent Water Authority from ten sites in the catchment of the Dover Beck over the period June 1975 to October 1977. Of these, five were described as being on gleys or gleyed brown earths of the Ollerton complex (Robson and George, 1971). These five were all grassed. Two sites, one grassed, the other in deciduous woodland, were on loamy brown earths of the Hodnet series (Robson and George, 1971), whilst another was grassed upon a loamy gleyed brown earth Hodnet complex soil. The remaining two sites were on Crannymoor series podzol sands (Robson and George, 1971). One of these was in mown grass, whilst the other was close by in a coniferous forest plantation. These last two are of most interest for this study, since the Crannymoor soil is well represented on the Sherwood Sandstone outcrop and similar in physical characteristics to the predominant Cuckney series soil. The other sites all displayed gleying, characteristic of seasonal waterlogging and indicative of a shallow water table.

The records relating to these sites from the report of Gardner (1981) are reproduced in Appendix 1.

2.3 THE BICTON PARK EXPERIMENT

A joint experiment between the Earth Resources Centre of the University of Exeter and IH, with participation by the south west region of NRA, is being conducted in the valley of the River Otter in south Devon. The soil is a sandy loam of the Bromsgrove series (Hollis & Hodgson, 1974) and the site is grassed. A description of the experimental setup has been given by Cooper *et al.* (1990). Water balances from this site are available from 1988.

3 The Characteristics of the Proposed Greenwood Community Forest Area

3.1 GENERAL

A map of the area, showing the main features of interest, appears as Figure 1. Much of the information in this Section is taken from the publication of Ragg *et al.* (1984).

3.2 GEOLOGY

The solid geology of the area is dominated by the Sherwood Sandstone, which extends in a band northwards from Nottingham into Yorkshire. It overlies Permian limestone, which outcrops in the west of the area. The sandstone is overlain by Triassic mudstones, which lie along the eastern edge of the area.

Drift is relatively uncommon, the only deposits of note being glacio-fluvial drift in the major river valleys, particularly that of the Trent.

3.3 RELIEF

Relief is relatively subdued over the area. The landscape is undulating with a general fall from about 140 m above ordnance datum in the north west of the proposed forest area to 20 m in the Trent valley in the south-east.

3.4 SOILS

The soils reflect the characteristics of their parent geology. Together with rainfall variations, these are expected to exert the most influence over the water balance of the area.

To the west, bordering the Erewash valley, clays and loamy clays of the Denchworth and Bardsey associations predominate, but, moving eastwards, these soon give way to the soils of the Sherwood Sandstone outcrop, principally the Cuckney association. These are fairly shallow (less than about 1 m) loamy sand soils, developed over sandstone. Under woodland, they may be podsolised, such as in the Crannymoor series. Delamere association soils are dominant in places. These are similar soils, though more acidic and shallow (less than about 0.6 m), overlying massive red sandstone and are found most often under heath or old forest.

Worcester association soils are found in the south-east of the area, between Calverton and Burton Joyce. These are clays or clay loams developed on the Permo-Triassic Mudstones. Hodnet soils, slightly better drained than those of the Worcester Association, occur on the very south-eastern edge of the area in the Dover Beck valley.

Ollerton soils are very sandy and occur in low-lying areas, where drainage is poor.

Bromsgrove soils are somewhat more loamy than Cuckney soils and so may be expected to

Figure 1 *The Proposed Greenwood Community Forest area. Numbers on the east and north sides are National Grid Reference 10 km square designators. The proposed forest boundary is shown in heavy outline.*

a) Simplified solid geology

b) Simplified soil map

c) Relief in metres a.o.d.

d) Mean annual rainfall over the area in mm

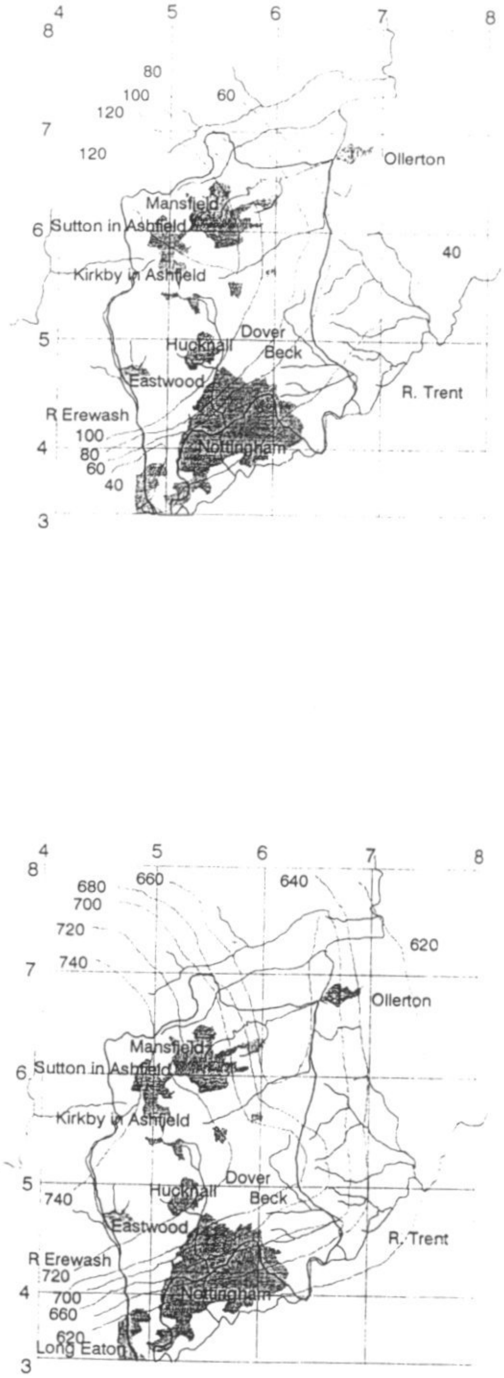


Figure 1 (cont)

have a greater water holding capacity and partition more water into evaporation and less into drainage and hence aquifer recharge.

3.5 CLIMATE

The dominant climate influence is likely to be rainfall. Potential evaporation is very conservative over lowland England. Mean rainfall distribution follows the relief contours quite closely, with highest rainfall in the north-west of the area, up to about 750 mm, and lowest in the south-east, at about 610 mm. A Meteorological Office synoptic station is located at Watnall; the mean annual rainfall is 716 mm. The range of annual rainfall is thus from about 5% above that of Watnall to about 15% below it.

3.6 LAND USE

Land use in the area is predominantly arable, particularly on the lighter soils. The heavier soils in the west and the clay loams in the south east of the area of interest support livestock, particularly cattle.

Existing forestry is believed to account for 2,700 ha (6%). This figure is being revised at present; the inclusion of smaller parcels of woodland may bring the proportion closer to 11% (4,800 ha).

Irrigation, particularly of potatoes and grass, is important on the light soils.

4 Investigation of Impacts on Water Resources Quantity

The approach taken to investigate the impact of afforestation on quantity of water recharging the Sherwood Sandstone aquifer has been through use of the model SMDMOD, developed for long-term water use calculations within the Broadleaf Woodland study conducted previously for NRA (Harding *et al.*, 1992). The model has been validated against datasets obtained in previous IH studies.

4.1 THE MODEL

The model, in Microsoft QuickBasic, was substantially rewritten so that a standard form of calculation could be performed for all crops, with just the parameters changed to account for different crop or soil types. The model operates on a daily time step and requires, apart from parameters which describe the effect of a particular crop and/or soil, daily values of rainfall and potential evaporation (usually Penman ET). In order from the top downwards, the equations used are:

4.1.1 Interception

Daily interception, I, is described by:

$$I = ifac\ [\ 1 - \exp(-iexp\ .\ R)] \tag{1}$$

where *ifac* and *iexp* are parameters specific to the crop. In particular, *ifac* is the maximum possible amount of water which can be lost by interception in any one day.

Interception is a complex process. In many situations, it has been found that significant amounts of water stored on the vegetation canopy evaporate whilst rain is falling. The interception store is therefore both filled and emptied simultaneously and the total quantity of water lost by interception depends on duration and intensity of rainfall, number of events per day, the interval between storms and the meteorological conditions both during and between storms. Estimation of interception loss from daily measurements involves making assumptions about all of these factors. Nevertheless, good success has been achieved in predicting daily interception in this way. Calder (1990) and Gash (1979) discuss the issues involved and provide the justification for this modelling philosophy.

Rainfall in excess of interception is added to the soil water store.

4.1.2 Transpiration

Transpiration depends on four factors. Firstly, it is assumed to be controlled by potential evaporation. Forest canopies are more efficient at absorbing radiation than grass (i.e. it has a lower albedo) and hence a factor *etmod* is applied to increase potential evaporation to account for this. There may also be an adjustment (involving multiplication by a parameter *devfac*) to take account of incomplete ground cover or canopy development during part of the growing season. Then the effect of soil water deficit needs to be taken into account. It is assumed that if the deficit is smaller than some value, *ecrit*, then transpiration takes place at the appropriate (adjusted) potential rate. For deficits greater than this, transpiration, T, proceeds at a rate:

$$T = PET\ .\ efac\ .\ \exp(-evexp\ .\ smd\ /\ ecrit) \tag{2}$$

where

PET = the daily adjusted potential evaporation ($etmod.\ devfac.ET$);

efac and *evexp* are factors controlling the rate at which evaporation drops with increasing deficit;

smd = the soil water deficit at the time;

$ecrit$ = the critical value of soil water deficit, above which transpiration starts to reduce below potential.

efac and *evexp* are not independent. They are related by:

$$efac = \exp(\ evexp) \tag{3}$$

so that transpiration takes place at potential rate for $smd = ecrit$.

There are, therefore, only three independent parameters which control transpiration.

Finally, account is taken of the reduction of transpiration by interception. During and shortly after rainfall, the canopy is wet and several mm of water is available for evaporation rather more easily than that which must diffuse out of the stomata into the atmosphere. Transpiration is thus suppressed until the canopy has dried. In the model, the amount of transpiration which would have occurred during this time is subtracted from that calculated using Equation (2). The proportion of the day experiencing wet canopy conditions, *rdur*, is assumed to be proportional to rainfall, which effectively assumes a constant intensity of rain and one event per day:

$$rdur = 0.0446\, r \tag{4}$$

where r is the daily rainfall in mm.

rdur is limited to a maximum value of 1.

Transpiration is then adjusted by multiplying T by $(1 - rdur)$.

4.1.3 Drainage from the Soil

A single-layer soil drainage model is used. That is, there is one soil water store, characterised by a parameter *smd*, which is conventionally called a soil moisture deficit. The amount of water in this store controls both drainage from the soil, to recharge the aquifer, and transpiration, through Equation (2). The drainage model used is:

$$d = dfac\ .\ \exp(-\ dexp\ .\ smd) \tag{5}$$

for $smd > 0$ and:

$$d = -smd \tag{6}$$

if $smd < 0$.

In conventional soil models employing the soil moisture deficit concept, drainage is usually assumed equal to zero if *smd* is positive and equal to *-smd* if it is negative (i.e. it is sufficient to restore it to zero if there is a surplus of water). The conventional model operates if *dfac* is set to zero. In instances where *dfac* is not zero, the concept of a soil moisture deficit breaks down. Model results show that the value of *smd* tends to stay at values of a few hundred mm for reasonable values of *dexp* for the winter period and hence there is always some control on transpiration from soil water stress unless *ecrit* is also set at a relatively high value. Values of *ecrit* cannot, therefore, be divorced from values of the drainage parameters and so intercomparison between soils or different model forms requires some caution.

4.1.4 Operation of the Model

The model operates on a daily time scale. The sequence of calculation is as follows.

Transpiration is first calculated according to Equation (2). Then interception is calculated according to Equation (1) and the wet canopy duration using Equation (4), with transpiration adjusted for the wet canopy duration as in Section 4.1.2. Drainage is calculated from

Equations (5) and (6). Lastly, the soil moisture deficit, *smd*, is adjusted by adding the total evaporation (transpiration + interception) and the drainage and subtracting the rainfall for the day. Calculation then proceeds for the next day.

4.2 CROPS AND SOILS SIMULATED

4.2.1 Crops

The crops simulated were those used in the earlier study (Harding *et al.*, 1992), with the addition of coniferous forest and the exception of beech, partly because it seemed unlikely that beech would be a likely choice of tree species on the acidic soils of the Sherwood Sandstone outcrop, partly because the best model found to represent its transpiration in the earlier work did not fit the functional form of Equation (2), and partly because there was little difference found by Harding *et al.* (1992) in the total evaporation from beech and ash. Ash was therefore the only broadleaf species simulated. Because of the similarity between ash and beech plantations found by Harding *et al.* (1992) it is hoped that the ash simulations would be reasonably representative of all broadleaf species likely to be planted in the Greenwood Community Forest.

The crops simulated were, therefore, grass, winter wheat, ash and coniferous forest.

4.2.2 Soils

The soil parameters were chosen to be representative as far as possible of the Black Wood site used by Harding *et al.* (1992) and a sandy soil similar to that of Thetford Forest used by Cooper (1980), Dolman *et al.* (1988) and Calder *et al.* (1983). The first of these soils allowed the model to be run with the same input data as was used by Harding *et al.* (1992) to ensure that the results could be reproduced and therefore that the model was operating as expected. It also gave a baseline against which the specific effects of the sandy soil could be compared. In the absence of detailed physical information on the sandy soils of the area, the Thetford soil was regarded as a good approximation and has the merit that there is quite a lot of information easily available, together with data to check the model output against.

4.3 MODEL PARAMETERS

4.3.1 Interception

Interception by both grass and winter wheat is assumed not to occur. Common observation shows that it quite clearly does, but the evaporation of this intercepted water is believed to take place at a rate so near to that of transpiration that, from a modelling point of view, there is no material difference and the model operation is simplified by setting *ifac* equal to zero.

For conifer plantation, with a year-round canopy, interception is assumed to depend only upon daily rainfall and not on the time of year. Calder (1990) suggested that *ifac* should be set equal to 6.9 mm and *iexp* to 0.099 mm^{-1} for upland Britain. This was for full canopy cover and climate conditions where rainfall is more prolonged than tends to be the case in eastern England. The data of Gash (1979) and Gash *et al.* (1980) suggest that a lower value for *ifac* is appropriate in these circumstances. The Thetford Forest canopy, for instance, allowed about 30% of rain to fall directly through to the ground. A value of *ifac* of two-thirds of the value suggested by Calder (1990) has been taken, i.e. *ifac* is taken as 4.6 mm and *iexp* is maintained at 0.099 mm^{-1}.

For modelling interception of the ash canopy, the parameters used by Harding *et al.* (1992) have been taken. The time of leafing and leaf fall are therefore assumed to be the same as in Hampshire, as is the degree of cover. For the period from 27 September to 30 May, *ifac* is assumed to be 1.84 mm and *iexp* is 0.108 mm^{-1}. During the summer, from 30 May to 27 September, *ifac* is assumed to be 0.75 mm and *iexp* is 2.04 mm^{-1}. These parameters suggest more interception loss from the ash when unfoliated than when foliated. Harding *et al.* (1992) drew attention to this and cast some doubts over whether this was reasonable. A factor in arriving at this conclusion is almost certainly that it was necessary to assume that unfoliated ash behaves in exactly the same way as unfoliated beech, since no measurements were available for ash in the winter. Nevertheless, in view of the success of the long-term modelling by Harding *et al.* (1992) and the lack of any other data, the same parameters for ash have been kept in the present work.

4.3.2 Transpiration

Grass was assumed to evaporate at the potential rate throughout the year unless the parameter *smd* was greater than *ecrit*. For greater deficits, Equation (2) operated, with *efac* 1.9 and *evexp* equal to 0.6523. These factors have been used by several workers, including Calder *et al.* (1983) and Harding *et al.* (1992). The soil-dependent factor in Equation (2) is *ecrit*, which was taken as 160 mm for the Black Wood soil, as used by Harding *et al.* (1992) and 53 mm for the sandy soil, as optimised by Calder *et al.* (1983) using the Thetford Forest grass clearing data of Cooper (1980).

The parameters assumed for Winter Wheat were basically the same as for grass, except that transpiration was adjusted by a factor *devfac* to account for development, senescence and harvesting of the crop. Before March 12, *devfac* is set to 0.1 and *ecrit* to 25 mm, to reflect the sparse ground cover and shallow root system of the overwinter crop. From March 12, increasing ground cover and growth of the root system is simulated by increasing both *devfac* and *ecrit* linearly until 31 May when *devfac* achieves a value of 1.1. *ecrit* is soil-dependent. The same values have been used as for grass, so that the maximum value for the Black Wood soil is taken as 160 mm and for the sandy soil it is 53 mm. After this, they remain at these values until 10 July, when senescence of the crop causes evaporation rates to reduce. *ecrit* is held at its summertime value, since the root system is still in place, but *devfac* reduces linearly down to a value of 0.1 by 10 August, when the crop is harvested. At this point, *devfac* and *ecrit* revert to their winter values of 0.1 and 25 mm. *efac* and *evexp* are taken the same as for grass, 1.9 and 0.6523.

For ash plantation, the course of events is simpler. The leafless period of the year is assumed to extend from 27 September to 31 March. During this time, *devfac* is set to 0.1, to account for evaporation from the forest floor and the understorey. From 31 March on, progressive foliation causes *devfac* to increase linearly to a maximum value of 0.74 on 30 May, at which value it remains until leaf fall on 27 September. Soil control comes again in the form of *ecrit*, which is taken as 500 mm for the Black Wood soil and 83 mm for the sandy soil. Note, however, that because the drainage models are effectively different (see succeeding Section), these two values of *ecrit* are not directly comparable. For Black Wood, *efac* and *evexp* were again taken as 1.9 and 0.6523. For the sandy soil, however, they were increased to 831.3 and 6.723. In the absence of other information, these parameters were taken the same as for coniferous forest. The rationale for these values is given below.

Coniferous forest remains foliated throughout the year. Like grass, there is, therefore, no seasonal dependence imposed upon the transpiration parameters. *devfac* was set at 0.9 to reflect an apparent inability by coniferous species to utilise all the available energy for transpiration. For Black Wood, *efac* and *evexp* were taken as 1.9 and 0.6523 and *ecrit* was set at 200 mm. For the sandy soil, results from the studies of Stewart (1988) and Dolman *et al.* (1988) were used. Stewart (1988) found that the response of surface resistance, g, to soil moisture deficit for the forest could be described by:

$$g = g_0\,(1 - \exp\,(a\,.\,smd)) \qquad (7)$$

for exp $(a\,.\,smd) < 1$ only.

Whilst the Penman-Monteith equation, for which this parameter g was derived, is not quite of the same form as that of the model used here, it is sufficiently similar that no appreciable error is expected to result from using it. The value of a found by Dolman *et al.* (1988) was 0.081 mm^{-1}, which, in terms of Equation (2) is the value of *evexp / ecrit*. *ecrit* was determined to be 83 mm, with a drainage model as described below, so that *evexp* becomes 6.723 and the consequent value of *efac* 831.3. This seems a very high value, but is a consequence of Equation (3) and demonstrates that the effect of soil water deficits is very strong on a sandy soil.

4.3.3 Drainage

Drainage for all the simulated grass and winter wheat runs was taken as conforming to the classical field capacity concept. i.e. no drainage occurred when the model soil had a positive value of *smd* and when *smd* became negative (water content was higher than field capacity), drainage occurred within a day to reduce the soil to field capacity. This was accomplished by making drainage equal to *-smd* for values of *smd* below zero and *dfac* zero in the model. This was regarded as satisfactory for shallow-rooted crops in which the quantity of water held within the root zone was in any case small, but for deep-rooted forest plantation, the total profile depth was at least 2 m at Black Wood (Harding *et al.*, 1992) and relatively slow drainage needed to be allowed for. For the ash, therefore, on the Black Wood soil, *dfac* and *dexp* were set to 2.24 mm and 0.00427 mm^{-1}, whilst for conifers they were 2.77 mm and 0.00977 mm^{-1}. For the sandy soil, the classic field capacity concept was assumed to apply and *dfac* set to zero for all crops. This was partly because sandy soils are expected to drain to a stable value much more rapidly than finer textured ones, but more to ensure compatibility with the models used by Dolman *et al.* (1988) and Calder *et al.* (1983), who both used this form of drainage model.

4.4 DATA INPUT

4.4.1 Rainfall

Daily values of rainfall were obtained for sites near to each of the soil water data sites. For Black Wood, this was the same as had been used by Harding *et al.* (1992). For Thetford Forest it was the Forestry Commission meteorological site at Santon Downham and for Bicton

Park, it was a meteorological site in the grounds of the Agricultural College which is situated there.

For the modelling of sandstone recharge in the proposed Greenwood Forest area, rainfall data from the Meteorological Office station at Watnall were taken. To account for rainfall variations over the area, these were multiplied by 0.85 and 1.05 to simulate the range of rainfall over the outcrop (see Section 3.5).

4.4.2 Potential Evaporation

Daily values of Penman potential evaporation were available for Grendon Underwood, an IH site in Buckinghamshire, for 1967-86. Similar data were also obtained, by courtesy of Nottingham University School of Agriculture, for Sutton Bonington, between Nottingham and Loughborough, for the period 1976-91. These were both slightly more recent and from an area much closer to the area of interest. Black Wood and Thetford simulations were performed using the Grendon Underwood data, whilst Bicton Park and the Greenwood Community Forest calculations used the Sutton Bonington data. In the case of Bicton Park, this was because of the periods available.

Differences between the two sets of data were small. The Sutton Bonington data tended to give slightly higher values by about 5%.

4.5 MODEL RUNS

In all, seven model runs were made. These are detailed below.

Run 1. This used Black Wood parameters and the meteorological data used by Harding *et al.* (1992). It was, in fact, a repeat of the runs performed by Harding *et al.* (1992) to check that the reformulated model performed as expected.

Run 2. This used Black Wood parameters with the Watnall rainfall data and Sutton Bonington potential evaporation. This gave baseline figures, with which the effect of the sandy soil could be evaluated.

Run 3. This used the sandy soil parameters, with rainfall from Santon Downham and potential evaporation from Grendon Underwood. It was run to serve as a check on whether the model gave realistic values for evaporation and drainage, when compared with the field results reported by Cooper (1980) over the period 1974-76.

Run 4. This also used the sandy soil parameters, with rainfall from Bicton Park and potential evaporation from Sutton Bonington. It was run to serve as a check on whether the model gave realistic values for evaporation and drainage, when compared with the field results reported by Cooper *et al.* (1990) over the period 1988-89. Data is available for a longer period, but unfortunately the rainfall record is not complete.

Run 5. This is the first run to simulate the effect of a Greenwood Community Forest. It used Watnall rainfall, Sutton Bonington potential evaporation and sandy soil parameters for the period 1976-91.

Run 6. This was similar to run 5, but rainfall input was reduced to 85% of the Watnall value. Otherwise, everything else was identical. This is the lowest rainfall in the proposed Greenwood Community Forest area.

Run 7. As for run 6, but rainfall was increased to 5% above the Watnall value This is the highest rainfall in the proposed Greenwood Community Forest area.

5 Results and Discussion

5.1 COMPARISON WITH CALCULATIONS OF HARDING *ET AL.* (1992)

Results of annual evaporation calculated for the Black Wood site using the model used in this report and the calculations of Harding *et al.* (1992) are shown in Table 1. Identical results were obtained for grass, ash and conifers (in fact conifer results were not reported by Harding *et al.* (1992) but use of their model gave identical results to the new model). However, for winter wheat, total annual evaporation calculated by the model used for this report was some 90 mm per year lower than that reported by Harding *et al.* (1992). The difference seems to be due to an error in the Harding *et al.* (1992) model, which results in evaporation being overestimated during periods of low deficit. However, Harding *et al.* (1992) commented that their model already appeared to underestimate evaporation. For a thin chalk soil in Cambridgeshire, similar to that at Black Wood, Cooper *et al.* (1990) reported total evaporation over a year by a winter wheat crop to be very similar to that of grass (458 mm compared with 465 mm). Wellings (1984) reported similar results from winter barley and grass for a site very close to Black Wood. Unfortunately, it has not been possible in the time available to investigate this discrepancy further, but clearly the winter wheat calculations need to be treated with considerable scepticism, and in the absence of more detailed information, assume that evaporation from winter wheat is similar to that of grass.

5.2 THETFORD FOREST COMPARISON

Table 2 shows comparisons of annual evaporation and drainage calculated by Cooper (1980) for Thetford Forest with those using the present model. Total evaporation for 1974 calculated by the model was some 67 mm higher than that "measured" by Cooper. However, the method used by Cooper relied on soil water measurements using the zero flux plane (ZFP) method during summer months and evaporation estimates based on meteorological data in the winter. No such measurements were available for 1974 and so very crude guesses were used, which may help to explain the poor agreement in this year. For 1975 and 1976, two very dry years, the model results agree remarkably well with experimental measurements. It may also be relevant that Dolman *et al.* (1988) obtained predicted transpiration some 15 mm higher than that measured by Cooper (1980) for the summer period of 1974, but agreement in 1975 and 1976 was much better.

For the grass site in Thetford Forest, the modelled evaporation results are on average higher

***Table 1** Annual evaporation in mm calculated for the Black Wood site using the model used in this report and the calculations of Harding et al. (1992).*

			PRESENT WORK				HARDING ET AL. (1992)			
Model parameters			Grass	W. Wheat	Ash	Conifer				
ifac	mm		0	0	.75	6.9				
iexp	mm^{-1}		0	0	2.04	.099				
efac			1.9	1.9	1.9	1.9				
evexp			.6523	.6523	.6523	.6523				
ecrit	mm		160	160	500	200				
etmod			1	1	1.17	1.17				
dfac	mm		0	0	2.24	2.77				
dexp	mm^{-1}		.00427	.00427	.00427	.00977				
smdi	mm		0	0	100	100				
Year	**Rain**	**ET**	**Grass**	**W. Wheat**	**Ash**	**Conifer**	**Evap. Grass**	**Evap. Wheat**	**Evap. Ash**	**Evap. Beech**
1967	831.1	494.6	494.6	302.9	422.1	780.1	495	405	422	445
1968	860.5	441.0	441.0	268.7	364.5	695.7	441	394	364	407
1969	682.9	511.5	511.5	331.5	425.2	699.5	511	421	425	433
1970	719.7	503.5	489.0	311.0	427.3	657.5	489	360	427	444
1971	755.4	464.1	464.1	283.2	382.2	667.9	464	420	382	404
1972	765.3	448.0	448.0	272.3	381.0	674.6	448	376	381	410
1973	537.9	493.0	493.0	298.6	386.1	564.0	493	394	403	488
1974	736.1	461.2	453.7	289.2	376.8	583.0	454	342	377	399
1975	658.7	518.2	486.3	322.1	432.2	651.8	486	376	432	451
1976	606.1	545.1	468.6	328.7	431.1	557.9	469	362	430	432
1977	744.4	444.0	443.9	274.5	381.2	655.6	444	353	381	*393
1978	690.9	447.6	447.5	264.3	383.5	630.2	447	342	384	415
1979	762.1	416.7	416.7	256.2	375.9	678.6	417	377	376	416
1980	692.4	462.9	462.9	286.5	379.5	625.2	462	349	379	401
1981	811.9	444.0	444.0	265.3	383.8	688.9	444	382	384	427
1982	843.6	485.3	485.3	288.7	410.2	732.8	485	365	410	436
1983	716.5	506.8	499.9	293.2	409.3	706.5	500	407	409	444
1984	834.7	510.9	504.2	286.7	422.2	728.3	504	365	422	463
1985	752.1	476.3	476.3	299.7	406.8	690.3	476	403	407	434
1986	807.0	439.1	439.1	283.1	391.1	693.0	439	373	391	414
Average	740	476	468	290	399	718	468	378	399	423

* Misprinted as 493 mm in Harding *et al.* (1992)

Table 2 Comparisons of annual evaporation and drainage in mm calculated by Cooper (1980) for Thetford Forest with those using the present model.

			PRESENT WORK				COOPER (1980)	
Model parameters			Grass	W. Wheat	Ash	Conifer		
ifac	mm		0	0	.75	4.6		
iexp	mm^{-1}		0	0	2.04	.099		
efac			1.9	1.9	831.3	831.3		
evexp			.6523	.6523	6.723	6.723		
ecrit	mm		53	53	83	83		
etmod			1	1	1.17	1.17		
dfac	mm		0	0	0	0		
dexp	mm^{-1}		.00427	.00427	.00427	.00977		
smdi	mm		0	0	0	0		
Evaporation								
Year	**Rain**	**ET**	**Grass**	**W. Wheat**	**Ash**	**Conifer**	**Grass**	**Conifer**
1971	662.6	464.1	410.7	268.1	384.5	544.2		
1972	544.5	448.0	408.2	248.6	357.7	521.9		
1973	544.9	493.0	454.0	286.7	379.2	521.5		
1974	713.7	461.2	373.5	239.4	382.9	548.1	313	481
1975	585.7	518.2	368.0	249.7	308.8	480.7	298	466
1976	535.8	545.1	332.4	235.6	292.3	427.4	305	410
Drainage								
1971	662.6	464.1	252.4	394.6	278.1	119.0		
1972	544.5	448.0	137.5	295.9	186.7	54.5		
1973	544.9	493.0	89.2	258.1	165.6	0.0		
1974	713.7	461.2	340.8	474.4	330.9	157.3	352	255
1975	585.7	518.2	210.5	328.3	270.2	100.2	304	166
1976	535.8	545.1	196.2	294.1	237.7	102.4	241	137

than the measured values by 53 mm per year. Cooper (1980) suggested that even his measurements may be higher than the true figure, since evaporation was assumed equal to Penman ET when no ZFP was observed. However, when a ZFP was present, at no time was evaporation as high as ET, suggesting that ET was an overestimate of evaporation during at least some of the no-deficit period.

5.3 BICTON PARK COMPARISON

Table 3 shows a comparison between the water balance of a grassed site at Bicton Park measured by the same methods as at Thetford and model results. For this site, the measured evaporation is higher than the modelled value by 21 mm and 80 mm for the two years reported. This may be due in part to the use of ET values for another part of the country (ET is often reported significantly higher close to the coast), but it is likely that the large difference in 1990 can be only partially accounted for in this way. The Bicton soil is more loamy than that at Thetford, particularly in the upper horizons. This would be expected to reduce water stress on a crop and hence increase evaporation. The results seem, therefore, to be reasonable.

Table 3 Comparison between the water balance of a grassed site at Bicton Park measured by Cooper et al. (1990) and model results.

			PRESENT WORK				COOPER ET AL. (1990)
Model parameters			**Grass**	**W. Wheat**	**Ash**	**Conifer**	
ifac	mm		0	0	.75	4.6	
iexp	mm^{-1}		0	0	2.04	.099	
efac			1.9	1.9	831.3	831.3	
evexp			.6523	.6523	6.723	6.723	
ecrit	mm		53	53	83	83	
etmod			1	1	1.17	1.17	
dfac	mm		0	0	0	0	
dexp	mm^{-1}		.00427	.00427	.00427	.00977	
smdi	mm		0	0	0	0	
Evaporation							
Year	**Rain**	**ET**	**Grass**	**W. Wheat**	**Ash**	**Conifer**	**Grass**
1985	686.0	487.6	392.5	234.3	371.3	530.2	
1986	805.8	507.7	480.7	287.5	407.1	656.9	
1987	761.5	461.1	387.1	246.5	362.1	525.1	
1988	767.3	510.4	475.9	271.9	409.3	613.5	497
1989	827.8	608.6	399.7	235.0	351.3	549.2	480
Drainage							
1985	686.0	487.6	294.2	451.7	314.7	156.5	
1986	805.8	507.7	325.1	518.3	398.7	148.9	
1987	761.5	461.1	372.8	513.6	398.2	235.4	
1988	767.3	510.4	293.3	496.8	359.1	161.3	333
1989	827.8	608.6	424.9	590.3	474.4	270.5	308

5.4 COMPARISONS WITH IH SOIL MOISTURE DATA BANK

The comparisons made in the above paragraphs are of modelled evaporation, interception and drainage with the same quantities measured by an independent means. These data are not, generally speaking, widely available. In consequence, it has become a common practice to use a surrogate variable to calibrate and/or verify models which calculate evaporation and drainage from soil profiles. Water content measurements are widely available, and this is the most common monitored variable against which the output of models is compared. There are clearly dangers in this approach, but in most cases there is little alternative at present. This was the approach taken by Calder *et al.* (1983) and also of Gardner (1983) and Gardner & Field (1983), when evaluating the success of the Meteorological Office MORECS model, using the databank compiled by Gardner (1981).

Figure 2 shows a comparison of soil water content between sandy soil simulations made using the SMDMOD model and measurements reported in the IH soil water databank (Gardner, 1981) for grass and conifers growing on Crannymoor series soil.

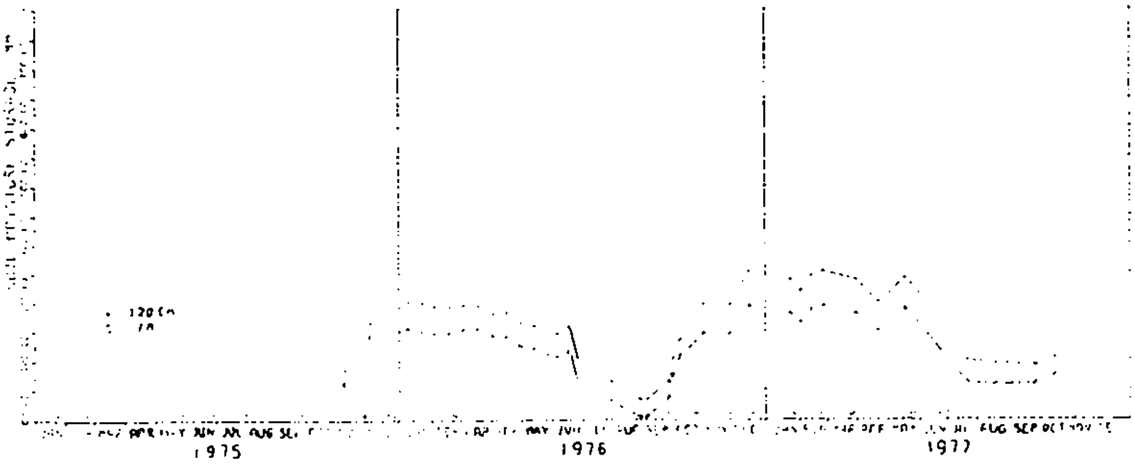
Reasonable agreement is obtained, with both observations and model predicting about 50 mm less water in the profile under conifer than under grass in 1976. Unfortunately, the simulation did not start until the beginning of 1976 and, under both grass and conifer, the profile did not appear to have regained field capacity after the dry summer of 1975. This highlights the need to have a period of simulation prior to that for which comparisons are made to allow the model to settle down and obviate the influence of starting conditions.

5.5 EFFECTS OF AFFORESTATION WITH BROADLEAF SPECIES ON THE WATER BALANCE OF THE SHERWOOD SANDSTONE AQUIFER

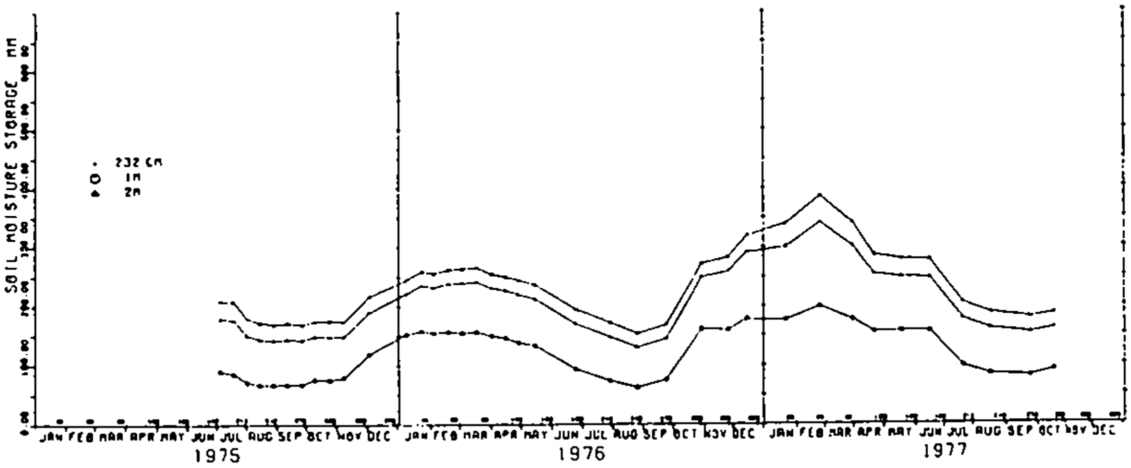
Table 4 shows predicted evaporation, interception and drainage from the four types of land cover, simulated over a period of 16 years for the Black Wood soil with Watnall rainfall and potential evaporation from the Sutton Bonington site. Tables 5, 6 and 7 show similar simulations for a sandy soil using rainfall at 1.0, 0.85 and 1.05 times the Watnall values for each day.

Comparison of Tables 4 and 5 shows that the effect of sandy, as opposed to chalky, soil parameters on the simulation is to reduce evaporation, and hence increase likely aquifer recharge by about 70 mm in the case of grass, 31 mm for winter wheat, 30-48 mm for ash and 70-86 mm for conifer plantations. The range of values for some crops is a consequence of whether drainage or evaporation is being looked at and reflects soil water storage differences. Interception is an important component of the water balance of both conifer and ash. This is dependent only upon rainfall, and hence for ash is identical for both soils. However, the value of *ifac* for conifers was set at 6.9 mm for the Black Wood parameters and at 4.6 mm for those associated with sandy soils, decreasing predicted mean interception loss by 140 mm per year. The small difference for winter wheat is a consequence of low evaporation generally. Problems with credibility of these figures were discussed in Section 5.1.

Of more interest, in the present case, is the likely effect of rainfall variations on recharge. A decrease in annual rainfall of 15% from a mean of 713 mm to one of 606 mm (as in the south-east of the proposed forest area), leads to a decrease in evaporation of 23 mm (5.2%), 9 mm (3.4%), 18 mm (4.7%) and 54 mm (9.2%) for grass, winter wheat, ash and conifer.



Site: F9 **PM Texture:** SANDSTONE **Soil** PODZOL (CRANNYMOOR) **Landuse:** MOWN GRASS



Site F10 **PM Texture:** SANDSTONE **Soil** PODZOL (CRANNYMOOR) **Landuse:** CONIFEROUS WOOD

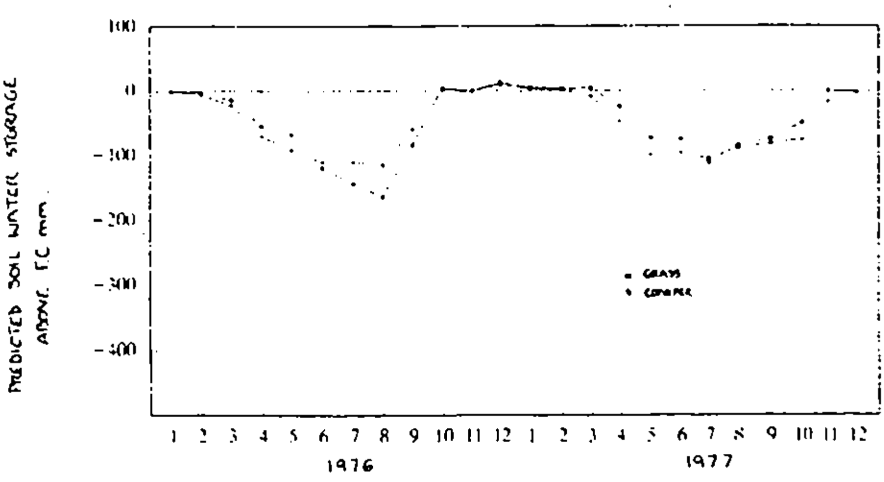


Figure 2 Comparison of measured (top and middle) and modelled (bottom) soil water storage for a sandy soil in the Dover Beck catchment.

Table 4 Predicted evaporation, interception and drainage in mm from the four types of land cover, simulated over a period of 16 years for the Black Wood soil with Watnall rainfall and potential evaporation from the Sutton Bonington site.

Model parameters			**Grass**	**W. Wheat**	**Ash**	**Conifer**
ifac	mm		0	0	.75	6.9
iexp	mm^{-1}		0	0	2.04	.099
efac			1.9	1.9	1.09	1.9
evexp			.6523	.6523	.6523	.6523
ecrit	mm		160	160	500	200
etmod			1	1	1.17	1.17
dfac	mm		0	0	2.24	2.77
dexp	mm^{-1}		.00427	.00427	.00427	.00977
smdi	mm		0	0	100	100
Evaporation						
Year	**Rain**	**ET**	**Grass**	**W. Wheat**	**Ash**	**Conifer**
1976	550.8	586.3	503.2	341.6	478.7	659.6
1977	826.4	555.3	544.1	316.3	451.1	744.4
1978	771.9	490.0	490.0	282.4	405.0	678.5
1979	834.0	512.3	512.3	292.9	433.9	751.3
1980	743.4	507.7	507.7	290.4	416.4	704.2
1981	789.4	507.9	507.0	283.7	421.1	708.1
1982	782.9	549.0	549.0	307.5	427.1	717.5
1983	676.6	501.0	498.2	272.1	403.3	664.7
1984	722.1	531.5	525.7	300.5	427.7	665.4
1985	650.7	487.6	487.6	277.6	397.8	618.8
1986	788.8	507.7	507.7	300.4	419.2	686.7
1987	718.6	461.1	461.1	263.5	385.6	660.6
1988	723.0	510.4	510.4	277.4	412.5	696.4
1989	649.3	608.6	549.1	330.7	484.1	645.9
1990	645.3	601.0	547.6	308.0	451.1	623.3
1991	535.5	503.0	487.5	266.8	408.8	533.4
Mean	713.0	526.3	511.8	294.5	426.5	672.4
Drainage						
1976	550.8	586.3	74.3	196.3	289.0	114.1
1977	826.4	555.3	257.3	523.0	296.7	62.4
1978	771.9	490.0	280.2	489.4	305.4	50.4
1979	834.0	512.3	321.8	541.2	389.4	77.6
1980	743.4	507.7	235.8	451.4	366.9	71.4
1981	789.4	507.9	282.3	507.3	357.8	65.0
1982	782.9	549.0	233.1	474.5	340.5	61.2
1983	676.6	501.0	205.8	405.0	338.0	58.2
1984	722.1	531.5	169.7	422.0	289.0	47.3
1985	650.7	487.6	163.2	372.7	268.8	43.4
1986	788.8	507.7	270.2	477.5	297.4	50.3
1987	718.6	461.1	268.6	466.4	341.0	63.4
1988	723.0	510.4	212.1	445.5	361.9	64.7
1989	649.3	608.6	159.6	318.6	239.4	36.5
1990	645.3	601.0	86.8	336.3	204.2	30.2
1991	535.5	503.0	78.1	269.8	190.0	30.1
Mean	713.0	526.3	206.2	418.6	304.7	57.9

***Table 5** Predicted evaporation, interception and drainage in mm from the four types of land cover, simulated over a period of 16 years for the Thetford soil with Watnall rainfall and potential evaporation from the Sutton Bonington site.*

Model parameters		Grass	W. Wheat	Ash	Conifer
ifac	mm	0	0	.75	4.6
iexp	mm^{-1}	0	0	2.04	.099
efac		1.9	1.9	831.3	831.3
evexp		.6523	.6523	6.723	6.723
ecrit	mm	53	53	83	83
etmod		1	1	1.17	1.17
dfac	mm	0	0	0	0
dexp	mm^{-1}	.00427	.00427	.00427	.00977
smdi	mm	0	0	0	0

Evaporation

Year	Rain	ET	Grass	W. Wheat	Ash	Conifer
1976	550.8	586.3	355.3	257.0	305.9	434.0
1977	826.4	555.3	441.9	267.2	385.1	591.0
1978	771.9	490.0	474.8	276.0	405.0	635.5
1979	834.0	512.3	445.6	256.7	397.5	640.4
1980	743.4	507.7	448.6	269.8	416.4	607.3
1981	789.4	507.9	433.6	253.0	366.7	613.1
1982	782.9	549.0	510.8	290.7	426.9	690.7
1983	676.6	501.0	413.9	239.2	340.4	582.0
1984	722.1	531.5	430.0	264.6	391.6	586.6
1985	650.7	487.6	464.3	269.1	397.7	613.7
1986	788.8	507.7	458.2	262.5	399.1	651.9
1987	718.6	461.1	441.1	261.1	385.6	597.1
1988	723.0	510.4	500.3	273.5	412.5	648.4
1989	649.3	608.6	408.0	251.2	335.4	516.9
1990	645.3	601.0	408.9	267.9	361.6	502.5
1991	535.5	503.0	388.4	249.8	330.5	471.7
Mean	713.0	526.3	439.0	263.1	378.6	586.4

Drainage

Year	Rain	ET	Grass	W. Wheat	Ash	Conifer
1976	550.8	586.3	182.6	280.9	233.3	107.3
1977	826.4	555.3	399.0	572.1	452.8	246.9
1978	771.9	490.0	295.4	495.8	366.8	134.5
1979	834.0	512.3	388.5	577.4	436.6	194.1
1980	743.4	507.7	294.8	472.0	325.8	136.5
1981	789.4	507.9	355.7	538.0	424.0	175.4
1982	782.9	549.0	271.2	491.3	355.2	92.1
1983	676.6	501.0	263.2	437.9	336.6	100.7
1984	722.1	531.5	292.3	457.8	330.8	129.4
1985	650.7	487.6	186.6	381.1	252.6	43.1
1986	788.8	507.7	319.7	515.4	380.0	122.9
1987	718.6	461.1	288.6	468.8	343.1	129.9
1988	723.0	510.4	222.2	449.5	310.4	100.7
1989	649.3	608.6	241.8	398.1	313.9	106.4
1990	645.3	601.0	235.1	376.4	282.8	141.8
1991	535.5	503.0	148.6	286.8	205.9	78.2
Mean	713.0	526.3	274.1	450.0	334.4	127.5

Table 6 Predicted evaporation, interception and drainage in mm from the four types of land cover, simulated over a period of 16 years for the Thetford soil with 85% of Watnall rainfall and potential evaporation from the Sutton Bonington site.

Model parameters			**Grass**	**W. Wheat**	**Ash**	**Conifer**
ifac	mm		0	0	.75	4.6
iexp	mm^{-1}		0	0	2.04	.099
efac			1.9	1.9	831.3	831.3
evexp			.6523	.6523	6.723	6.723
ecrit	mm		53	53	83	83
etmod			1	1	1.17	1.17
dfac	mm		0	0	0	0
dexp	mm^{-1}		.00427	.00427	.00427	.00977
smdi	mm		0	0	0	0
Evaporation						
Year	**Rain**	**ET**	**Grass**	**W. Wheat**	**Ash**	**Conifer**
1976	468.2	586.3	336.8	246.2	282.6	397.6
1977	702.4	555.3	411.6	257.2	356.0	532.6
1978	656.1	490.0	444.1	266.1	397.7	565.6
1979	708.9	512.3	429.7	253.9	375.2	581.0
1980	631.9	507.7	415.4	253.6	402.3	548.5
1981	671.0	507.9	422.3	249.1	346.5	567.9
1982	665.5	549.0	495.6	284.5	422.4	624.0
1983	575.1	501.0	399.9	236.4	322.7	544.1
1984	613.8	531.5	399.7	250.6	372.9	533.0
1985	553.1	487.6	445.2	265.1	379.9	548.8
1986	670.5	507.7	442.2	256.7	379.4	598.2
1987	610.8	461.1	409.8	252.2	380.2	540.0
1988	614.6	510.4	471.5	266.6	408.2	581.1
1989	551.9	608.6	390.7	241.7	308.3	478.3
1990	548.5	601.0	382.4	253.6	330.3	458.5
1991	455.2	503.0	361.0	238.0	305.8	426.6
Mean	606.1	526.3	416.1	254.5	360.7	532.0
Drainage						
1976	468.2	586.3	120.4	211.0	175.9	62.7
1977	702.4	555.3	303.6	456.2	356.2	179.7
1978	656.1	490.0	210.2	390.0	258.3	88.5
1979	708.9	512.3	279.4	455.1	333.7	128.5
1980	631.9	507.7	216.8	377.0	228.6	98.2
1981	671.0	507.9	248.4	423.2	325.5	87.8
1982	665.5	549.0	169.1	380.2	242.4	58.9
1983	575.1	501.0	175.6	339.1	252.7	38.1
1984	613.8	531.5	214.3	363.5	241.2	58.2
1985	553.1	487.6	108.2	287.7	172.9	28.7
1986	670.5	507.7	219.0	404.5	282.9	39.5
1987	610.8	461.1	210.4	368.2	239.0	77.6
1988	614.6	510.4	142.6	347.9	206.3	75.2
1989	551.9	608.6	161.7	310.2	243.7	32.0
1990	548.5	601.0	164.9	294.1	217.5	89.1
1991	455.2	503.0	104.2	218.1	150.2	60.6
Mean	606.1	526.3	190.6	351.6	245.5	75

Table 7 Predicted evaporation and drainage in mm from the four types of land cover, simulated over a period of 16 years for the Thetford soil with 105% of Watnall rainfall and potential evaporation from the Sutton Bonington site.

Model parameters		**Grass**	**W. Wheat**	**Ash**	**Conifer**
ifac	mm	0	0	.75	4.6
iexp	mm^{-1}	0	0	2.04	.099
efac		1.9	1.9	831.3	831.3
evexp		.6523	.6523	6.723	6.723
ecrit	mm	53	53	83	83
etmod		1	1	1.17	1.17
dfac	mm	0	0	0	0
dexp	mm^{-1}	.00427	.00427	.00427	.00977
smdi	mm	0	0	0	0

Evaporation

Year	**Rain**	**ET**	**Grass**	**W. Wheat**	**Ash**	**Conifer**
1976	578.3	586.3	361.3	260.3	312.7	446.0
1977	867.7	555.3	451.7	270.6	394.2	609.2
1978	810.5	490.0	483.1	278.4	406.7	657.5
1979	875.7	512.3	450.6	257.5	401.5	654.9
1980	780.6	507.7	458.8	274.6	418.3	626.4
1981	828.9	507.9	437.4	254.3	373.1	623.6
1982	822.0	549.0	512.7	292.4	428.2	707.2
1983	710.4	501.0	418.0	240.1	345.8	591.9
1984	758.2	531.5	439.2	267.3	395.6	603.5
1985	683.2	487.6	469.6	270.2	399.2	633.5
1986	828.2	507.7	462.6	264.6	403.7	665.6
1987	754.5	461.1	450.3	261.7	387.1	615.5
1988	759.1	510.4	503.9	275.0	413.8	670.3
1989	681.8	608.6	413.8	254.5	344.5	528.4
1990	677.6	601.0	417.6	272.8	371.8	517.0
1991	562.3	503.0	397.5	253.6	338.4	486.2
Mean	748.7	526.3	445.5	265.5	383.4	602.3

Drainage

Year	**Rain**	**ET**	**Grass**	**W. Wheat**	**Ash**	**Conifer**
1976	578.3	586.3	203.4	304.5	253.5	122.2
1977	867.7	555.3	431.2	610.6	485.7	270.5
1978	810.5	490.0	325.7	532.0	403.7	151.1
1979	875.7	512.3	425.3	618.4	474.3	221.2
1980	780.6	507.7	321.8	504.3	361.0	154.5
1981	828.9	507.9	391.5	576.3	457.1	204.4
1982	822.0	549.0	308.5	528.7	393.1	114.7
1983	710.4	501.0	293.0	470.8	365.1	118.6
1984	758.2	531.5	319.2	491.3	362.9	154.7
1985	683.2	487.6	213.7	412.5	283.7	50.3
1986	828.2	507.7	354.2	552.2	414.3	153.6
1987	754.5	461.1	316.0	504.6	378.0	147.9
1988	759.1	510.4	254.7	484.1	345.3	109.4
1989	681.8	608.6	268.3	427.3	337.3	132.9
1990	677.6	601.0	258.6	403.7	304.9	159.5
1991	562.3	503.0	166.3	309.8	224.9	84.2
Mean	748.7	526.3	303.2	483.2	365.3	146.9

Corresponding decreases of interception are 8 mm (8.0%) for ash and 23 mm (10.6%) for conifers. The effect on drainage (i.e. aquifer recharge) is, on average, a decrease of 84 mm (31%) for grass, 98 mm (22%) for winter wheat, 89 mm (27%) for ash and 52 mm (41%) for conifers. Interestingly, the reduction in recharge under conifers is the smallest numerically, but the largest percentage.

An increase in annual rainfall of 5% to a mean of 749 mm as in the north-west of the proposed forest area), leads to an increase in evaporation of 7 mm (1.5%), 2 mm (0.9%), 5 mm (1.3%) and 16 mm (2.7%) for grass, winter wheat, ash and conifer. Corresponding increases of interception are 3 mm (2.7%) for ash and 7 mm (3.4%) for conifers. The effect on drainage (i.e. aquifer recharge) is, on average, 29 mm (11%) for grass, 33 mm (7%) for winter wheat, 31 mm (9%) for ash and 19 mm (15%) for conifers.

The conclusion is that rainfall differences cause drainage changes proportionally 2 -3 times larger, the effect on drainage is much greater than on evaporation and the effect is greatest for the crops which produce least drainage.

The effect of the different crops is that for all soils and all climatic zones considered, the amount of evaporation is in the order conifer > grass > ash > winter wheat and drainage is consequently in the reverse order. However, considerable doubts surround the winter wheat figure and it may be better to assume that it is likely to be about the same as grass for all areas. At Black Wood, the difference in recharge between grass and ash plantation was 72 mm (23%). Reduction of rainfall to that of the Watnall site increases this difference to 99 mm (39%), whilst introduction of the sandy soil causes the differences to decrease again to 60 mm (20%). It is difficult to apportion the change due to rainfall and soil in a simple manner. Evaporation by grass at Black Wood was very close to the potential rate in 12 out of 22 years. Recharge beneath this crop on this soil is therefore very sensitive to rainfall differences, but evaporation is not. By contrast, the ash evaporation is much more sensitive to rainfall through the interception term and hence changes in rainfall change evaporation by more and affect drainage less in absolute amount. On a sandy soil, however, rainfall has a greater effect on evaporation by grass, since it is more sensitive to deficits and the difference between the two crops is correspondingly reduced.

5.6 UNCERTAINTIES IN THE RESULTS

Uncertainty in the results comes from a number of sources. Quantification of these is important to be able to know how much confidence should be placed in the results. From the information available, there is no rigorous way in which this may be done, but examination of the information presented allows some rough estimates to be made.

5.6.1 The Model Structure

The model used has a simple structure, essentially the same for all crops. This is clearly unlikely to be an exact representation of any of the sub-processes modelled. The soil water reservoir is assumed to be a single storage which affects both drainage from the soil and evaporation. In practice, the situation is much more complicated and, at the very least, we expect the vertical distribution of water in the soil to affect both of these processes in different ways. We are constrained from introducing a better description of the processes (which is reasonably well understood, at least for drainage) by the need to keep the number of independent parameters small and also by the very great difficulty in obtaining reasonable estimates of the relevant parameters.

5.6.2 Model Parameters

Assume that the model structure is a reasonable representation of the important processes which determine evaporation and drainage from a soil profile. The problem of how to derive the relevant parameters then occurs. In the case of Black Wood, experimental data were available to fit predicted and measured soil water storage, interception parameters and transpiration response to soil water storage. A similar exercise was conducted for Thetford Forest and for the grass at Thetford. However, we have had to assume that the properties of the sandy soils of Nottinghamshire are sufficiently similar to those at Thetford that the response of transpiration to soil water deficit is the same. Furthermore, we have also had to assume that the response of transpiration by ash to soil water deficit for a sandy soil is the same as for conifers. For estimation of interception, it has been assumed that the canopy structure of ash at Black Wood would be the same as one planted in the Greenwood Community Forest. It may well be that ash is the wrong species to investigate, but that is the only one for which adequate data are available.

5.6.3 Input Data

There are, therefore, several unknown factors involved in transferring the models from one area of the country to another. With the exception of the comparisons shown in Figure 2, there is very little data with which to compare how successful the process may be. An estimate of the uncertainty in the calculations is clearly very difficult under these circumstances and must rely to a large extent on subjective factors.

5.6.4 Uncertainties in Outputs due to Errors in the Models and Parameter Values

Some estimate of likely uncertainty due to the model structure, the parameter values adopted and the input data can be gained from an examination of the information in Tables 2 and 3. The best agreement between model and experimental data is for the coniferous forest at Thetford, whilst measured evaporation by grass disagrees at both Thetford and Bicton by an average of just over 50 mm per year, albeit in different directions. An uncertainty of approximately 50 mm per annum seems, therefore, a reasonable estimate for the modelling uncertainty caused by the variety of factors mentioned above.

In addition to this, there is an additional uncertainty caused by the structure of the forest canopy in the case of conifers. The Thetford canopy was quite open, with about 30% of rainfall reaching the surface of the forest floor directly. This made the use of a value of *intfac* of 4.6 appropriate. However, a denser canopy would increase the amount lost as interception. This would be compensated only slightly by reduced transpiration and losses of perhaps an extra 150 mm per annum are plausible from this cause.

Similar uncertainties attend the broadleaf plantation results. Here, the unknown factors are the properties of particular species, planting density and the presence or otherwise of an understorey. Since recreational uses are likely to be an important consideration in possible planting of the community forest, it is likely that the canopy cover will be quite open, allowing plenty of light through to the forest floor. This is likely to encourage the development of a copious understorey. At Black Wood, it was found that evaporation from the understorey beneath ash compensated very closely the reduced evaporation from the main canopy compared with the much denser beech without understorey. Canopy density may, therefore, not be too important an issue.

Greatest uncertainty attends arable crops. The model used here appears to give unrealistically low evaporation. For thin chalk soils, arable crops evaporated almost the same amount of water as grass over a year, although the distribution in time was somewhat different. No data have been seen to make a similar comparison for sandy soil. An additional problem in the proposed Greenwood Community Forest area is that irrigation of crops is very common. The water for this comes mainly from the aquifer, so that, in the absence of appreciable return flow, this extraction is an additional loss to the groundwater resources. Conversion of land from farming to forest will thus provide a benefit to water resources, although the likely scale of this is not known at present.

6 Greenwood Community Forest: effect on groundwater quality

6.1 INTRODUCTION

If the Greenwood Community Forest goes ahead as presently planned, this could mean the conversion of up to 10000 ha of land to forestry. About 60% of the area being considered is underlain by the Sherwood Sandstone aquifer and this could mean an increase from about 10% to 25-35% of the outcrop being covered by forestry. Since much of the present groundwater in the area has a nitrate concentration at or close to the EC limit, the conversion of farmland to woodland should be beneficial in the long run since it is likely to reduce nitrate leaching from the newly forested areas by at least a factor of two to three. Important factors are the type of land converted (derelict, arable, or grassland), and the size and shape of the woodland planted. The tree species planted may also be important but relatively little is known about this.

6.2 HYDROGEOLOGICAL BACKGROUND

The most important aquifer in the proposed forest area is the Sherwood (Triassic) Sandstone (Fig. 1). It contains a number of important public supply boreholes. The aquifer is unconfined and the groundwaters usually contain detectable tritium (Edmunds *et al.*, 1982) indicating that there is a contribution of groundwater of recent origin.

The eastern boundary of the proposed forest lies near the boundary with the Mercia Mudstone and therefore beyond this point the Sherwood Sandstone is confined. The regional groundwater flow is predominantly from west to east.

6.3 EFFECT ON WATER QUALITY

There have been no detailed studies on the effect of afforestation on groundwater quality in the area and it is therefore necessary to extrapolate from studies elsewhere. Since the effect of afforestation depends on the existing groundwater quality and the specific change in land use envisaged, this is briefly reviewed below.

6.3.1 Existing water quality

Groundwaters from the unconfined Sherwood Sandstone in this region are characteristically well-aerated, Ca-Mg-HCO_3-type waters. They are probably of recent origin, mainly younger than 100 years, and can be affected by agricultural inputs and mine drainage. The water quality will reflect land use changes although the response at the pumping station is likely to take decades rather than just a few years.

We do not have a comprehensive set of water quality data for boreholes in the region but a recent groundwater survey completed by BGS (Edmunds and Smedley, 1992) in the northern part of the proposed forest area gave the following data for nitrate, chloride and bromide:

Borehole	**NO_3-N**	**Cl** mg/l	**Br**
Far Baulkner 3	13.5 (8.1)	30 (18)	0.086
Amen corner 1	12.0 (7.5)	46 (87)	0.150
Clipstone 1	11.6	285	2.96
Rufford 3	2.8	126	1.03
Rufford 4	5.3 (2.5)	31 (69)	0.148
Farnsfield 1	12.2 (10.4)	31 (24)	0.097

The figures in parentheses are from the 1975 sampling (Edmunds *et al.*, 1982). The data indicate that nitrate concentrations in the unconfined Sherwood Sandstone in this area are presently high, and in many cases are close to the drinking water limit of 11.3 mg/l NO_3-N. These nitrate concentrations have increased over the last fifteen years and are likely to continue to do so for at least another decade. This steady increase in nitrate concentration reflects agricultural inputs including the ploughing up of established grassland since the Second World War. The Cl concentrations have also changed significantly since 1975 which indicates a more complicated picture - maybe a change in the proportion of mine drainage, for example. The low nitrate concentrations at Rufford pumping station may reflect its position just east of Clipstone Forest but the site is known to be complicated and is affected by mine drainage, and river water recharge. Data for the Clipstone Forest borehole would be interesting.

Some of the bromide concentrations are unusually high and although these are correlated with higher than normal chloride concentrations, the Br/Cl ratio is also high (about 1:100 compared with 1:300 which is more typical of groundwaters). Since high Br/Cl ratios are usually found where there is breakdown of organic matter this suggests that there might be a component of groundwater from the Coal Measures in these samples.

6.3.2 Effects of afforestation on nitrate leaching

Much depends on the type of land where the trees will be grown. This is likely to be a combination of derelict land including old mine workings and agricultural land. The most important effect is likely to be the reduction in N fertilizer input to both arable land and grassland, but there are likely to be short-term effects due to the disturbance that takes place during the establishment phase. This could include the leaching of herbicide and an increased nitrate loss when woodland is established on formerly undisturbed land. This initial effect is likely to last no more than a few years.

Recent research has shown that N leaching from highly fertilized grassland can be as great as from arable land. The lack of annual ploughing may also be important since this promotes the breakdown of soil organic matter. The introduction of good agricultural practices (minimal use of autumn applied N, more and earlier planting of winter cereals) in recent years has led to significant reductions in nitrate leaching, maybe by a factor of two (Parker *et al.*, 1991). Therefore the peak period of nitrate leaching may already have passed. Some of the Sandstone outcrop area is used to grow potatoes - nitrate leaching from these areas is likely to be high. The concentration of nitrate in current recharge from agricultural land is likely to be in the range 10-50 mg/l NO_3-N.

The amount of leaching from the new forest areas will reflect many factors such as the size of atmospheric inputs, the age of the forest, tree density and species. For example, there seems to be considerably less leaching under ash compared with beech. No studies have looked at oak which may be an important component of the new planting.

The major long term effects of afforestation on groundwater quality are due to (i) a change in the amounts of atmospheric and other inputs to the aquifer; (ii) increased recycling of essential solutes in the soil zone; and (iii) edge effects.

Previous studies indicate that afforestation increases the scavenging of N-species from the atmosphere particularly ammonia gas and ammonium-containing particulates. At Black Wood in Hampshire, total N deposition in the throughfall beneath beech was about twice that in the open areas (13 kg N/ha/yr compared with 6 kg N/ha/yr) (Harding *et al.*, 1992). Other estimates based on deposition velocities of N species suggested fluxes five or six times greater than this but these seem unrealistically high. There may be additional inputs not seen in the throughfall measurements due to direct uptake of N by the canopy and deposition in the autumn as leaves, for example.

However, whatever the inputs, N cycling in forests is quite efficient and so leaching tends to be low although not as low as might at first be thought. Extensive drilling at Black Wood indicated that the concentration of nitrate leaching beneath beech varied from less than 1 mg/l to more than 20 mg/l NO_3-N . It was greatest in the open areas in the forest where the nutrient cycle of the forest had been broken and least within 30 m of the edge of the forest. Extrapolating from the results at Black Wood, the average concentration of nitrate-N leaching from mature beech woodland is likely to be between 5-10 mg/l. It is likely to be less than 5 mg/l under ash, maybe considerably less. Therefore there is likely to be a reduction of nitrate leaching over present agricultural practice by a factor of at least two to three times in the forested areas.

At the exposed edges of forests, nitrate leaching may be considerably less than this. This could be important in small woods (less than one hectare) or where trees are planted in elongated strips. Shelter belts seem quite a likely option for the Sandstone areas.

6.3.3 Impact on groundwater quality of new planting for the Greenwood Community Forest

The final details of the Community forest have yet to be decided. The total designated area of the Community Forest currently being considered is 44000 ha of which approximately 2700 ha (6%) are currently believed to be forested; this figure is being revised by including smaller parcels of woodland and may end up closer to 11% of the total area. It is proposed to establish some 10000 further hectares of forestry in the area which would mean planting forest on 24% of the non-forested area and would result in 29% of the area being forested. The outcrop of the Sherwood Sandstone is approximately 26000 ha or about 59% of the area. It seems likely that the final area of Community Forest may be less than the 44000 ha currently being considered.

If we assume a uniform location of the forests, then up to 6000 ha of Sandstone outcrop could be planted over a period of a decade or more. If all the new trees were on outcrop, this would occupy about 41% of the outcrop area as opposed to only about 6%-11% at present (this latter figure is calculated assuming a uniform distribution of trees at present - in fact it appears that a disproportionate amount of the existing Sandstone outcrop area is already forested). Therefore the Community forest would probably change the Sandstone outcrop land use from say 10% forested at present to perhaps 25-35% forested in the future. This is a major change. From a water resources point of view, such afforestation would seem a good long-term strategy for nitrate-sensitive areas. The only provisio is that when the trees eventually approach maturity, a sound management scheme should be introduced to prevent the accumulated soil nitrogen being mineralized and leached to the groundwater.

The scavenging action of forests will increase the input of acidic substances from the atmosphere and there is also likely to be a reduction in inputs of agricultural lime if agricultural land is converted into woodland. However, the Sherwood Sandstone aquifer is generally well-buffered in the area and so this increased input of acidity is unlikely to affect groundwater quality adversely.

6.3.4 Time of response of groundwater quality to changes in land use

This is difficult to judge precisely but changes in pumped water quality will be slow and it is likely to take a decade or more to reverse present trends. A regular monitoring programme at a few key sites would be useful. This should be started before the proposed changes take place.

7 Conclusion

In all likely scenarios, it appears that broadleaf woodland is likely to have lower evaporation than grass or cereal crops by about 60 ± 50 mm a^{-1}. The amount by which this is lower is dependent on the factors investigated here, such as rainfall variations both spatially and from year to year. Other factors not considered are different agricultural crops; irrigation, which is common in the area, and different broadleaf species, in particular the effect of an understorey.

Coniferous forest, by maintaining a leafed canopy over the whole year, allows both transpiration and interception to exceed the corresponding values for broadleaf plantation. Serious water resources problems could well result if significant amounts of coniferous plantation were introduced onto the aquifer outcrop.

The effect on water quality is expected to be beneficial, particularly for nitrate, but any changes are likely to take effect over decades.

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APPENDIX

Records in the IH Soil Moisture Databank relevant to the Proposed Greenwood Community Forest Area

SITE GROUP: F

INVESTIGATOR: G Chubb
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OBJECTIVES

The data was collected as part of a two and a half year investigation of soil moisture regimes in the Doverbeck catchment, a small catchment which drains south-eastwards from the Bunter sandstone outcrop into the river Trent, approximately 15 km east of Nottingham. In total 12 pairs of access tubes were installed throughout the catchment. The data from only 10 of the sites have been included in the databank; the mean of the data from each pair of tubes was used.

OPERATIONAL DETAILS

Frequency and period of readings: Monthly or more frequently, commencing in June 1975 and continuing until October 1977.
Reading depths: At 10 cm intervals from the surface to depths of 140 to 250 cm depending on how difficult it was to install the access tubes. The series of readings began at different depths at different sites.
Calibration: No calibration was prepared for the sites and so the appropriate Institute of Hydrology calibrations were used.

SITE DESCRIPTION

SITE: F1

Grid Ref: SK658480
Soil: Gleyed brown earth (Ollerton complex)
Landuse: Mown grass
Elevation: 35 m
PM Texture: Sandy alluvium/colluvium

The access tubes were installed in an area of rough grass in the grounds of Epperstone Pumping Station. The site is almost level being upon the colluvium-alluvium just below the break of slope at the valleyside. The site is probably sheltered to the north east by the valleyside slope and to the north west by a hedgerow of tall trees about 15 m away. The rough grass sward was mown quite frequently

Soil: The soil is probably an example of the gleyed brown earth phase of the Ollerton complex of gleyed soils. These soils occur on sandy gravelly alluvium derived from the Bunter Sandstone (Robson and George 1971). At the site the textural horizonation of the profile was as follows: 0 to 30 cm, sandy loam; 30 to 50 cm, sandy loam with mottling; 50 cm plus, stony mottled loam.

SITE: F2

Grid Ref: SK658482
Soil: Gleyed brown earth (Ollerton complex)
Landuse: Permanent pasture
Elevation: 35 m
PM Texture: Sandy alluvium/colluvium

Located in a field on the north westside of site F1 in permanent pasture, this site was very similar to site F1, level, but sheltered by the line of trees on its east side.

Soil: The soil was also an example of the Ollerton complex gleyed brown earths (see F1)

SITE: F3

Grid Ref: SK659477
Soil: Gley (Ollerton complex)
Landuse: Permanent pasture
Elevation: 30 m
PM Texture: Sandy alluvium

This site was to the south east of the Epperstone Pumping Station about 40 m from the Dover beck. The access tubes were protected in a small fenced enclosure located adjacent to the hedge of a field of permanent pasture. The hedge probably afforded some shelter to the site.

SITE GROUP: F (continued)

Soil: The soil was probably an example of a ground water gley of the Ollerton Complex (Robson and George 1971). The texture of the surface horizons was sandy loam and given its proximity to the stream, its lower horizons must be very gleyed. The height of the water table varied from 20 cm to 350 cm during the recording period

SITE: F4
Grid Ref: SK649477 *Elevation:* 46 m
Soil: Gley (Ollerton complex) *PM Texture:* Sandy alluvium/colluvium
Landuse: Unkempt grass

The site was located in the uncultivated corner of a field of a market garden. It was almost level being upon the alluvial and colluvial material accumulated at the side of the valley floor. It was vegetated by grass and a variety of weeds and sheltered by a hedge about 5 m away on the north side.

Soil: The soil was another example of the Ollerton complex of groundwater gleys (see above). The texture of the soil horizon was as follows: 0 to 20 cm, fine sandy loam susceptable to surface panning; 20 to 45 cm, structureless sandy loam; 45 cm plus, loamy sand.

SITE: F5
Grid Ref: SK649475 *Elevation:* 60 m
Soil: Brown earth (Hodnet) *PM Texture:* Loam
Landuse: Unkempt grass

This site was located about 100 m up slope from F4 on the lower slope of the north-west facing valley side. The site was exposed in all directions and located in an area of uncultivated weedy ground in the middle of the nursery.

Soil: An example of the Hodnet series of brown earths, the soil profile was described as follows: 0 to 20 cm silt loam; 20 to 50 cm, silt loam with few black manganiferous corrections; 50 cm plus, silty clay loam of firm consistency. These soils, described by Robson and George (1971) occur on the interbedded marls, siltstones and sandstones of the Keuper Waterstone and are moderately or well drained. The profile, with some evidence of temporary waterlogging might alternatively be assigned to the Hodnet complex of gleyed brown earths.

SITE: F6
Grid Ref: SK639480 *Elevation:* 45 m
Soil: Gleyed brown earth (Hodnet complex) *PM Texture:* Loam
Landuse: Unkempt grass

This site was located in a nursery garden to the west of Woodborough on the gentle lower east facing valley side slope. The access tubes were installed in an uncultivated weedy corner of a field and sheltered by high bushes about 10 m to their west side.

Soil: The soil was probably an example of the Hodnet complex of gleyed brown earth developed upon Keuper waterstones (see F5).

SITE: F7
Grid Ref: SK641478 *Elevation:* 40 m
Soil: Gley (Ollerton complex) *PM Texture:* Sandy alluvium
Landuse: Unkempt grass

Situated on alluvium within 20 m of a small tributary to the Dover beck, this site was flooded intermittantly during the wintermonths. It was almost due east of F6 but on the opposite side of the stream. The site was vegetated by grass and weeds and partially sheltered to the west by trees adjacent to the stream.

SITE GROUP: F (continued)

Soil: The soil was similar to that of the flood plain site at Epperstone, F3, ie. a groundwater gley of the Ollerton complex developed in sandy alluvium.

SITE: F8

Grid Ref: SK633502	*Elevation:* 61 m
Soil: Brown earth (Hodnet)	*PM Texture:* Loam
Landuse: Woodland	

This was a moderately sloping site (6^{o}) in a lower valley side slope position located at the edge of Epperstone Park Wood. The vegetation is grass and bracken below deciduous trees.

*Soil:*Another brown earth of the Hodnet series similar is that at site F5 and developed on the Keuper Waterstone. A 25 cm deep surface horizon overlay 45 cm of very slightly mottled silt loam.

SITE: F9

Grid Ref: SK613544	*Elevation:* 91 m
Soil: Podzol (Crannymoor)	*PM Texture:* Sandstone
Landuse: Mown grass	

Far Baulker pumping station is located in an exposed position just below the crest of the Bunter sandstone escarpment 2 km north west of Oxton. The access tubes were installed in the mown grass of the grounds on the east side of the station.

Soil: The soil was assigned to the Crannymoor series of podzols but it had evidently been cultivated and organic A horizon destroyed. The Crannymoor series is characteristic of the Bunter sandstone and the profile was of loamy sand texture (Robson and George 1971).

SITE: F10

Grid Ref: SK611545	*Elevation:* 90 m
Soil: Podzol (Crannymoor)	*PM Texture:* Sandstone
Landuse: Coniferous wood	

This site was near to F9 but 8 m within the forestry commission plantation of conifers to the north side of the pumping station. The access tubes were midway between two trees, about 3 m from each. The trees are mature and there is an understorey of grass, bracken and bramble and a deep litter of twigs and pine needles. The site slopes gently to the north west.

Soil: A very typical example of the Crannymoor series of podzols. The texture of the upper part of the profile was described as follows: 0 to 5 cm, partially decomposed litter of pine needles; 5 to 35 cm, loose loamy sand with bleached grains; 35 to 40 cm thin iron stained loamy sand; 45 cm plus, stony sand

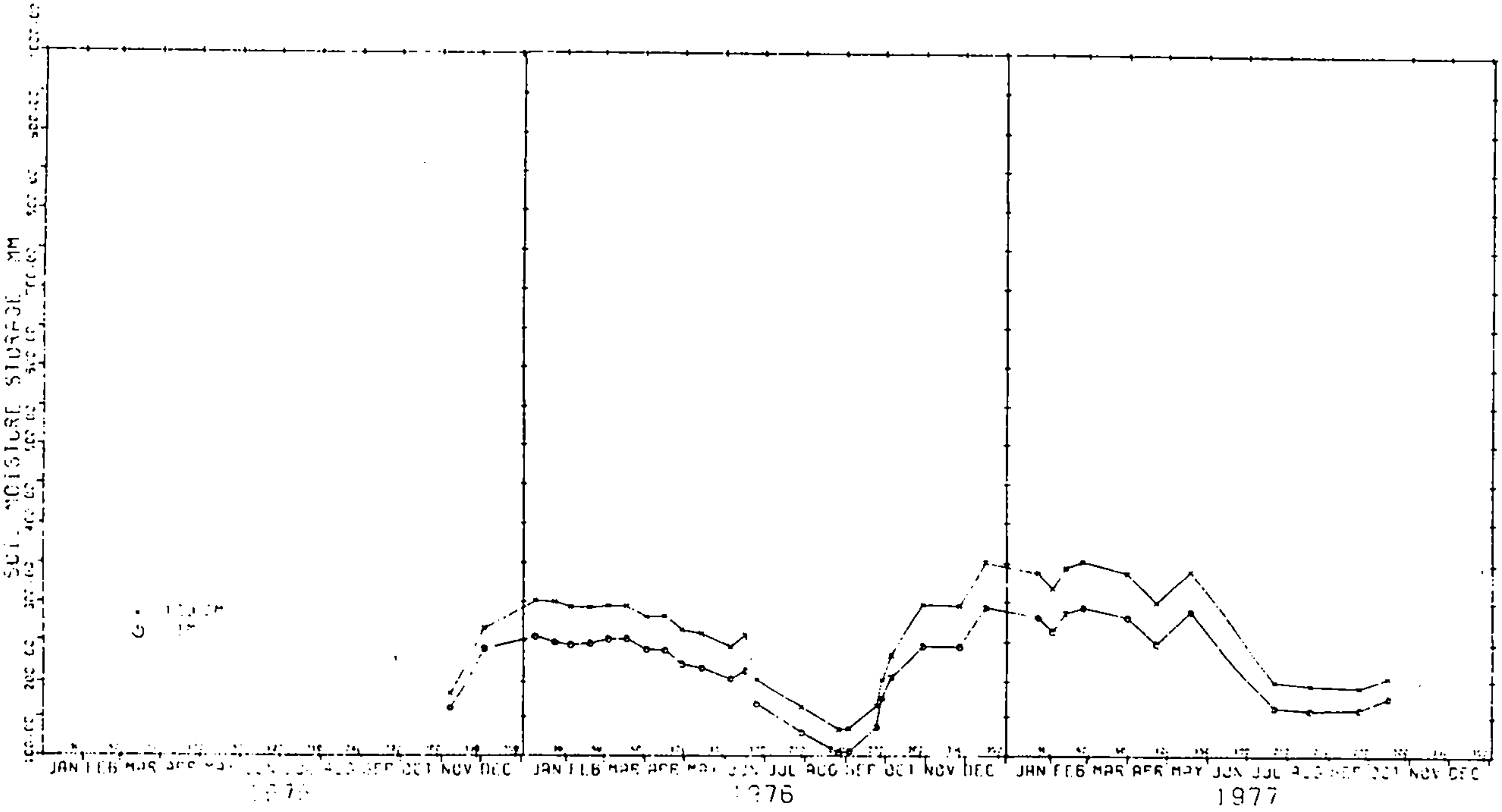

FIGURE 4

Site: F9 **PM Texture:** SANDSTONE **Soil:** PODZOL (CRANNYMOOR) **Landuse:** MOWN GRASS

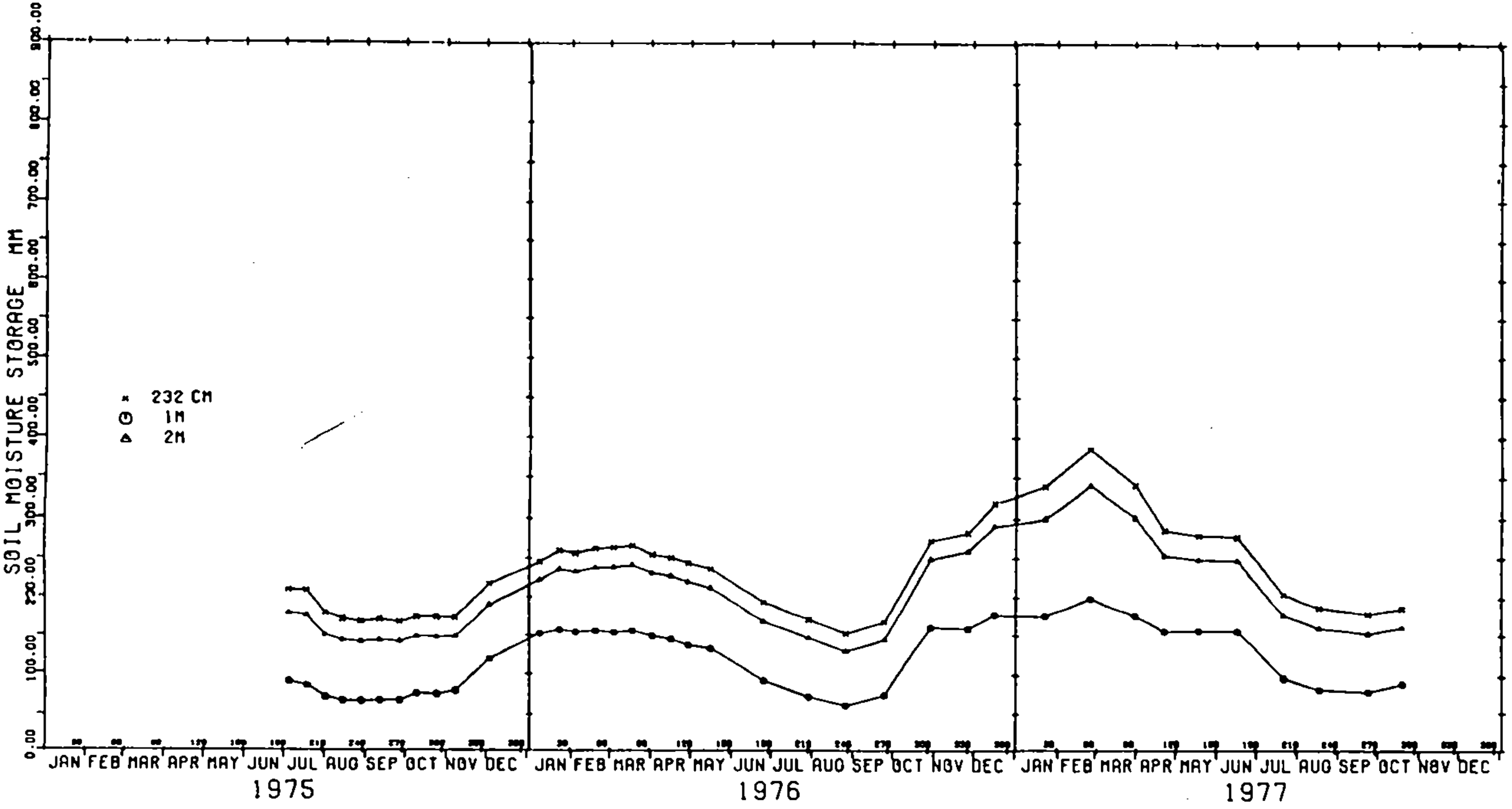

FIGURE 5

Site: F10 PM Texture: SANDSTONE Soil: PODZOL (CRANNYMOOR) Landuse: CONIFEROUS WOOD

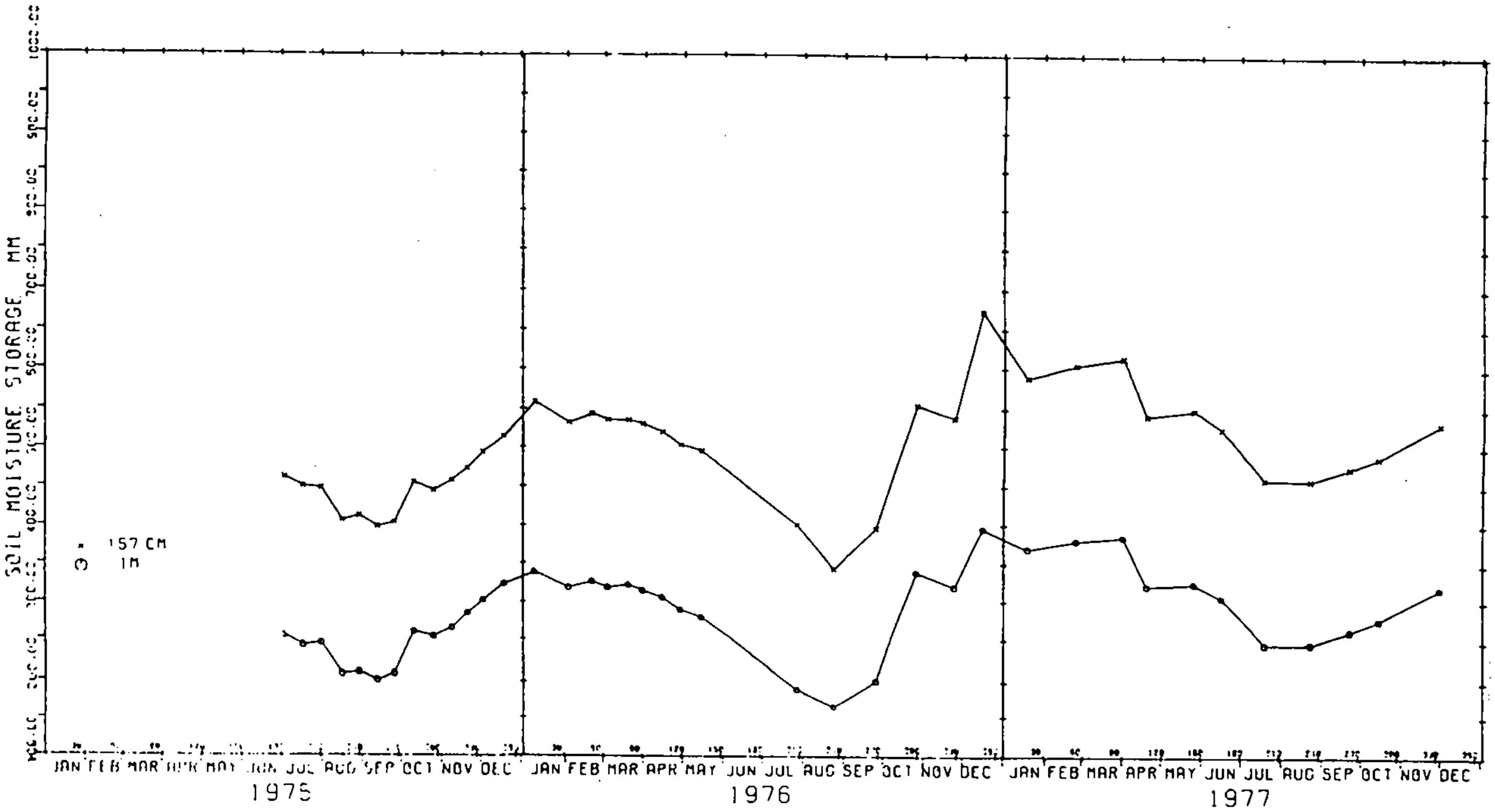

FIGURE 33

Site: F1 **PM Texture:** SANDY ALLUVIUM/COLLUVIUM **Soil:** GLEYED BROWN EARTH (OLLERTON COMPLEX) **Landuse:** MOWN GRASS

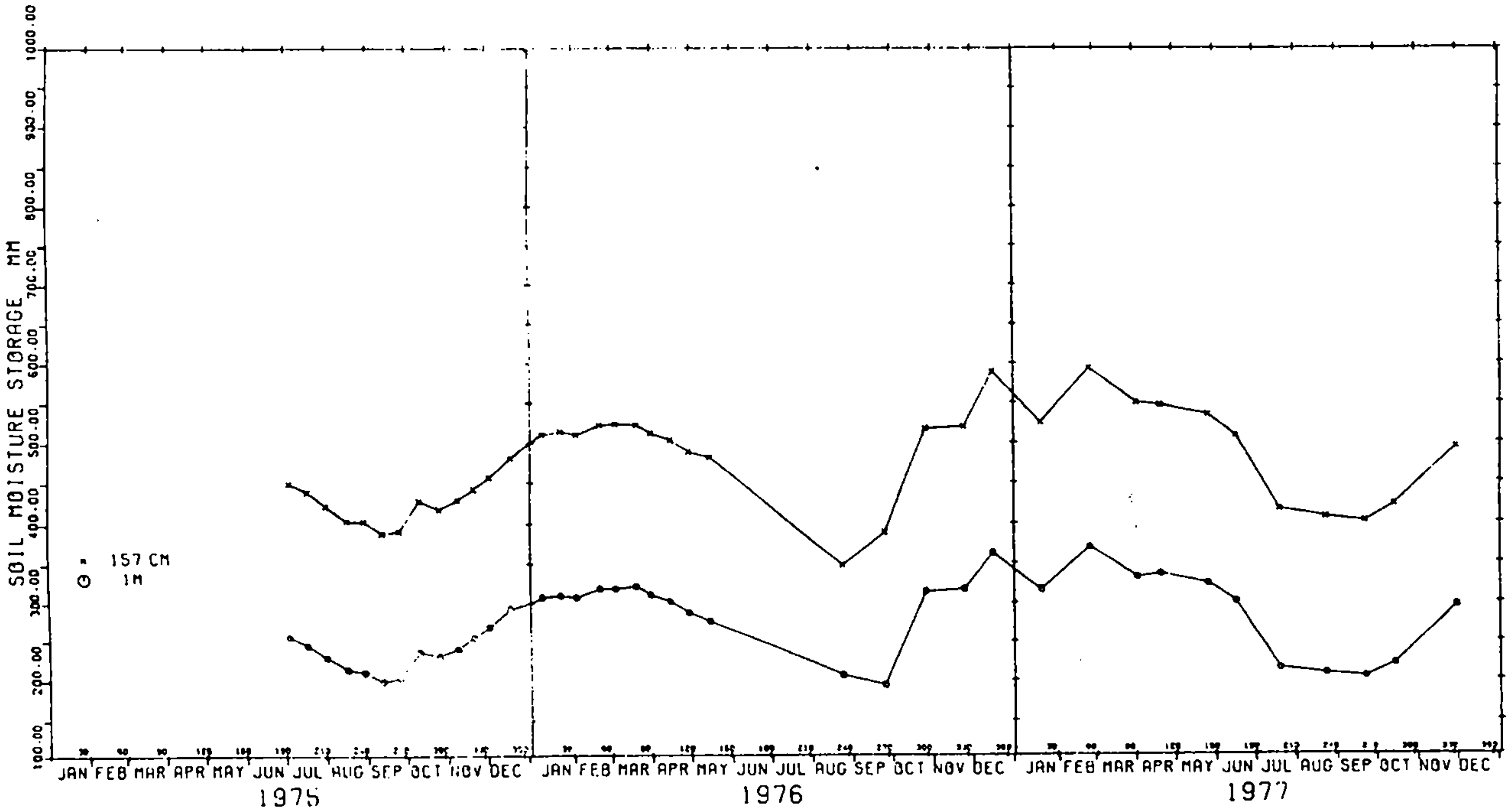

FIGURE 34

Site: F2 **PM Texture:** SANDY ALLUVIUM/ COLLUVIUM **Soil:** GLEYED BROWN EARTH (OLLERTON COMPLEX) **Landuse:** PERMANENT PASTURE

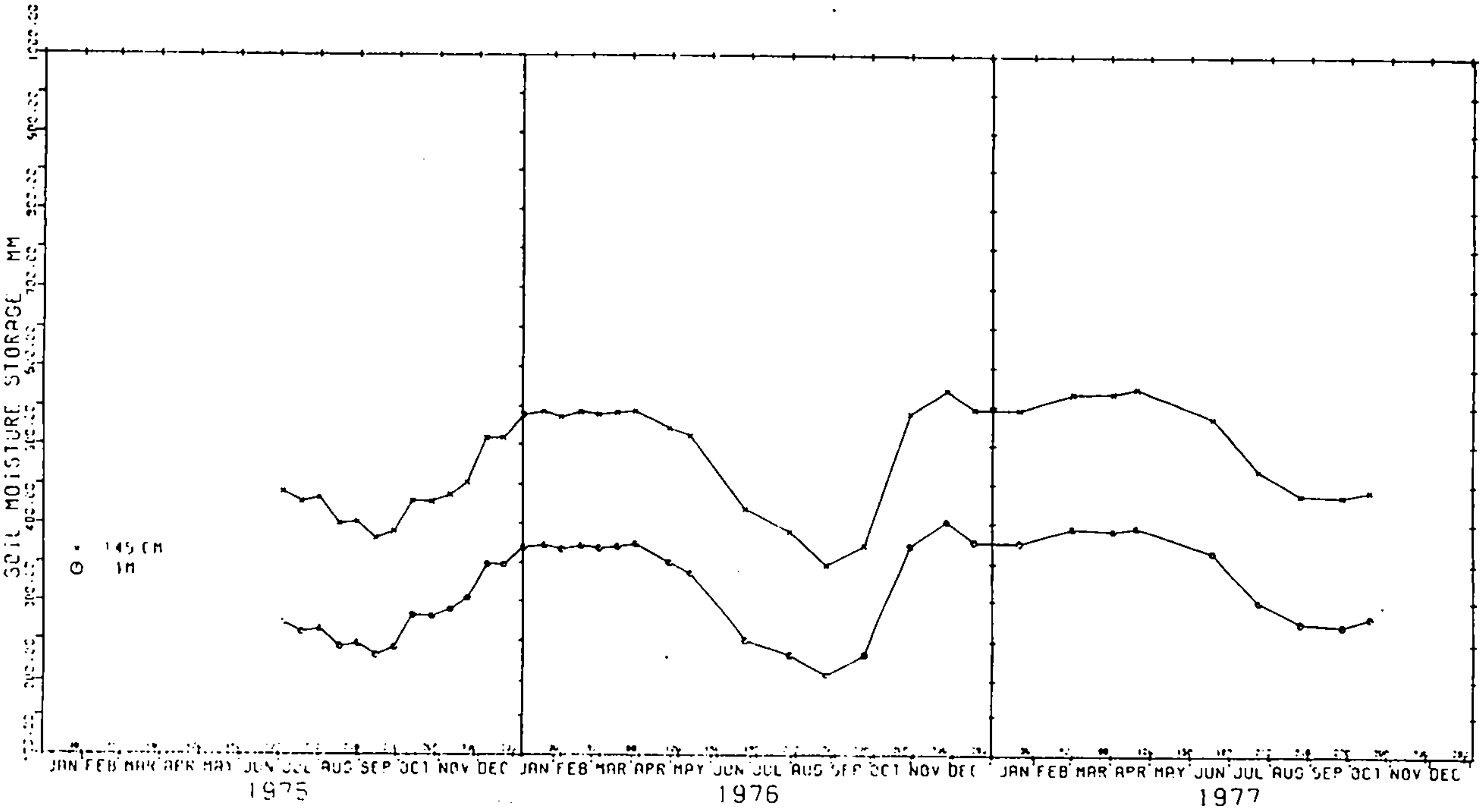

FIGURE 35

Site: F5 **PM Texture**: LOAM **Soil**: GLEYED BROWN EARTH (HODNET) **Landuse**: UNKEMPT GRASS

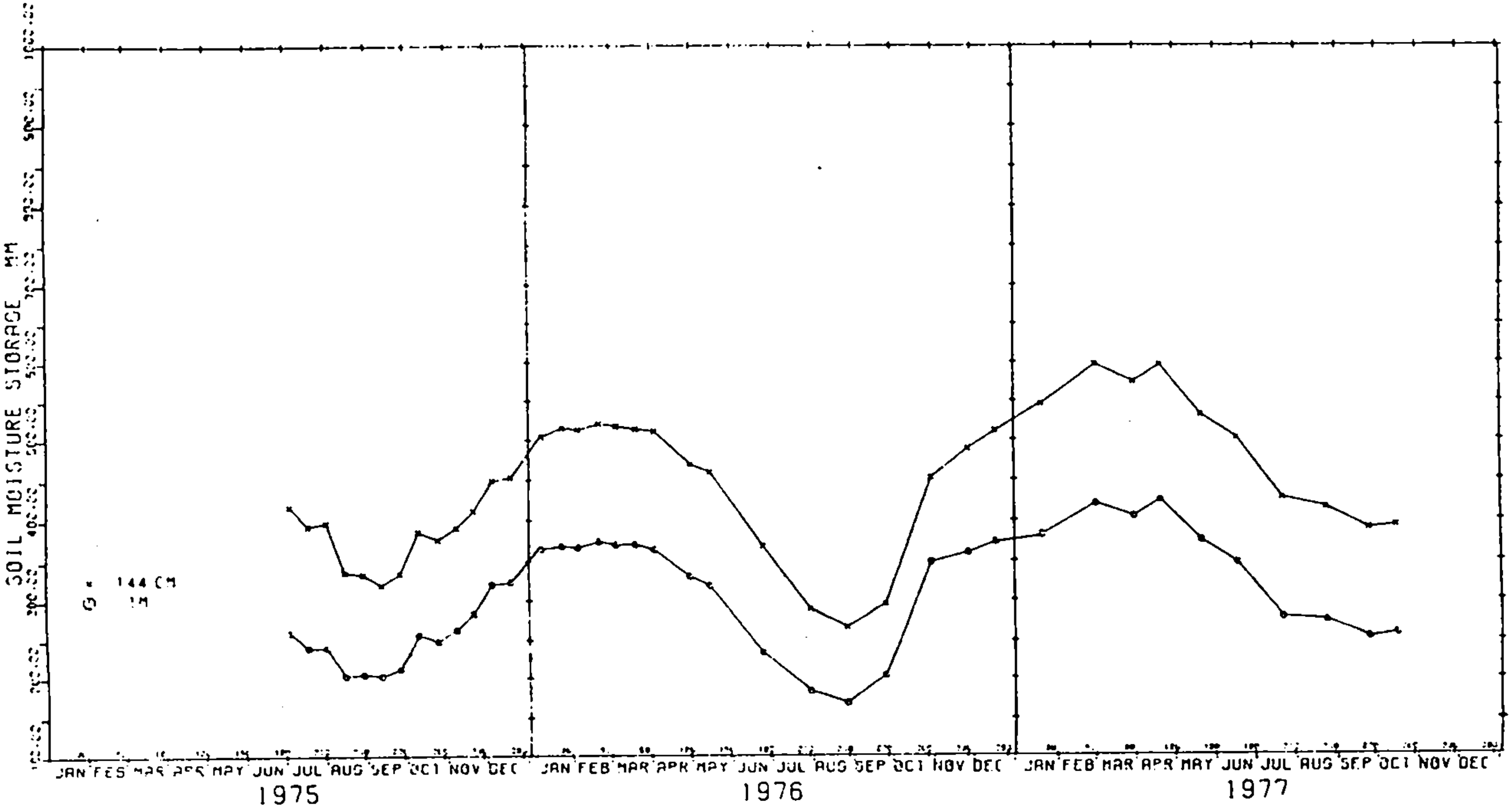

FIGURE 36

Site: F6 **PM TExture:** LOAM **Soil:** GLEYED BROWN EARTH (HODNET) **Landuse:** UNKEMPT GRASS

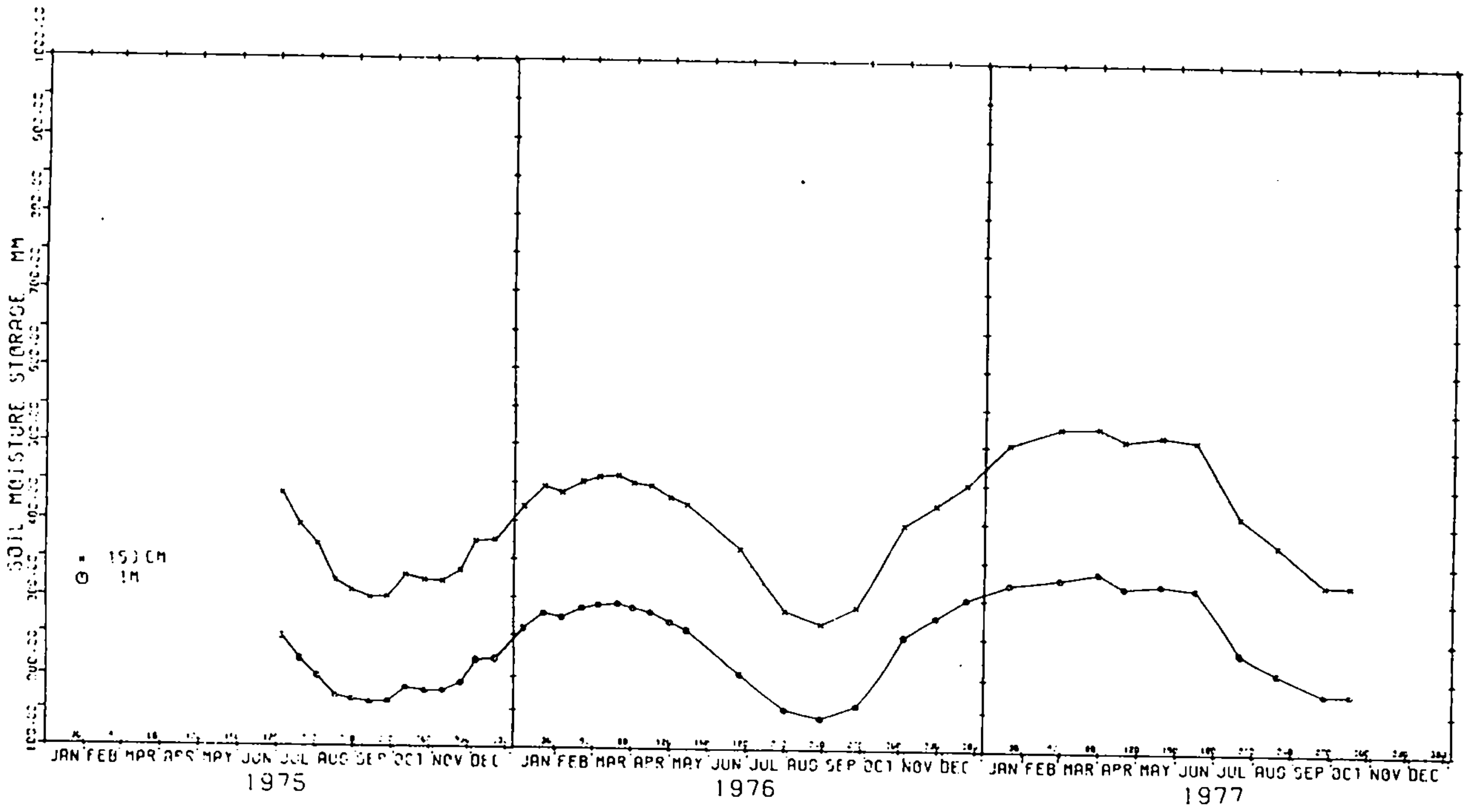

FIGURE 37

Site: F8 **PM Texture:** LOAM **Soil:** GLEYED BROWN EARTH (HODNET) **Landuse:** WOODLAND

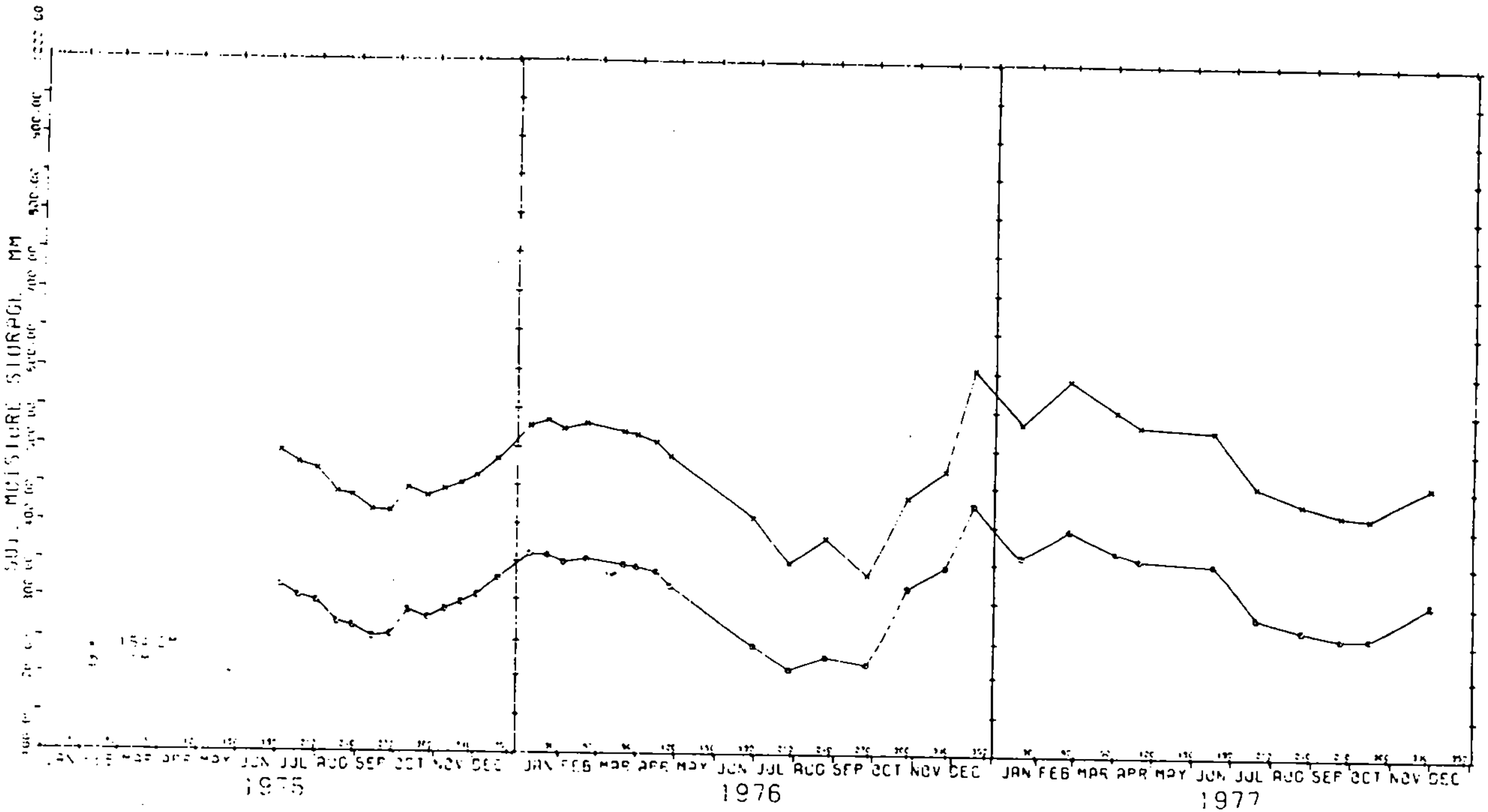

FIGURE 61

Site: F3 **PM Texture:** SANDY ALLUVIUM **Soil:** GROUNDWATER GLEY (OLLERTON COMPLEX) **Landuse:** PERMANENT PASTURE

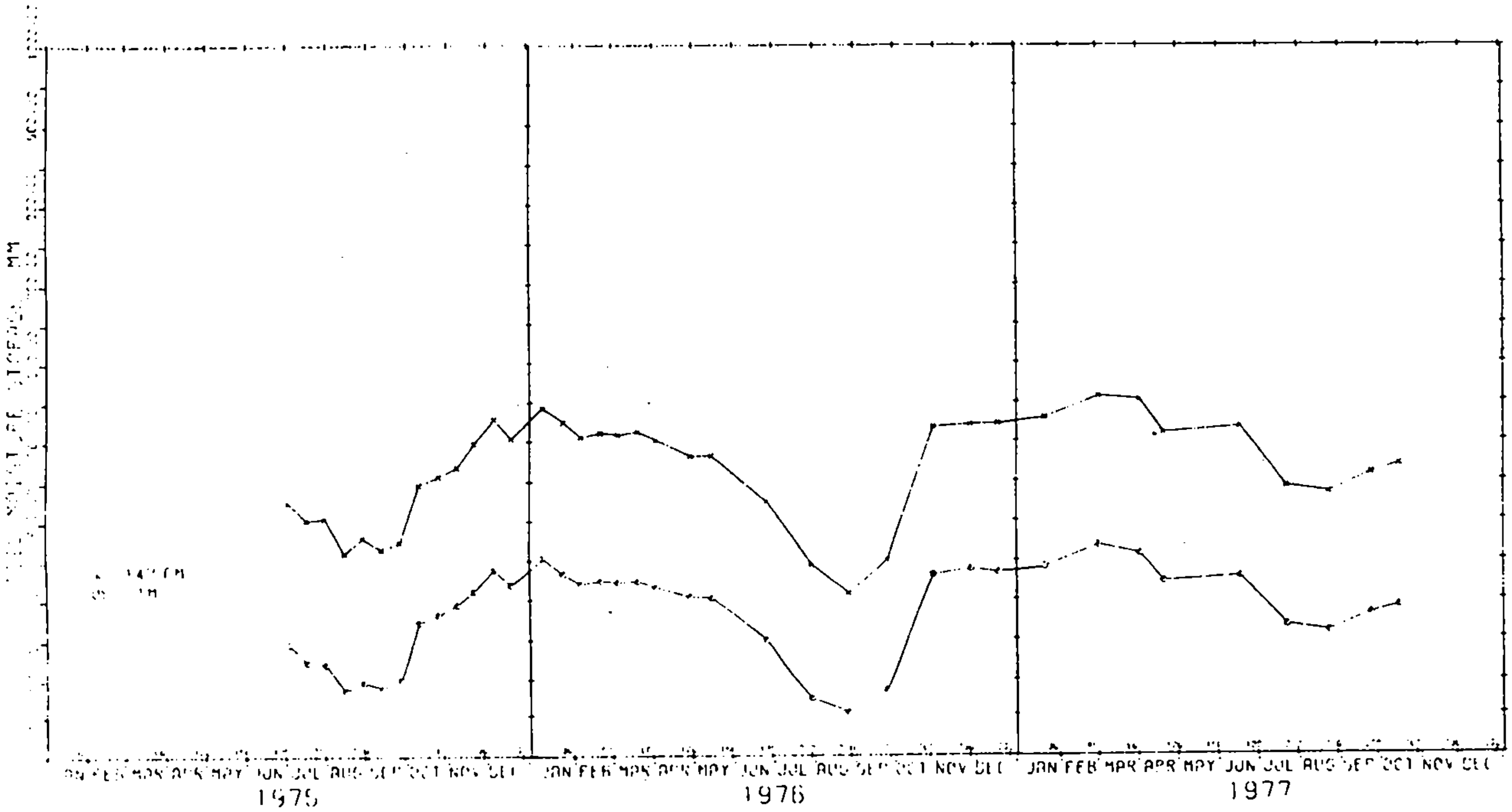

FIGURE 62

Site: F4 **PM Texture:** SANDY ALLUVIUM **Soil:** GROUNDWATER GLEY (OLLERTON COMPLEX) **Landuse:** UNKEMPT GRASS

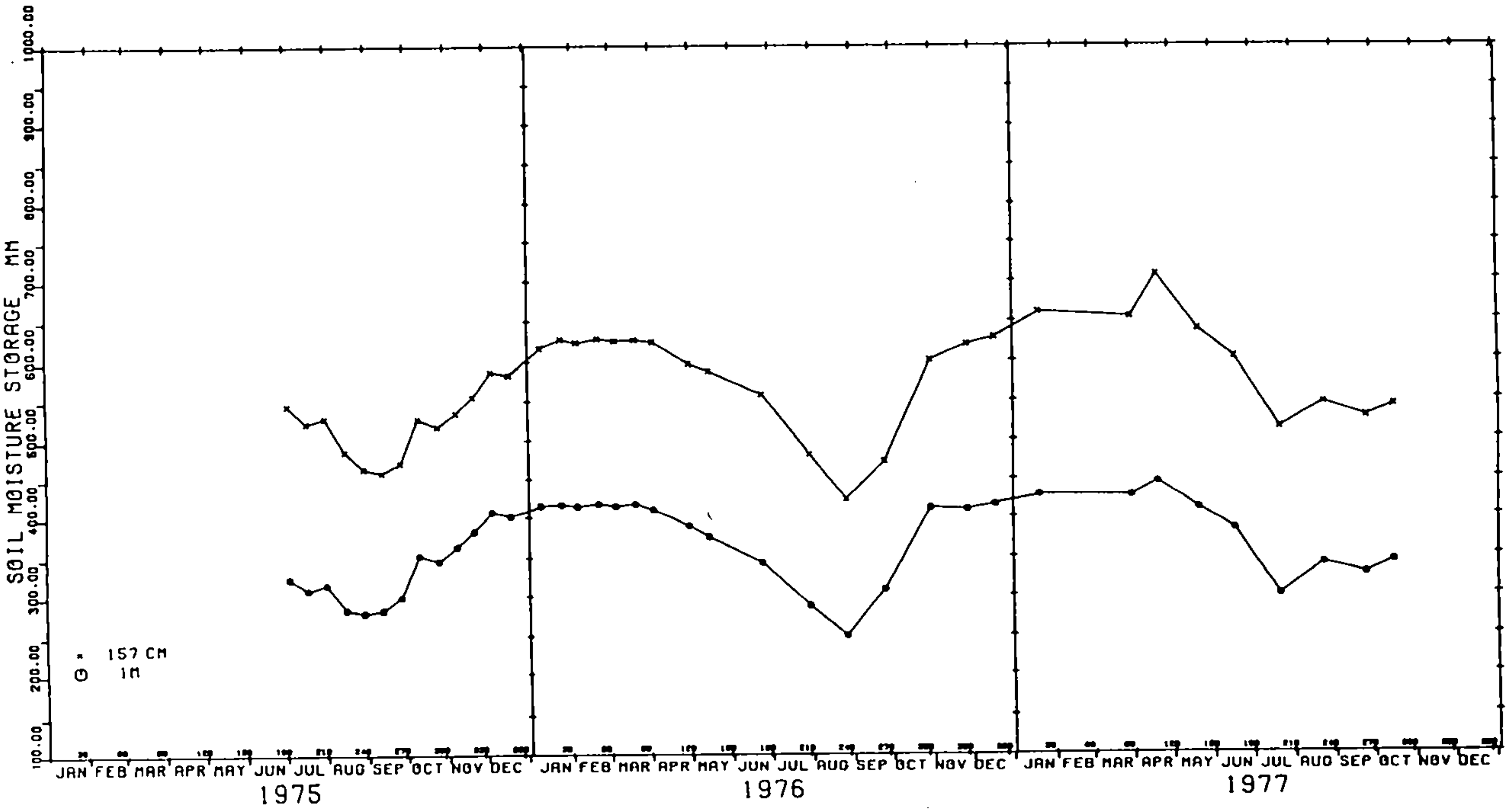

FIGURE 63

Site: F7 PM Texture: SANDY ALLUVIUM Soil: GROUNDWATER GLEY (OLLERTON COMPLEX) Landuse: UNKEMPT GRASS

Texture	Soil type	Parent material	Soil series	Site code	Fig. No.
BROAD BEANS					
Sand	Gleyed brown earth	Terrace sands	Arrow	K1	31a
				K2	31b
				K3	31c
CABBAGE					
Loam	Gleyed brown earth	Terrace sands	Arrow	K4	32a
		Brick earth	Wickmere	J2	42c
LEEK					
Sand	Gleyed brown earth	Terrace sands	Arrow	K5	32b
REDBEET					
	Gleyed brown earth	Terrace sands	Arrow	K6	32c
SUGAR BEET					
Sand	Gleyed brown earth	Chalky drift	Moulton or Ashley	J1	42b
APPLE ORCHARD					
Loam	Brown earth	Triassic marl and sandstone	Greinton	P1	22
				P2, P3, P4	-
		Drift and Triassic marl	Tickenham	O1	24
		Triassic marl and sandstone	Greinton	P5	23
				P6, P7, P8	-
CONIFEROUS WOOD					
Sand	Podzol	Bunter sandstone	Crannymoor	F10	5
Loam	Rendzina	Chalk-sand drift	Newmarket-Methwold	T16	21
	Brown calcareous	Chalk-sand drift	Worlington	T15	28
MIXED WOOD					
Sand	Gleyed brown earth	Calcareous grits	Kington	Q9	30
Loam	Gleyed Brown earth	Keuper water-stones (marls, silts and sandstones)	Hodnet	F8	37